BREE 495 - Engineering Design 3

Department of Bioresource Engineering - McGill University

DESIGN PROJECT REPORT

Automated Liquid Nutrient Analyzer for in-situ Quality Control

Professor: Chandra Madramootoo

Client: Circulus AgTech (Mohamed Debbagh, CTO)

Submitted by

Ilias Hader

Yuxing Han

Nina Cardenas

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LIST OF ACRONYMS AND ABBREVIATIONS

Automated Liquid Nutrient Analysis	ALNA
American National Standards Institute	ANSI
American Society of Agricultural and Biological Engineers	ASABE
American Society of Mechanical Engineers	ASME
American Society of Safety Professionals	ASSE
Bayonet Neill-Concelman	BNC
Computer-Aided Design	CAD
Continuous Liquid Interface Production	CLIP
Canadian Standards Association	CSA
Dosing Box	DB
Electrical Conductivity	EC
Ethylene Propylene Diene Monomer	EPDM
Fused Deposition Modeling	FDM/FFM
Inside Diameter	ID
Ion-Selective Electrode	ISE
Ion-Sensitive Field-Effect Transistors	ISFET
Liquid Nutrient Analysis	LNA
Normally Closed	NC
Nutrient Film Technique	NFT
Normally Open	NO
NODE-Red	NR
Outside Diameter	OD
Organic Liquid Fertilizer	OLF
Polycarbonate	PC
Polyethylene terephthalate	PET
Pondus Hydrogenii	pH
Polypropylene	PP
Polyvinyl Chloride	PVC
Raspberry Pi	RPi
Stereolithography	SLA
Total Soluble Solids	TSS
Underwriters Laboratories	UL
Ultraviolet	UV

ABSTRACT

This design consists in designing an automated physicochemical data-retrieving system for the analysis of liquid fertilizer produced in bioreactors built and operated by Circulus AgTech. The final design is an integrated vessel made of stainless-steel beaker, and a stereolithography-printed insert, with all associated electronics for the dosing of upstream solutions, as well as for the automatic fetching of data from the probes. The design implementation covers all elements including upstream and downstream tanks, and is being automated through the help of Raspberry Pi-controlled pumping and analysis elements, with the software being developed in both NodeRED and Python. The design satisfies all client criteria, and is set to be fully operational by February 2022.

Keywords: NodeRED, liquid nutrient analysis, sensor system, dosing box, tank system.

1. INTRODUCTION

Nowadays, the presence of hydroponic systems in the world is growing rapidly. The ever-changing climate conditions the world faces have urged farmers to find ways to keep growing food in more controlled and protected environments, to offset transportation costs as well as environmental impacts. This happens especially in Canada and its harsh climate. With climate change and the frequency of extreme weather events increasing, crops can have a yield reduction superior to 50% when subject to the outside conditions (*The Impact of Climate Change on Canadian Agriculture*, n.d.).

This has placed an important challenge in the food industry, which found a way to continue working beyond those limitations, such as implementing hydroponic systems all over the country (Allard, 2021). However, it is worth noting the relevant drawback of high inorganic fertilizer use in these systems, since the plants are not in contact with any soil nutrients, so the main source of survival for plants is the water solution with fertilizer.

In hydroponics, plants need specific and controlled doses of nutrients, when low doses will cause deficiencies whereas high doses will poison them (Setiawati et al., 2019). This increases costs for the grower, pollutant presence in wastewater, and unhealthy inorganic food intake for consumers, who have shown the trend to distance themselves more from such consumption as time passes. In present times, several occasions of droughts of inorganic fertilizers have caused prices to soar and producers to begin searching more avidly for an alternative solution (Elkin, 2021).

To solve this, companies have started to put in place systems to address many of these issues, as is the case with Circulus AgTech, based in Montreal. They have studied the synthesis of organic fertilizers from waste, such as manure, fish waste, and biomass, applying bioreaction processes, seemingly having promising results in terms of crop quality and quantity (as per Circulus AgTech's CTO and CEO, 2021). Moreover, the potential benefits of incorporating organic fertilizers into a system are the long-term cost savings, the environmental net-positive by reducing both inorganic and organic waste significantly, human health protection, and the avoidance of plant damage (Ersek, 2021).

To further facilitate this and gain in efficiency, the team has worked on re-inventing the company's novel automated liquid nutrient analyzer to better promote the usage of organic fertilizers in hydroponic systems and reducing e, with the guidance of Circulus AgTech CTO, Mohamed Debbagh, and the support of our professors, especially Dr. Chandra Madramootoo.

1.1 Mission Statement

Vision Statement: Automation of data-fetching and testing calibration for a combination chamber, within a hydroponic system.

Mission Statement: Set up a physicochemical data retrieving system in the calibration chamber with automated data transfer to technicians with due regard to system calibration.

1.2 Previous Design

The legacy system consisted of two separate, in-series chambers - one solely for calibration, the other for liquid nutrient analysis. Four solenoids valves upstream delivered all the solutions (High/Low calibration, water, liquid nutrient) into the calibration chamber, which would then be channeled through the second chamber via tubes linked to a peristaltic pump. An interesting feature of the system, which was devised by Circulus AgTech, is that it solely uses off-the-shelf components, chiefly among them standard pipes to build the chambers; according to Circulus AgTech stakeholders, the standard pipe sizing was determined to have the minimum solution depth for accurate data points gathering. Moreover, the analysis vessel was made of both opaque polyvinyl chloride and transparent polycarbonate, the latter being used for "visual inspection of the liquid depth".

The system was deemed unsustainable by Circulus AgTech after a year of operation given that it needed replacement of components every 3 months while requiring consequent human input - to visually inspect the liquid level depth, to put all six of the sensors one by one in the calibration chamber for calibration, and so on.

A selection of issues that the design team has identified is detailed below:

- Separate chambers: having two chambers through which all solutions go through poses the issue of complexity given that it requires a significant amount of tubing and connections, as well as pumping capacity between both chambers in the form of a peristaltic pump. It is also inefficient in so that, for each calibration, an operator needs to be present to remove the probe from the analysis chamber, put it in the calibration chamber for low calibration, wait for the low calibration, wait for the flushing, wait for the high calibration, wait for the flushing, to then put the probe back to its initial place in the analysis vessel; this has to be done for all six sensors that Circulus AgTech uses.
- Horizontal design: The liquid nutrient has a high biological activity, and Circulus' CTO admitted to us that it should be completely removed from the system as soon as possible in order to limit corrosion and deposits against the tube walls. As per the comments of a Circulus AgTech operator, and despite putting the chamber at a slight angle, there is still biofilm accumulation at the bottom.
- Standard piping sizes: the pipe inner diameter was calculated to be just enough for optimal depth. However, it turns out that, with water running, it wasn't enough in multiple instances for accurate data acquisition.
- Transparent tubing for visual inspection: the aforementioned liquid nutrient, coupled with sunlight coming through the transparent polycarbonate walls, has led to consequent eutrophication.

The figures below detail the CAD rendering of the previous design, as well as a real-life implementation of it at Circulus AgTech's Headquarters in Montréal's Centrale Agricole.

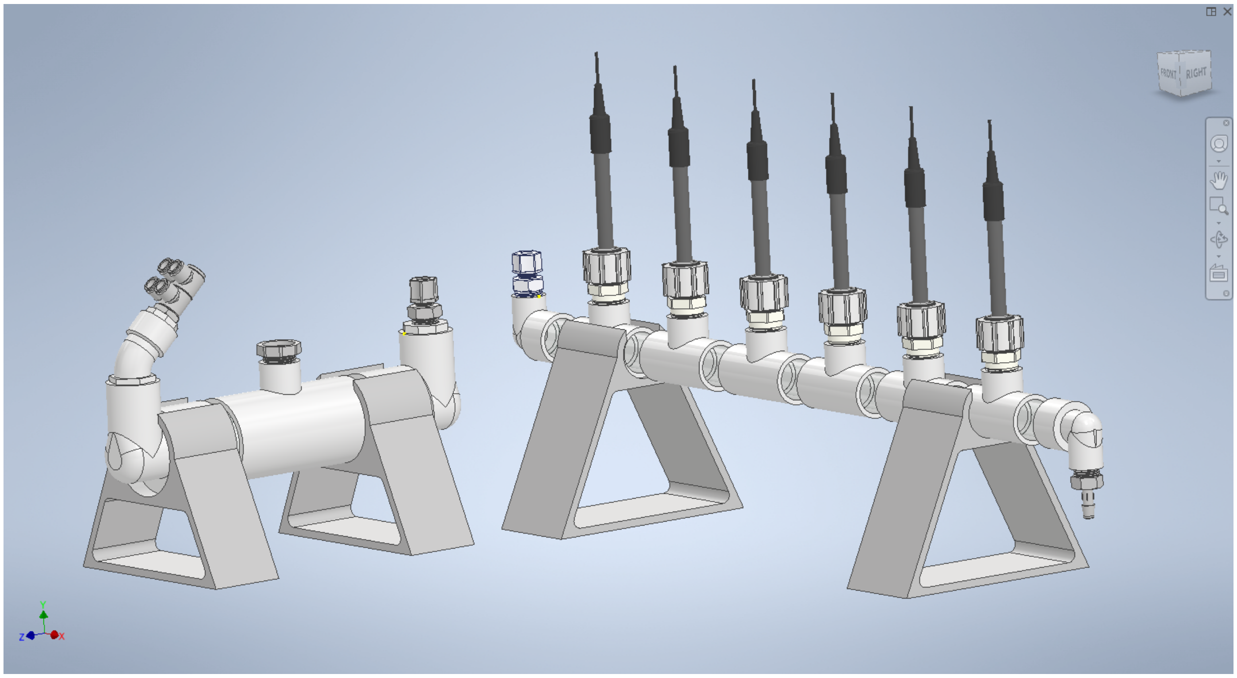


Figure 1. CAD Rendering of the Previous Design, with the Calibration Chamber (left) and Analysis Vessel (right).

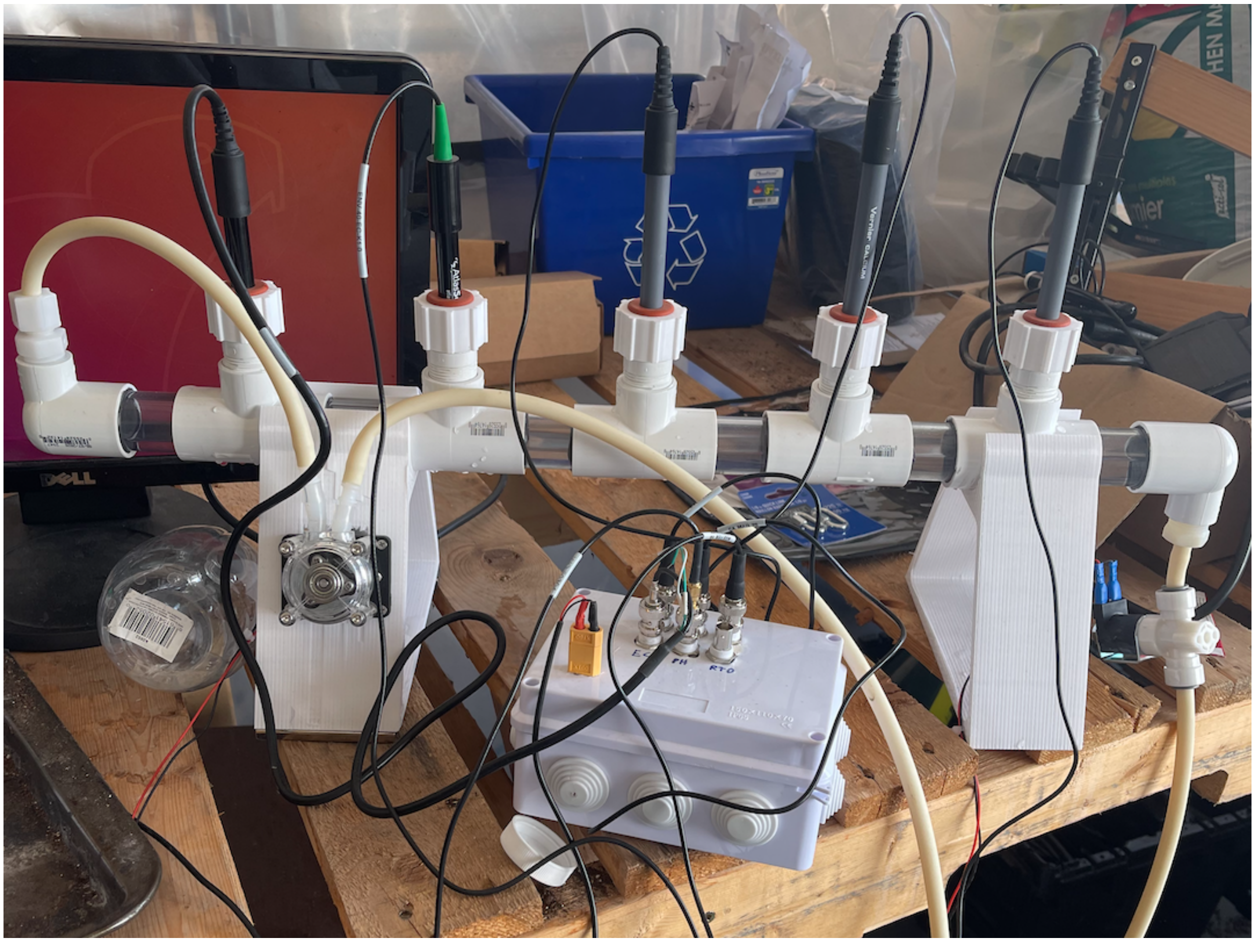


Figure 2. Physical system (Analysis Vessel) currently at Circulus AgTech's Centrale Headquarters.

1.2.1 Approach

This report describes the engineering approach employed to come to a final design of the automated liquid nutrient analyzer for the AgTech Industry, and our corporate partner Circulus AgTech in particular; this is also supplemented by a walkthrough of the prototype construction.

First, the relevant background information extracted from the literature is given, and covers aspects about liquid nutrient analysis, sensors and their usage, as well as additive manufacturing techniques which ought to be used.

Second, the design alternatives are compared, a comparison further complemented by a cost analysis, all the help of engineering decision matrices, where applicable; the resulting best alternative or combination of best subcomponents will constitute our final design.

Third, a detailed description is given about the manufacturing and building process for the prototype; to the possible extent, tests will also be conducted and documented so as to inform us regarding the design's performance and compliance with design constraints.

Lastly, the report is concluded by critically appraising both the design process and the design itself, and recommendations as well as lessons learned are detailed once the issues encountered are fully described.

2. LITERATURE REVIEW

2.1 Nutrition-Related Parameters for Plant Growth

In closed hydroponics systems that use drainage solutions to regenerate high quality organic nutrient solutions with regular input from a bioreactor, they generally employ a nutrient film technique (NFT) where the plants sit along in channels of pipes with their roots suspended inside, and nutrient solutions run across the pipes leaving a thin film to keep the roots moist (Mohammed & Sookoo, 2016).

For the purpose of monitoring the system's physiochemical environment and regeneration of nutrient solutions, common factors essential to the plants' root-zone environment are: electrical conductivity (EC), pondus Hydrogenii (pH), nitrate (NO_3^-), ammonium (NH_4^+), potassium (K^+), and calcium (Ca^{2+}) (Canna, n.d., Brechner & Both).

In systems where the EC and pH values of the nutrient solutions fluctuate constantly since water and nutrients are being extracted by the plants at different levels and rates. One of the chemical reactions associating a solution's EC and pH is salt hydrolysis, "in which one of the ions from a salt reacts with water, forming either an acidic or basic solution" (Flowers, Theopold, Langley, & Robinson, 2019). These factors reflect the solubility, availability, and absorbability of nutrients (Wortman, 2015), crucial to plant growth.

2.1.1 Electrical Conductivity

EC measures the ability of a material or medium to conduct electricity (Oliveira, Georgieva, & Feyo de Azevedo, 2002), and is directly affected by the amount of nutrients present in the solution since they exist in the form of salts. When more nutrients are added, the EC value of the solution rises as a result of increased ions available to transport electrons. Thus, EC could be used to indicate the amount of nutrients present in the solution.

EC is monitored to prevent hindering plant growth. A relatively lower EC indicates a lower salt concentration, which means the plants could be under fertilized, resulting in decreasing growth. Whereas a higher EC leads to osmotic stress, nutrient imbalance and more (Singh & Dunn, 2017). Higher levels of salt in the nutrient solution makes it difficult for plant roots to extract water, limiting water availability and creating a physiologically dry substrate (Electrical Conductivity, why it matters, n.d.).

In multiple cases, a higher or lower EC of nutrient solution in hydroponic systems was found to be harmful to the plants. Ding et al. found suppressed growth and quality of pakchoi cultivated in a hydroponic system in which the nutrient solutions had very high or low EC, specifically it decreased plants fresh and dry weight, leaf size, transpiration rate, taste score and more (Ding, et al., 2018). In 2017, it was demonstrated by a study on papayas that elevated EC led to reduced growth and inhibited photochemical capacity (Lopes Peçanha, et al., 2017). Lopes Peçanha et al. proposed that a high EC substrate could lead to a reduction of osmotic potential, diminishing water uptake, thus resulting in reduced cell expansion (Lopes Peçanha, et al., 2017). The effect of EC of nutrient solution in hydroponics was also studied using Evolutionary Algorithms on zucchini plants by Liopa-Tsakalidi, Savvas, and Beligiannis. They chose 2 conditions of EC, 2.2 dS/m which falls under the appropriate range for plant growth, and 4.4 dS/m which is higher than desired. It was found that elongation of leaf blades and petiole lengths was suppressed in the high EC condition, and was also linked to water availability to plant roots and leaves (Liopa-Tsakalidi, Savvas, & Beligiannis, 2010).

However, studies also showed that higher EC might improve the taste of fruits by increasing the total soluble solids (TSS) content. A study on tomatoes grown in hydroponics has shown that a fall-winter cycle of tomatoes in an EC level of 4.5 dS/m had higher content of TSS throughout most of their developmental stages (Rodrígueza, et al., 2019). Moreover, Rodrígueza et al. learned that fruits of higher TSS content were “positively perceived by the sensory panel” (Rodrígueza, et al., 2019). Similar result was concluded in the study of zucchini plants. Fruit in the low EC condition (2.2 dS/m) had a TSS content of 5.19 0.11 Brix while fruit in the high EC condition (4.4 dS/m) had 5.48 0.10 Brix, and was considered significantly different.

2.1.2 pH

pH values express the hydrogen ion concentration of an aqueous solution as the negative log10 of it (Blackstock, 1989)(Williams, Kenyon, & Adamson, 2010). The pH scale starts at 0 and ends at 14, which as stated by Blackstock, "covers all the concentrations of hydrogen ions that could be found in dilute aqueous solutions and biological systems". A pH value of 7 is considered to be neutral and usually the pH of pure water at room temperature is 7 (Government of Northwest Territories). A solution is acidic when pH is smaller than 7, whereas a solution is basic or alkaline when pH is larger than 7 (Blackstock, 1989). In other words, pH reflects the acidity of the solution.

pH is crucial to plant growth as it affects availability of essential nutrients (Horrocks & Vallentine, 1999). It was stated in much literature that nutrient uptake of plants is optimized in the range of pH 5.5 to 6.5 (Wortman, 2015). Too low of a pH in plants could cause easy dissolvement of most nutrients, resulting in an excess of other nutrients such as manganese, aluminum, and iron (Kroeze, n.d.). Kroeze also mentioned that higher pH would result in precipitation of certain nutrients such as calcium, iron, and phosphate which are all essential nutrients. However specific effects of pH on the various nutrients in hydroponics have not been studied thoroughly.

It is critical to maintain the pH value within the optimal range. Singh et al. conducted a study to test the effects of three pH modifiers used to lower pH, which are pH down (phosphoric acid), lime juice, and white vinegar (Singh, Dunn, & Payton, 2019). From the results of the study, it could be concluded that using pH down as a method of reducing the pH of hydroponics solution is the most ideal for common plants.

2.1.3 Ions

To maintain focus on the scope of this project, which is automation, Circulus provided nutrient elements for sensing. They are present in the nutrient solutions as ions which are listed as follows:

- Nitrate, NO_3^-
- Ammonium, NH_4^+
- Potassium, K^+
- Calcium, Ca^{2+}

The table below identifies a summary of the main functions of the corresponding plant macronutrients.

Nutrient	Functions
Nitrogen (N)	Protein synthesis: growth and yield
Potassium (K)	Transport of sugars, stomata control, increase plant resistance towards diseases, counteracts salinity
Calcium (Ca)	Major building block in cell walls, increases plant resistance towards diseases

Table 1. Summary of main functions of plant macronutrients (Haifa, n.d.)

2.2 Liquid Nutrient Analysis Techniques

2.2.1 Electrical Conductivity Regression

In the study performed by Moral et al. (2005), it was concluded that the determination of electrical conductivity of a sample is one of the most appropriate methods for the estimation of nitrogen and potassium in organic waste, with high accuracy and relatively easy procedure. One method to find the relationships between electrical conductivity and concentration is to analyze the linear regression and correlation between both parameters (Stevens, 1995). In the study by Moral et al. the relationship between ammoniacal nitrogen and EC and between potassium and EC, were found to be, respectively:

$$AN = 0.105\,EC + 0.097;\ r = 0.914 \quad \textbf{(1)}$$

$$K = 0.1356\,EC + 0.2145;\ r = 0.907 \quad \textbf{(2)}$$

where

AN = ammoniacal Nitrogen (kg/m^3)

K = Potassium (kg/m^3)

EC = electrical conductivity (dS/cm)

r = correlation coefficient (unitless).

Concurrently, in a different experiment performed by Scotford et al. (1998) using waste slurry, the relationship between ammoniacal nitrogen concentration and the electrical conductivity was also determined to be linear. However, the electrical conductivity correlation method does not seem to work well with organic-dependent nutrients, such as Phosphorus or organic Nitrogen (Moral et al., 2005).

2.2.2 Spectrophotometry

This method uses a spectrophotometer device to measure the concentration of either metallic or non-metallic elements by observing the light reflection properties of the sample. Each element possesses a specific absorbance behaviour, meaning that the number of photons absorbed or reflected by the sample will differ depending on the substances present (Poole & Kalnenieks, 2000). The instrument applies this principle to send out a light beam to pass through the solution, which then diffracts into a spectrum of wavelengths. The spectrophotometer records the light intensities, or photons, emitted (Chemistry LibreTexts, 2020).

Absorbance can be calculated as follows (Poole & Kalnenieks, 2000):

$$A = log\frac{I_t}{I_0} \qquad \textbf{(3)}$$

where

A = absorbance (unitless)

I_t = light intensity after the beam of light passes through the solution

I_0 = light intensity before the beam of light passes through the solution.

Furthermore, the linear relationship between absorbance and concentration is described by the Beer-Lambert Law (Poole & Kalnenieks, 2000):

$$A = \varepsilon cl \qquad \textbf{(4)}$$

where

A = absorbance (unitless)

ε = molar absorption coefficient (($M^{-1}cm^{-1}$)

c = molar concentration (M)

l = optical path length (cm).

Spectrophotometry requires careful calibration of the system (Eyring & Martin, 2013) to ultimately provide an accurate and accessible method for obtaining nutrient content of a sample solution. On the other hand, these devices are not specifically made for unattended field use (Myers, 2019).

2.2.3. Potentiometry

Literature investigation suggests that using potentiometry methods to measure concentration of ions in solutions, such as with the application of ion-selective electrode sensors (ISE) or ion-sensitive field-effect transistors (ISFET), is one of the most widely researched and applied techniques nowadays, due to their high sensitivity, selectivity, speed and suitability for *in situ* applications (Thottan et al., 1994), with the main drawback being the cost and overall complexity of operating most of these sensors, as is the case of ISEs (Garcia et al., 2018). For these reasons, the next subsection will discuss the literature findings with more depth than the methods previously mentioned. In comparison with spectrophotometry, this method is relatively less expensive and requires less infrastructure (Cámara-Martos & Moreno-Rojas, 2016, 166).

2.4. Ion-Selective Electrode Sensors

2.4.1 Operation and Principle

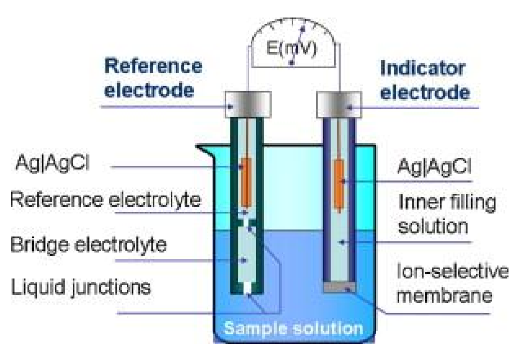


Figure 3. ISE working schematic (Lindner & Pendley, 2013).

Ion-selective electrodes, or ISEs, apply the electrochemical analysis method of potentiometry and consist of an ion-specific indicator half-cell, a reference half-cell and a voltmeter connected between them, as can be seen in Figure 3 above. The ion-specific indicator contains a membrane at the end of its body and in contact with the solution most commonly made of glass, of polymer film, or of a water-insoluble precipitate (Lindner & Pendley, 2013). When in contact with the solution, the ion-selective half-cell produces a small potential measured against the reference half-cell depending on the activity of the target ion in the measured sample, following Eq. 5.:

$$E_{ISE} = E_I - E_{ref} \tag{5}$$

where

E_{ISE} = potential difference (in mV) between indicator and reference half-cell

E_I = measured potential (in mV) of indicator half-cell of ion I

E_{ref} = constant potential (in mV) of reference half-cell

Moreover, the relationship between the potential measured through the ISE and the ionic activity is described by the Nernst's equation (Lindner & Pendley, 2013):

$$E_{ISE} = E_0 - 2.303 \frac{RT}{nf} log\ a_I \text{ (aq)} \tag{6}$$

where

E_0= constant standard potential (in mV) between indicator and reference half-cell

R = Universal gas constant = 8.314 $J.mol^{-1}.K^{-1}$

T = Temperature (in K)

F = Faraday constant (96485 $C.mol^{-1}$)

n = valence of the ion (charge of ion)

a_I = ion activity of ion I in aqueous solution

While different companies develop ISE sensors, Vernier and Atlas Scientific can be highlighted as important ones for educational and experimental purposes. The model chosen to be exemplified here is a combined Nitrate ISE from Vernier, since this company has high quality sensors that are experiment-tailored and appropriately simplified.

Figure 4. Nitrate ISE probe from Vernier (*Nitrate Ion-Selective Electrode BNC*, n.d.).

Specifications

- Range (mV) Electrode Amplifier: -450 mV to +1100 mV
- Range (concentration): 1 to 14,000 mg/L (or ppm)
- Reproducibility (precision): ±30mV
- Interfering ions: $ClO4^-$, I^-, $ClO3^-$, F^-
- pH range: 2.5–11 (no pH compensation)
- Temperature range: 0–40°C (no temperature compensation)
- Electrode slope: +55 ±3 mV/decade at 25°C
- Electrode resistance: 0.1 to 5 MΩ
- Minimum sample size: must be submerged 2.8 cm

2.4.2 Concentration Conversion

According to Dr. Axel W. Bier (2009), due to the selectivity characteristic of ISEs, the ion activity of a solution can be expressed as an approximated equation of the concentration of the desired ion, described in Eq. 7. This confirms that as the target ion concentration of the sample changes, there is a reflection in the change in ion activity and its subsequent potential reading.

$$a_I = C + C_0 \qquad \textbf{(7)}$$

C = ion concentration we ought to measure (either ppm or mg/L)

C_0 = detection limit.

Since F and R are constant, and n and T are known (the electrode is ion-specific), the Nernst equation can be turned into:

$$E = M\, log(C + C_0) \qquad \textbf{(8)}$$

$$M = -\ 2.303\frac{RT}{nF} \qquad \textbf{(9)}$$

where

M = ideal ISE slope.

A common assumption being that C_0 ~ 0, the equation can be further simplified and rewritten to calculate the specific ion's concentration in the sample:

$$\boldsymbol{C = 10^{[(E - E0)\ /\ M]}} \qquad \textbf{(8)}$$

2.4.3 Circuitry

The most common way to use ISEs is with the aid of a Raspberry Pi computer or Arduino control system and a respective ISE sensor interface shield. Sensor interfaces for ISEs include amplifiers that convert the small electric potential signal from the sensor into a readable value by computers and microcontrollers. In Fig. 5, a RPi board is connected to a circuit board for ISE probes. Even though it is not shown in the figure, the circuit board connects to the ISE sensor.

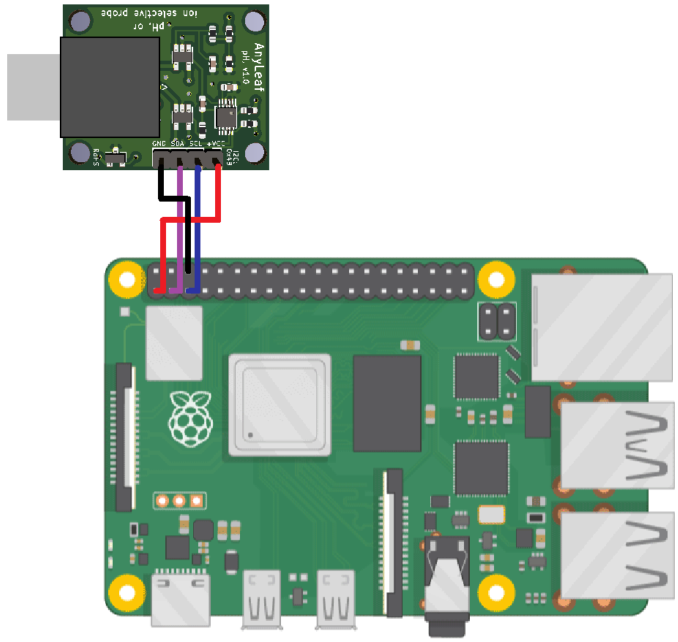


Figure 5. Circuitry drawing of RPi + ISE circuit board.

2.4.4 Calibration

A calibration sequence consists mainly of a controlled and well-documented procedure that verifies whether one or more measuring devices are consistent with their performance specifications and/or respect the tolerance levels of a modelled acceptable result, while providing a method for the re-attainment of such results. For any given device, a calibration sequence can be designed and tailored to evaluate and quantify the performance and set out to run a method that returns the device's measurement readings within a desirable range, minimizing the need for manual maintenance or repair (Bucher, 2004, 185). The procedure should include solutions and documentation for how to assess if a device is within an acceptable deviation range, and what is the correction procedure for re-attainment of the desirable range (Amsbary, 2012).

While different types of calibration methods can be encountered, depending on the type of system and instruments, when looking specifically at the mechanical calibration of devices such as ISE sensors, the methods can be narrowed down to direct calibration such as one-point, two-point or multi-point calibration.

In all methods of direct calibration, a potential reading is obtained without calibration. The calibration serves the purpose of converting potential (mV) readings from a solution sample into a measured concentration (in either ppm or mg/L) accurately. For the case of two-point calibration, the governing equation to convert the readings is de facto the applied Nernst equation with a C_0 = 0 assumption, and Eq. 8 can be modified to suit the calibration procedure:

$$C = 10^{[(E-E_0)/M_m]} \quad \textbf{(9)}$$

and

$$M_m = -[(\text{Low Standard - High Standard})/\#\text{ of decades}] \quad \textbf{(10)}$$

where

C = concentration of ion to be measured (mg/L or ppm)

E = measured potential of sample (mV)

E_0 = measured potential at C = 1 mg/L [*specific ion measured*] concentration

M_m = measured electrode slope in mV/decade

decade = difference factor between the used standard solutions.

The first step in two-point calibration is thus to compute the electrode slope with two standard solutions, a high concentration and a low concentration one, which will give a curve allowing for the conversion of a potential reading in mV into a reading in either ppm or mg/L.

2.4.5 Rinsing

It is recommended by many instrumentation companies to clean ISE probes between measurements to guarantee reading accuracy, and some of them will be discussed in this section, as well as some maintenance measures post-rinsing.

The company Omega Engineering published on their website measurement considerations regarding ISEs. It was stated that rinsing of the electrodes in between measurements is a necessity for ideal reading accuracy (Omega, 2019). Deionized and distilled water were proposed as appropriate rinsing solutions and the water should be as a steady stream when in contact with the ISEs to avoid damage (Omega, 2019). Drying of the probe should be gentle and it is more preferable to minimize physical contact between the drying cloth and the probe. Thus, a method of shaking to get rid of excess water was proposed, though much care should be taken to avoid hitting the probe against something (Omega, 2019).

Similarly, rinsing was also proposed as a general cleaning method and also an essential step before calibration by the company ThermoFisher Scientific for their fluoride ISE (Thermo Scientific, 2016). During calibration, it was suggested to rinse the electrode with distilled water and then the ISE would be ready to be put into calibration solutions. As for post rinsing methods, it was also recommended to refrain from wiping or rubbing the electrode (Thermo Scientific, 2016). Moreover, it is also important to rinse out the fill solution used to store the ISEs when doing maintenance such as polishing the sensing surface (Thermo Scientific, 2016).

The company Van London also has some recommendations as to the maintenance of their pH and ORP electrodes. Due to the sensing environment of these electrodes, a more rigorous procedure of general cleaning was provided. The first step was to soak the electrode in diluted household laundry bleach and 0.1-0.5% liquid detergent solution in hot water, while accompanying vigorous stirring for at least 15 minutes (Van London, n.d.). Then it should be followed by a 15-second rinsing under warm tap water and the process is finished with soaking the electrode in storage solutions for at least 10 minutes (Van London, n.d.). Maintenance procedures for various types of deposits were also mentioned. Basically, the deposits should be dissolved using corresponding solutions and then the ISE can go through rinsing to get rid of all the deposits, before being put back into the storage solutions (Van London, n.d.).

To conclude, rinsing is an essential procedure to be taken both in between measurements and during calibration procedures for all types of ISEs and is necessary to ensure accurate readings.

2.5 Fluid Transport

2.5.1 Pumps

In the transportation of fluids, pumps are essential components of a transportation system. When transporting liquid solutions, peristaltic pumps have shown to be efficient and easy to set up. The primary working principle of these pumps is that of compressing and decompressing the tubing consequently producing a vacuum which draws the fluid to move (*How Do Peristaltic Pumps Work?*, n.d.).

2.5.1.1 Pumping Circuitry

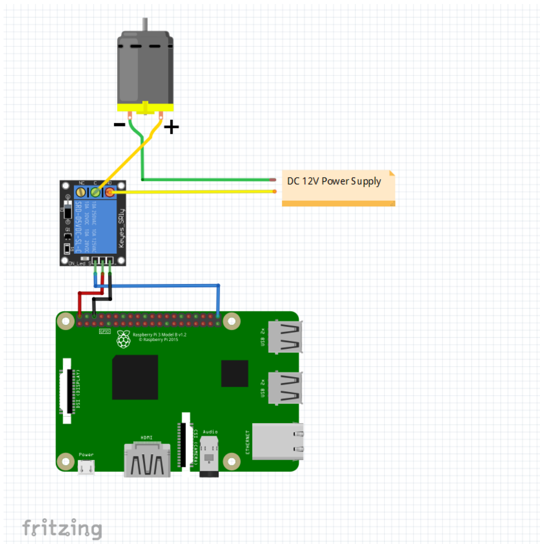


Figure 6. General circuitry of connection between RPi, relay and pump (*5V Relay (Raspberry Pi) Steps*, n.d.).

2.5.2 Valves

In automated systems, valves are an usual part of the solution for autonomous and remote control of flow.

The solenoid valve is an electromechanical device that will create an electromagnetic field if it receives an electrical current which then activates the movement of the plunger, enabling automation of liquid or gas control (Burkert, n.d.). Because of the unique characteristics, it is also common to use solenoid valves for accurate control of liquid/gas dispense, where the exact amount is distributed each time. Another example application is leak prevention. The valves would be installed in the flow and shut down whenever a leak is detected.

Typical two-way general-purpose solenoid valves have one inlet and outlet. They consist of a solenoid coil, a plunger, a compensating spring and the valve body (How does a 2-way normally closed solenoid valve work?, n.d.). These valves could be further categorized by the applied operations and constructions. There are two types of operations applied on the valves which are normally closed (NC) and normally open (NO) and the two constructions are direct-acting and internally piloted (Solenoid Valves, n.d.). In this spec sheet provided by the company Emerson, it was stated that the operations are identified according to the state of the valve when the plunger is de-energized. A normally closed solenoid valve will have no flow when the plunger is de-energized and vice versa. As for the constructions applied, it was specified that when energized, the core in a direct acting valve (NC) directly opens the orifice in the valve body, whereas in an internally piloted valve, this process is assisted by a pilot orifice and is common in solenoid valves with larger orifices.

Additional specifications to note when choosing solenoid valves are the pipe size and body materials. Common body materials include aluminum, brass, stainless steel and plastic (Solenoid Valves, n.d.). These parameters contribute to the behaviors of the valves. They could be catered for various pressure settings, response time, and general services.

It is important to calibrate the valves in accordance with the desired purposes. In the field of neuroscience, solenoid valves are used to modulate the flow and sequence of chemical stimulation by reason of their ability of precise control of solutions (Auzmendi & Moffatt, 2009). Auzmendi and Moffatt stated that the ability of figuring out the delay between a signal sent and the real actuation will increase the reliability of relevant modulations. They mentioned that factors contributing to the delay are within every step of the actuation. The actuation starts with the application of an electric potential across the solenoid coil, which takes the same amount of time as the inductive time constant. The electric current induced by the potential will generate a magnetic field after the magnetic diffusion time has passed. The plunger inside the coil also does not move to the proposed position instantaneously, adding more time to the delay. In the communication, they introduced a method to help measure the delay by monitoring the exact time the valve opens and closes. In this project, the influence of the delay will be assessed once the model or prototype of the system is built. This method proposed by Auzmendi and Moffatt will be beneficial if the delay is deemed to be significant.

The circuitry of a valve is usually the same as that of the pumps shown in the subsection above, with a solenoid valve connected to the relay board instead.

2.6 Additive Manufacturing

In order to both build a functional prototype and have a competitive end-product, there is a need for a means of manufacturing the vessel that combines three characteristics: lightweight construction, custom-made manufacturing, on-demand production. For on-demand, non-factory production that includes tailor-made, and lightweight subcomponents, additive manufacturing is the most viable option.

Moreover - from a space optimization perspective - and in order to hold the sensors inside the vessel, internal components are required, and these components can have a complex design that eliminates the option of acquiring them by assembling off-the-shelf items from suppliers such as McMaster-Carr. As such, additive manufacturing will be used for the entirety of the holding vessel design.

In order to do so, all the parts need to be drawn using Computer Aided Design (CAD) tools to then be transformed into a Standard Tessellation Language (STL) file format for further slicing, ahead of printing the proper. The latter allows users to fine-tune printing parameters such as:

- Layer thickness (printing resolution);
- Printing speed;
- Infill selection (material density and pattern).

Once the aforementioned setup is completed, the software estimates the time to completion and issues a so-called G-code, which can then be read by the 3D printer as printing instructions.

The three most common materials used for additive manufacturing, owing to their availability, mechanical properties and low cost of procurement are:

- ABS (Acrylonitrile Butadiene Styrene);
- PLA (Polylactic Acid);
- PETG (Polyethylene Terephthalate Glycol).

Additive manufacturing also exists in different versions to print with harder materials like metals (aluminum, for instance), but they were vetted out of the study’s scope given their high costs, and lack of use cases for our design since plastics provide better chemical inertia; as such, they were not further pursued. As for plastics additive manufacturing, the two most used techniques are: stereolithography (SLA), and fused filament modelling (FD; the below outlines what they entail and their use cases.

2.6.1 Fused Filament Modelling (FFM)

FFM is the most widespread plastic additive manufacturing method and relies on polymer extrusion. The process starts with a thermoplastic filament, which can be acquired in the form of circular spools of extruded filament, with the most common diameter being 1.75 millimeters. The filament goes through heating before entering a moving nozzle that deposits the melted polymer on the printing platform in a bottom-up fashion, all through a die to obtain a uniform density.

The bottom-up fabrication comes at the cost of requiring more structural support to prevent thermal warping, which in turns requires more materials; however, this technique is so widespread and readily available that this extra cost is offset from the onset. As per the technique itself, the most common materials are commodity thermoplastics that do not have too high a fusion temperature and whose non-Newtonian properties are not incompatible with the extruder; as such, ABS and PLA are the most used materials for this manufacturing technique. For the sake of our study, and given that engineering thermoplastics as well as professional FFM printers are not available in our location, the use of engineering thermoplastics will be limited to the SLA technique.

2.6.2 Stereolithography (SLA) Manufacturing

Stereolithography is a fast-prototyping technique for part fabrication of 3D polymers. It is the first developed additive manufacturing method and relies on the polymerization process, under which a resin in liquid form is submitted to laser irradiation, thus resulting in the solidification of the irradiated material. The process is such that parts are created by curing consecutive layers of the resin until formation of the desired shape.

Stereolithography’s advantages are - among others - the flexibility of materials that can be used, the wide range of shapes that can be rendered thanks to it, as well as the speed and accuracy of manufacturing; the result is a smooth-shaped part. However, it can be challenging to combine both complex geometric shapes with sturdy properties from a mechanical standpoint; the main challenge being that parts are more brittle, and are thus not the ideal material for some applications (Akbarzadeh, 2021).

As for other means of additive manufacturing, stereolithography entails post-processing to remove the required support materials, though to a lesser extent than with techniques such as fused filament modelling. Lastly, stereolithography presents the advantage of being compatible with more feedstock than fused filament manufacturing; for instance, the use of patented materials like Z-GLASS or Z-HIPS (Zortrax, 2021) is made possible, in addition to ABS and PLA.

2.7 Relevant Patents

1. *Method of predicting fertilizer performance (United States of America Patent No. CA 2564496, 2006)*

This patent owned by the Agrium Polymer Coatings Corporation presented a method of predicting the performance of a fertilizer by a computerized analysis of essential parameter requirements. The analysis could include various parameters such as re-application time, nutrient release indicator, amount of nutrients released and release rate. This method is capable of calculating and receiving at least one fertilizer.

The notion and workflow of the patent is consistent with this project. Most of the parameters mentioned in the patent are also desirable and applicable such as amount of fertilizer nutrient released and fertilizer nutrient release rate. However, this patent was filed 15 years ago and is extremely outdated in the data transmitting and software aspects. The ALNA system is anticipated to be able to show real time results of the analysis whilst preparing an organized downloadable file.

2. *Water and fertilizer all-in-one machine control system with crop nutrient demand analysis function and control method (China Patent No. CN111557159A, 2020)*

The patent features a machine control system that has a crop nutrient demand analysis function as well as a control method. Sensors were incorporated in this system to obtain the nutrient profile of the liquid fertilizer to better meet the demand of the crops. The sensors are also responsible for collecting growth information of the crops, which are used for an automated mixing and distribution of the liquid fertilizer.

This patent provides constructive inspiration for further versions of ALNA. There is a possibility of creating an embedded version of ALNA that combines mixing of the liquid fertilizer, analysis, and distribution of it in the irrigation system.

2.8 Relevant Standards

Canadian Standards Association group, made up of Canadian Standards Association (CSA), OnSpex and CSA International, is one of the leaders in the development, certification and testing of standards, and consumer product evaluation services (About CSA, 2012). The solenoid valves that are anticipated to be used in the system are CSA certified, meaning that they are tested against the North America standards requirements (Marks & Labels for North America, n.d.). It was also stated by the CSA group that their tests and certifications are in compliance with standards written by American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), American Society of Safety Professionals (ASSE), Underwriters Laboratories (UL), CSA, etc.

As Bioresource Engineers, the American Society of Agricultural and Biological Engineers (ASABE) also provides helpful standards online. As listed on almost every standard published by ASABE, ASABE consists of members from worldwide all of which are dedicated to the advancement of engineering applicable to agriculture, food, and biological systems (Published Standards, n.d.). The scope of this project falls perfectly within the fields and listed below are ones found to be potentially applicable.

1. *Guidelines for Measuring and Reporting Environmental Parameters for Plant Experiments in Growth Chambers*

ANSI/ASAE EP411.5 DEC2012 (R2016)

(American Society of Agricultural and Biological Engineers, 2012)

This standard provides guidelines for measurement of environmental parameters concerning the environment within a plant growth chamber.

The standard stimulates uniform and accurate data and results as this project will involve testing of the produced liquid fertilizers on prepared seedlings. Some of the parameters concerned in this standard are the following: air temperature, moisture concentration, oxygen concentration, nutrient concentrations, water content and pH. The definitions, measurement and reporting procedures are all specified in the standard for uniform and unambiguous results.

2. *Safety Devices for Chemigation*

ASAE EP409.1 MAR1989 (R2018)

(ASABE, 1989)

This standard is specific for the injection of liquid chemicals into the irrigation systems. The mentioned liquid chemicals include and are not restricted to liquid fertilizers, herbicides, insecticides, and fungicides. It allows safe and sustainable injection with properly engineered irrigation or injection systems.

In the scope of this project, the liquid nutrients are being dispensed through piping and valves either onto the ground through irrigation systems or into a hydroponic system. By following the aforementioned standard, the system and surrounding environment houses improved safety and sustainability.

3. *Design of Concrete Structures for Secondary Containment of Liquid Pesticides and Fertilizers*

ASAE EP514 JUN1996 (R2013)

(ASABE, 1996)

As the extent of this project and the company Circulus grows, larger containment facilities would be needed, which is the case in which this standard becomes beneficial.

4. *Agricultural machinery – Safety – Part 6: Sprayers and liquid fertilizer distributors*

ASAE ANSI/ASABE AD4254-6:2020 MAR2021

(ASABE, 2020)

This standard comes from a part of a more inclusive standard and focuses specifically on the safety of the liquid distributors used for fertilizer and other liquids. The standard is not available through McGill since it is adapted from an already existing ISO standard (ISO 4254-6:2020) with modifications, and royalty is required for every copy.

3. DESIGN PROCEDURE

3.1 Criteria, Alternatives, and Selected Components

The main objective of the design is to develop a brand new liquid nutrient analyzer while keeping the main tenets of the earlier version developed by Circulus AgTech e.g. connectivity, and the all-in-one calibration/rinsing/analysis of incoming liquid fertilizer. Though the earlier design technically was functional in so that data was fetched from it, and remotely so, it still falls short in the following ways:

- Since the calibration and analysis vessels are separate, there was a need for additional tubing and connectors, thus raising the risk of dysfunctionalities.

- The upstream tubing coming into the calibration vessel did not allow for all the input elements to come, thus raising the need for daily human involvement to plug the right tubing for the right operation at different stages during the day.

- The analysis vessel depth proved insufficient to obtain ionic concentration results at all times, which resulted in Circulus operators needing to visually make sure that sufficient depth was covered (hence the need for transparent tubing prone to eutrophication);

- The tubing material (PVC) proved not as chemically resistant as forecasted given the highly corrosive elements present in the liquid fertilizer (chiefly among them, nitric acid);

- Improper upstream and downstream liquid solutions delivery, which resulted in Circulus employees making-do with unfit-for-purpose tanks to store calibration solutions, city water, and effluents.

As a result, the proposed design must take these shortcomings into consideration on top of customer wants and needs. Building an ALNA system requires multiple key components, which can be subdivided into three broad nexuses:

(i) the analysis vessel proper, which encompasses the chamber, the placeholder for sensors and a float switch, as well as the eventual connections to upstream and downstream elements - a key aspect of this nexus is that it needs to resist corrosion from various strong acids that the liquid fertilizer contains;

(ii) the tanking system for both uptake of the concerned solutions e.g. calibration (high and low), rinsing (city water), analysis (biojuice), and to flush waste into;

(iii) the hardware with associated software, with microcomputers and their associated relays, power supplies, and transformers to control (a) the upstream solution delivery based on loop-specific protocols (for rinsing, calibrating, analyzing), and (b) the acquisition of data from the sensors once the analysis loop is triggered.

For the design to require less pieces, be easier to disassemble and maintain, and to maximize space usage, it was decided that all loops - e.g. calibration, analysis, and rinsing – would take place in a single chamber, as opposed to having two in-series components for calibration and analysis as seen in the previous design. It was also decided that horizontal tubing proved too risky in terms of probes depth and thus measurements quality, and a vertical chamber would be used instead; this however turns size into a factor that needs to be taken into consideration as the chamber would then need to be large enough to provide sufficient liquid depth for the probe, but not too voluminous otherwise the higher volume/cost in terms of water/calibration solution/liquid fertilizer waste would prove redhibitory. The solution to this issue has been to select a chamber that goes above the minimum volume requirement, and install a float-switch to avoid overflow and/or superfluous waste.

In order to limit the costs incurred over time, the components used need to satisfy the following criteria: high lifetime, corrosion resistance, and easy to acquire (Time x Cost). In the case of non-compliance with the former e.g. if a component does not satisfy lifetime, corrosion resistance, and acquisition criteria, it should at least be cheap and easily acquirable enough for a more regular replacement to not cause financial or functional stress.

It is to be noted that there is no equivalent to our system, and as such a section dedicated to macro-scale alternatives has not been devised; our purpose is to instead rely on detailed alternatives comparison for each physical subcomponent to obtain a well thought out design that satisfies the engineering design approach.

3.1.1 Vessel Chamber

This element is central for the ALNA system as it is linked to all other nexuses and is where liquid nutrient analysis takes place. As per the decision to lodge every loop into a single vertical chamber, the latter will need to satisfy several criteria from a functional, structural, and economic standpoint. These criteria were developed by the team after having conducted interviews with Circulus AgTech's CTO, and are laid out below.

Functional criteria	**Structural criteria**	**Economic criteria**
• Resistance to Nitric Acid; • Resistance to Phosphoric Acid; • Smooth inner finish for ease of liquid removal/flushing.	• Can withhold a minimum volume of 1.216L for liquid analysis (previous design's capacity); • Preferably can be filled up to 1.5L for forecasted scaling-up; • Weighs less than 500g; • Has a tubular shape for space maximization; • Can withhold machining operations (e.g. drilling) without breaking.	• Lifespan > 3 years; • Replacement under a 2-day threshold; • Cost < 100$.

Table 2. Categorized criteria for the ALNA Vessel Chamber.

In light of the aforementioned criteria, and after having discussed with various stakeholders e.g. Cube EUS, Mac 3D Printing, Circulus AgTech, and Pr. Akbarzadeh, it appears that the two solutions that satisfy our criteria, with ease of procurement and cost as foremost criteria, fall within two categories: off-the-shelf food grade beakers, or homemade, 3D-printed chambers. In broad terms, the former are better suited in terms of lifetime and corrosion resistance at a higher cost, while the latter are better in so that they are tailor-made volume wise, can easily be altered on computer before printing, are cheaper in terms of upfront costs, and can be locally produced e.g. at Circulus AgTech's Headquarters.

	FDM PETG	**FDM PC**	**FDM PP**	**SLA Standard Resin**	**PVC Tank**	**Stainless Steel Beaker**
Resistance to Nitric Acid (-2 to +2)	0	1	-1	-1	2	2
Resistance to Phosphoric Acid (0 to +2)	0	1	-1	-1	2	2
Finish Smoothness (0 to +1)	0	0	0	1	1	1
Functional Volume (0 to +1)	1	1	1	1	0	1
Weight	1	1	1	1	0	0
Malleability for Machining (0 to +2)	2	1	1	2	2	2
Lifespan (0 to +5)	2	2	2	2	3	5
Speed of procurement (0 to +5)	3	3	3	5	5	5
Cost (0 to +3)	3	3	3	2	1	0
Final grade	**12**	**13**	**9**	**12**	**16**	**18**

Table 3. Pugh Chart for the ALNA Vessel Chamber alternatives.

As documented in the above, non-3D printed elements have obtained the highest grades based on the grading key; they are the only ones to satisfy the structural and economic criteria though at a higher cost. This is however made up for given their lifespan, though the stainless steel beakers found on industrial supplier's websites ended up having the upper hand thanks to their higher lifespan, while remaining under the $100 threshold. The selected stainless steel beaker is detailed below with both a visual, as well as the physical properties as per the below.

Material	300 Series Stainless Steel
Capacity	67 oz. / 1,975 ml
Diameter	4 3/4"
Height	7 1/8"
Graduated	No
With Handle	No
Autoclavable	Yes
Environment	Food Industry, Sanitary
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (07/08/2021, 219 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	Yes
Schedule B	732690.8695
ECCN	EAR99

Figure 7. Visual and technical specifications for the stainless steel beaker.

3.1.2 Vessel Insert

In order to conduct liquid nutrient analysis, there is a need for the sensors and the float switch to stay put within the chamber, which ought to be done with the help of an insert to be put in the chamber that would hold and protect sensors and float-switch from impact.

With regards to the criteria for the vessel insert, it turns out that this subcomponent has no equivalent in the industry, so the modus operandi was to design it via CAD for Additive Manufacturing by applying the structural criteria, to then compare the different printing methods (SLA vs FDM) with different materials from a functional and economic standpoint. Table 4 below defines the criteria to be satisfied by the computer-aided design while Figure 8 is a rendering of the designed insert.

Structural criteria
• Must be able to support and maintain still 6 probes that are (i) 11cm long, (ii) ∅2cm, and (iii) with a probe head of 2.6cm, potentially with the help of grommets; • Must be able to lodge a float switch at its top;

• Must allow effluents to flow seamlessly at the bottom of the chamber by not going to the very bottom of it; • Must fit within the chamber selected above, with a planned diameter of 12.065cm and a planned height of 18.0975cm; • Must be able to lodge a 35mm to 50mm float switch screwed at the top, with ∅1cm to allow for choice of different float switches.

Table 4. Structural criteria for the Vessel insert ahead of Computer-Aided Drawing.

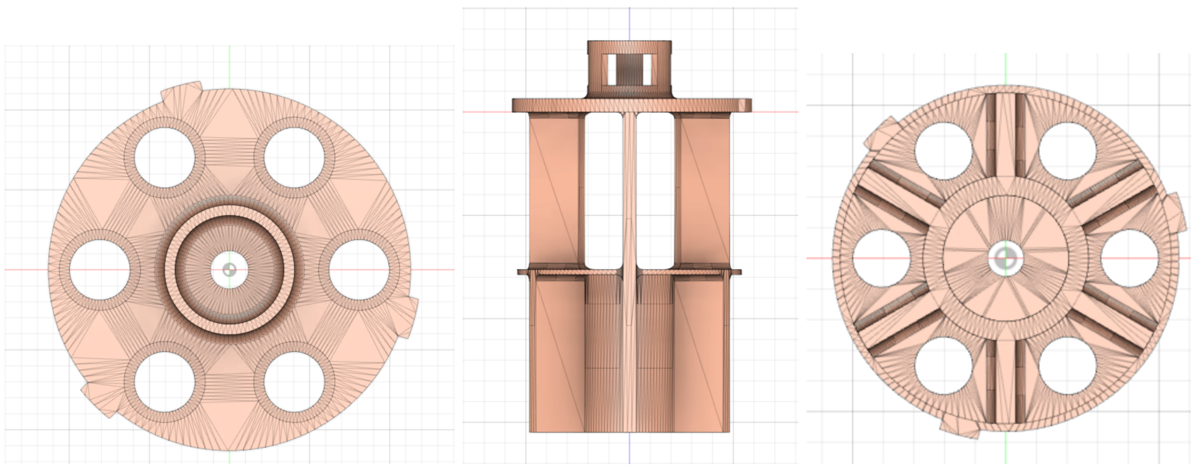


Figure 8. CAD Rendering of the Vessel Insert *(left: Top, center: Front, right: Bottom)*.

After having developed the insert design as per the criteria above, the subsequent criteria can be subdivided into functional, and economic. Table 5 lays out the said criteria for the insert. The functional criteria resemble those of the vessel chamber given that it, too, will be subjected to corrosive elements on a regular basis, while the economic criteria differ since there is no way to have the insert built for a long lifespan, which represents one of the limitations of Additive Manufacturing; the objective here is to reach a compromise between service life, cost, and printing speed. The insert will have a high replacement rate (every 6 months) as per the fact that it is produced by Additive Manufacturing.

Functional criteria	**Economic criteria**
• Resistance to Nitric Acid; • Resistance to Phosphoric Acid.	• Lifespan > 6 months; • Replacement under a 2-day threshold; • Cost < 100$

Table 5. Criteria for the CAD Vessel insert.

Given that the insert is to be 3D-printed, the team commissioned both CubeEUS and Mac 3D to both provide informed guidance as well as quotes for each type of suitable materials and printing method. Both printing contractors recommended FDM at first given

(i) the size of the desired insert which would not fit in CubeEUS' FormLabs machine, and (ii) because Mac 3D only has an FDM printer. All FDM prints had a printing time of 2 days and 8 hours, while SLA could produce it within 24 hours, owing to the design complexity which would require a high amount of structural support (it was lowered to 2 days with pre-slicing). This in turn leads to FDM requiring much more filament, though the cost would still be much lower than SLA ($40 from Mac 3D for FDM, $100 from CubeEUS for FDM, $200 for SLA). All materials and methods scored poorly for resistance to the two main acids, and scored about the same in terms of lifespan.

Moreover, the cost of SLA with Standard Resin ended up being considerably lowered by making use of a Circulus team member's FormLabs printer, which brought down the price to $40 per print, thus qualifying SLA Standard Resin as the least mediocre material to print with. A key takeaway is that both speed of printing and cost benefitted it. Table 6 below lays out the final result of our comparison.

	FDM PETG	**FDM PC**	**FDM PP**	**SLA Standard Resin**
Resistance to Nitric Acid (-2 to +2)	-1	-1	-1	-1
Resistance to Phosphoric Acid (0 to +2)	-1	-1	-1	-1
Lifespan (0 to +5)	2	2	2	2
Speed of printing (0 or +5)	0	0	0	5
Cost (0 to +3)	2	3	2	1
Final grade	**2**	**3**	**2**	**6**

Table 6. Pugh Chart for the ALNA Vessel Insert alternatives.

3.1.3 Valve

To achieve the purpose of full automation of the system, solenoid valves have been chosen as an essential part of solution transportation for autonomous and remote control of the flow. These valves are commonly used for accurate control of liquid dispense (Burkert, n.d.).

A brass normally closed liquid solenoid valve was chosen for this project. It has an actuating voltage of 12V and an actuating life of more than 50 million cycles (996 Brass Liquid Solenoid Valve, n.d.). During testing, it showed that our 12V 5A power supply is more than capable of powering the valve. The valve has two ½'' NPT outlets, which is taken into consideration during tubing selection. Moreover, it is also important to calibrate the valves in accordance with the desired purposes. In this case, when controlling the output of the ALNA, it was tested that the influence of the solenoid valve delay is negligible.

3.1.5 Sensors

Pertaining to the designed vessel, a few criteria arise for the selection of sensors. First and foremost, the sensors should be able to work without being interfered with each other in close proximity to each other, i.e. in the same vessel. Secondly, the sensors should cover major macronutrients needed for crop growth to produce an array of useful and relevant data. Lastly the connector of the probes should be taken into consideration when selecting the sensor interface for the computer.

The concern of interference was raised to the client Mohamed Debbagh when the updated design was first presented. After testing with multiple Vernier ORP sensors, a pH sensor, and an EC sensor being put in a beaker similar size to the proposed design, no noticeable interference among the sensors were documented and it was safe to say that little concern should be put on interference among the Vernier sensors.

The client's primary need is to get data of essential nutrients for several common vegetables such as tomato, lettuce, cucumber, and red pepper. After some literature review, the common macronutrients essential for these plants' growth are nitrogen (in the form of ammonium and nitrate), potassium, and calcium. Vernier ORP sensors thus were selected to record the concerning ions, in order to reach the goal of monitoring nutrient levels of the liquid fertilizer.

3.1.6 Tanks

As part of the updated design, our client notified us on October 28th that the scope of the project would have to encompass the upstream solution delivery in order to have a fully defined system, whereas the focus prior to that was solely on the vessel and its associated electronics. As such, an extraordinary meeting was conveyed on October 29th to discuss the client's needs, after which we refined the criteria. Our supplier scouting resulted in us deciding to source the tanks from McMaster-Carr, taking into account factors such as speed of procurement speed, quality of finish, customer service, delivery options, and institutional reputation.

Prior to this, Circulus AgTech operated with ad-hoc plastic tanks that were not properly sealed, which resulted in solution loss through evaporation as well as dust contamination. This not only led to opportunity costs but also to chemical hazards. The client thus expressed the need for four tanks: two to lodge low pH and high pH calibration solutions for the probes, one to lodge city water for the flushing sequences, and one to contain all effluents from the vessel operation. No tank is foreseen to contain liquid fertilizer as it will come directly from the bioreactor refined by another functional team at Circulus AgTech.

Our task therein consisted in (i) determining how often the tanks were to be refilled (or emptied for the waste tank), (ii) determining how much liquid each tank would need to withhold per operation cycle. The following criteria were derived from stakeholder and team meetings to answer these questions, followed by the assumption that will guide our selection for the tanks:

Criteria

a. All tanks must be low pH corrosion-resistant – special mention to the calibration tanks (though not required for the city water per se, it was still desired by the client, nor for the effluent tank as the solution is too diluted to be excessively aggressive towards the wall).
b. Calibration tanks must withhold a minimum of 2 months' worth of solution.
c. City water tank must withhold at least 3 weeks' worth of water.
d. Effluent tank must withhold at least 1 month's worth of solution.
e. Tanks must have a drain at their bottom.
f. Tanks must be sealable yet easy to open to refill.
g. Capital Expenditure per tank <$700 with lifespan >3 years.

Assumptions

1. Calibration sequence will be run once a day.
2. Calibration sequence measures low calibration solution and high calibration solution each time it runs.
3. Sampling sequences will be run once every 6 hours.
4. Sampling solution comes directly from the biofilter tank.
5. Rinsing sequence will be run after each measurement, be it sampling or calibration.
6. Rinsing sequence will fill the vessel twice in every iteration.

In light of the assumptions above, Table 7 lays out the constants, as well as the parameters leading us to the minimal volume for each tank. Lifespan and costs are discussed later in this report.

Constants

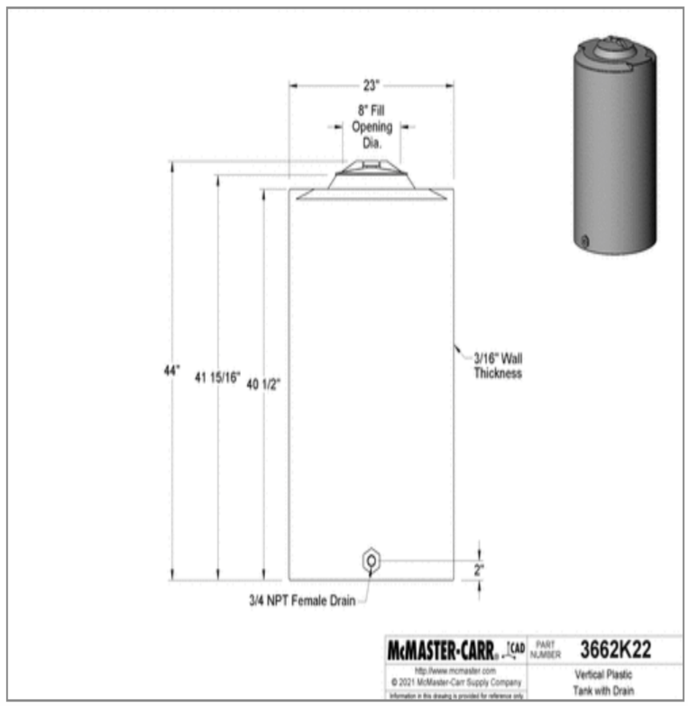
Volume of solution in vessel (L)					1.216
Number of days in a month (days/month)					30.437
Solution	**Tank Name**	**Frequency (# of draws/day)**	**Volume used (L/day)**	**Volume used (L/month)**	**Minimum tank volume (L)**
Low calibration solution	Low calibration	1	1.216	37.011392	38
High calibration solution	High calibration	1	1.216	37.011392	38
Biojuice	Biofilter	4	4.864	148.045568	N/A
City water	Rinsing	14	24.32	740.22784	741

Table 7. Constants and minimum volume tank volumes.

3.1.6.1 Rinsing Tank

In light of the elements above, the desired tank would need to withhold at least 22.82775 days' worth of water, for a daily volume used of 14.592L/day given the number of draws, which by multiplying fetches a tank volume of 333.1L. For cost reasons, the client requested that the closest volume to this while satisfying other criteria be selected. The team as such managed to select a 318.23L (70 gal US) tank made of UV-Resistant, food-grade polyethylene, with a drain at the bottom, and with an openable top for ease of refill.

Figure 9 below details the dimensioning of the tank as well as its technical specifications.



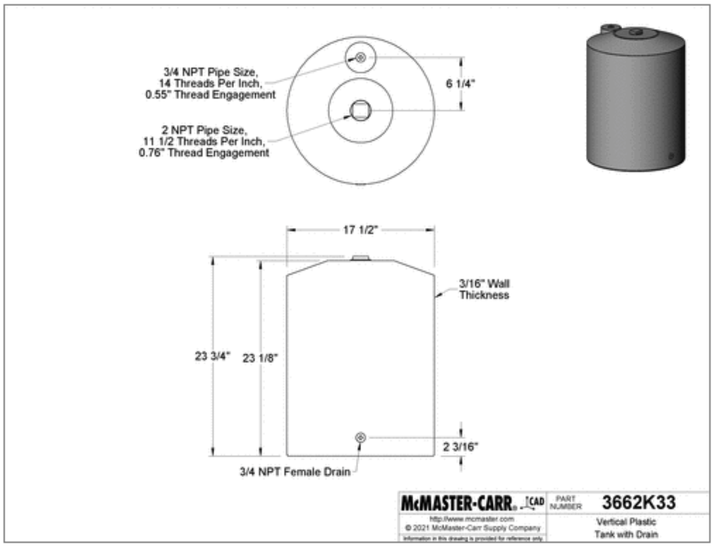
Tank Orientation	Vertical
Capacity	70 gal.
Diameter	23"
Height	44"
Thickness	3/16"
Number of Top Openings	1
Fill Opening Diameter	8"
Graduated	Yes
Graduation Marks	10 gal.
Material	Polyethylene Plastic
Color	White
Clarity	Semi-Clear
Drain	
Connection Type	Threaded
Pipe Size	3/4 NPT
Gender	Female
Material	Polypropylene Plastic
Seal Material	Santoprene Rubber
Maximum Temperature	100° F
UV Protection	UV Resistant
Includes	Fill Cap
RoHS	Not Compliant
REACH	Not Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	392390.0000
ECCN	EAR99

Figure 9. Rinsing tank dimensions, and technical specifications, as per McMaster-Carr.

3.1.6.2 Calibration Tanks

Considering the elements above, the desired tank would need to withhold at least 60.874 days' worth of calibration for each tank, for a daily volume used of 1.216/day, which by multiplying fetches a minimum tank volume of 74.0228L. For cost reasons, the client again requested that the closest volume to this while satisfying other criteria be selected. The team as such opted for a 83.28L (22 gal US) tank made, once again, of food-grade polyethylene plastic, with a drain at the bottom and two holes at the top for pumping, and with an openable top for ease of refilling. It is to be noted that these tanks are explicitly described as UV-Resistant, which prolongs their lifespan, while their size makes it possible to directly attach a pump to them for solution delivery.

Figure 10 below details the dimensioning of the two tanks, which are identical, as well as their technical specifications.



Tank Orientation	Vertical
Capacity	22 gal.
Diameter	17 1/2"
Height	23 3/4"
Thickness	3/16"
Number of Top Openings	2
Fill Opening Diameter	3/4", 2"
Graduated	No
Material	Polyethylene Plastic
Color	White
Clarity	Semi-Clear
Drain	
Connection Type	Threaded
Pipe Size	3/4 NPT
Gender	Female
Material	Polyethylene Plastic
Maximum Temperature	100° F
UV Protection	UV Resistant
Includes	Fill Caps
RoHS	Not Compliant
REACH	Not Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	392390.0000
ECCN	EAR99

Figure 10. Calibration tanks' dimensions, and technical specifications, as per McMaster-Carr.

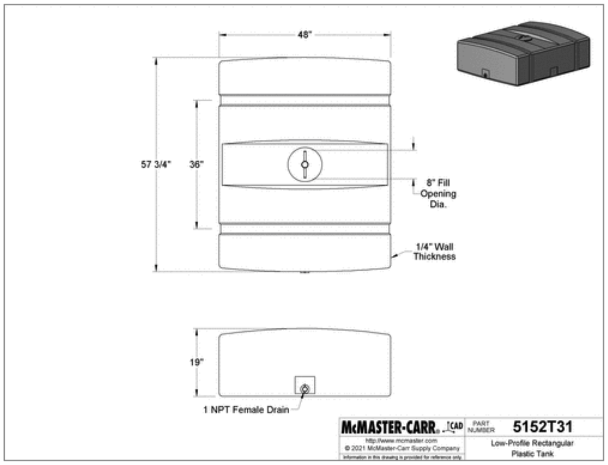
3.1.6.3 Waste Tank

In order to assess the volume required from the effluent tank, it is of interest to remember the overall ALNA sequence over a day:

→ Rinsing (x2) → Low pH calibration → Rinsing (x2) → High pH calibration → Rinsing (x2) → Biojuice analysis #1 → Rinsing (x2) → Biojuice analysis #2 → Rinsing (x2) → Biojuice analysis #3 → Rinsing (x2) → Biojuice analysis #4 → Rinsing (x2).

As such, the total volume used per day is equal to 24.32L (total number a draws, all of 1.216L), thus resulting to a minimum functional volume for this tank of 740.22784L. For cost reasons, the client requested a final time that the closest volume to this while satisfying other criteria be selected. The team as such opted for a 757.08L (200 gal US) tank made, once again, of food-grade polyethylene plastic, with a drain at the bottom to allow for easier flushing and with a cap at the top that can lodge tubing to channel the effluents there. This tank is also described as UV-Resistant, which prolongs its lifespan, while its size makes it possible to directly attach a pump though the layout would allow it to not necessitate that thanks to gravity. An additional interesting feature of it is that, unlike the previous tanks, the effluent tank is a parallelepiped, which means that it can be put underneath the biojuice production setup.

Figure 11 below details the dimensioning of the tank as well as its technical specifications.



Capacity	200 gal.
Width	57 3/4"
Depth	48"
Height	19"
Thickness	1/4"
Number of Top Openings	1
Fill Opening Diameter	8"
Graduated	Yes
Graduation Marks	1 gal.
Material	Polyethylene Plastic
Color	White
Clarity	Semi-Clear
Drain	
Connection Type	Threaded
Pipe Size	1 NPT
Gender	Female
Material	Polypropylene Plastic
Seal Material	Santoprene Rubber
Maximum Temperature	120° F
UV Protection	UV Resistant
Includes	Vented Fill Cap
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	Yes
Schedule B	392510.0000

Figure 11. Effluent tank dimensions, and technical specifications, as per McMaster-Carr.

3.1.7 Pumping

To transport solutions from input tanks to the ALNA vessel, pumps are needed for all input tanks. Adding pumps allows more flexibility in the arrangement of tanks, as well as ensuring automation of solution delivery.

Looking at the categories of pumps according to how energy is imparted to the solution, volumetric displacement pumps are more suitable for this project than kinetic and electromagnetic pumps (Britannica, n.d.). Volumetric displacement pumps are said to have the characteristics of delivering at an accurate flow rate, and are further divided into gear pump, rotary vane pump, and peristaltic pump (Giles, 2010).

While all three kinds of pumps could provide constant flow, the peristaltic pump is best suited for the ALNA. Gear pumps are mostly used on high-viscosity products that have lubricating properties, since they could generate high pressures for low flow rates (Giles, 2010). While rotary vane pumps are also especially suitable for pumping aqueous solutions, there is a high risk of contaminating the solutions when in contact with the vanes (Giles, 2010).

On top of delivering a constant flow of solutions, peristaltic pumps provide accurate metering, and no contamination will enter the solutions since the only part that will be in contact with the solution is the easily replaceable plastic tubing (Giles, 2010). From the figure below, it is clearly illustrated that the solution will not be in contact with materials other than the plastic tubing of the peristaltic pump.

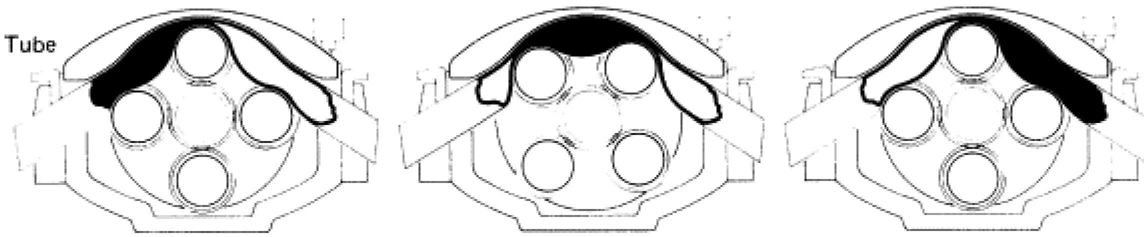


Figure 12. Peristaltic pump (Giles, 2010)

Four peristaltic liquid pumps were needed. These are Garosa G928 peristaltic metering pumps shown in the figure below. The rated working voltage is 12V with a DC brushed geared motor (G928 Peristaltic Liquid Pump, n.d.). It has a flow rate of 500mL/min. The pump tube uses a food grade silicone material and has a tube size of 6.4mm * 9.6mm (ID*OD), which will be taken into tubing sizing considerations.

Figure 13. Peristaltic Liquid Pump (Retrieved from Amazon.ca)

3.1.8 Tubing

All tubing in the system is responsible for delivering either input or output solutions, i.e., city water, high and low calibration solutions, and sample solutions, most of which are corrosive and prone to algae growth if given light. Main aspects to be considered are clarity, material, and sizes.

The decision criteria are that the material should be durable, it should be easy to source and replace for future upkeep and maintenance, and the size should be compatible with the peristaltic pumps that would be installed for each input tank. According to the specifications of the peristaltic pumps, the tube size should be 6.4mm * 9.6mm (ID*OD).

Some common corrosion resistant tubing materials are rubber, plastic, and steel (Tubing, n.d.). Steel tubing is ruled out for ease of installation and maintenance. Considering the final installation location of ALNA, which is inside a greenhouse in Mirabel Quebec, the tubing should also be UV-resistant to extend its lifetime. Following the ease of sourcing criteria, final selection was made on McMaster-Carr.

The tubing that fit all of the criteria is the UV-resistant opaque tubing for air and water. The tubing is offered in the material of polyvinyl chloride (PVC) plastic and ethylene propylene diene monomer (EPDM) rubber. Both materials would not degrade when exposed to ultraviolet (UV) light while the EPDM rubber provides extra flexibility and better durability in outdoor environments. EPDM rubber was not considered since the performance exceeded the system requirements and came at a much higher price. PVC plastic is more economical, in the meantime having enough flexibility (durometer 70A, which is considered soft), and can withstand temperatures from -5°F to 160°F (-20.56°C to 71.11°C) (UV-Resistant Soft Plastic and Rubber Tubing for Air and Water, n.d.).

The final decision is UV-resistant soft PVC plastic tubing for air and water with ¼′′ ID and 3/8′′ OD (6.35mm ID and 9.525mm OD), which fitted the peristaltic pumps perfectly during prototyping.

3.1.9 Software

One of the most important design criteria of our system was to achieve complete operational automation. In order to deliver this requisite, we designed a pseudo-code software solution for the ALNA's automated sensing and for the Dosing Box automated liquid transport control. This puts the project in motion, with functional communication between the already-developed Circulus's user command dashboard in the Node-RED platform, the ALNA RPi, and the Dosing Box RPi.

We found that the best way to describe the pseudo-codes while respecting the Non-Disclosure Agreements signed by our teammates with Circulus AgTech, was to define flowcharts for each process.

3.1.9.1 Logic for Pump Automation

<u>Criteria:</u>

- The program should take into account how long the pumps should be activated for, in order to simplify processes.
- The program should be designed under the MQTT communication protocol in order to receive/send commands with the rest of the programs in the server (ALNA, user interface dashboard).

Assumptions:

- The flow rate specification of the peristaltic pumps is 500 ml/min
- The volume of solution in the vessel is 1.216 L

Calculations:

$$Time\ for\ pump\ in\ state\ active \ = \ flow\ rate\ of\ solution \ \times \ total\ volume\ of\ solution\ in\ vessel \qquad (10)$$

$$Time\ for\ pump\ in\ state\ active \ = \ (500\ ml/min) \ \times \ (1.216\ L)$$

Therefore, the time that will take for the vessel to be full of solution is 2.43 minutes.

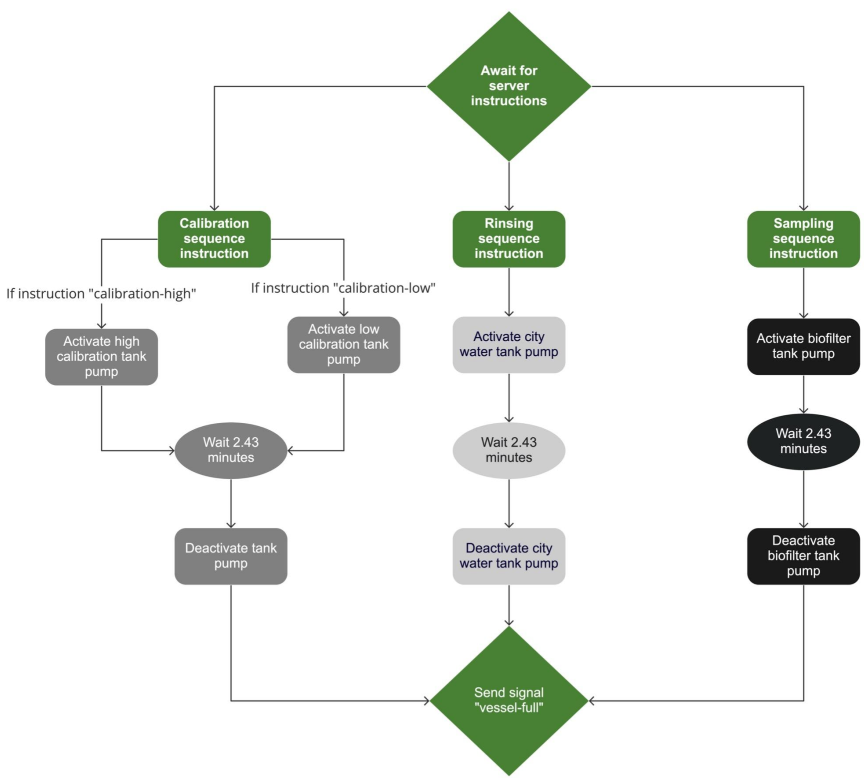


Figure 14. Dosing Box logic flowchart

3.1.9.2 Logic for Sensing Automation

Criteria:

- Implement simple sequences of action that allow for repetition, consecutively, and on a regular temporal basis, e.g.: calibration and sampling are similar in the sensing process
- Since the Node-RED user interface sends important commands to the server, software must run on MQTT communication protocol in order to receive/send commands and perform actions.
- ALNA's Python program should have access to the sensor interface and control the valve, to simplify the coding integration.

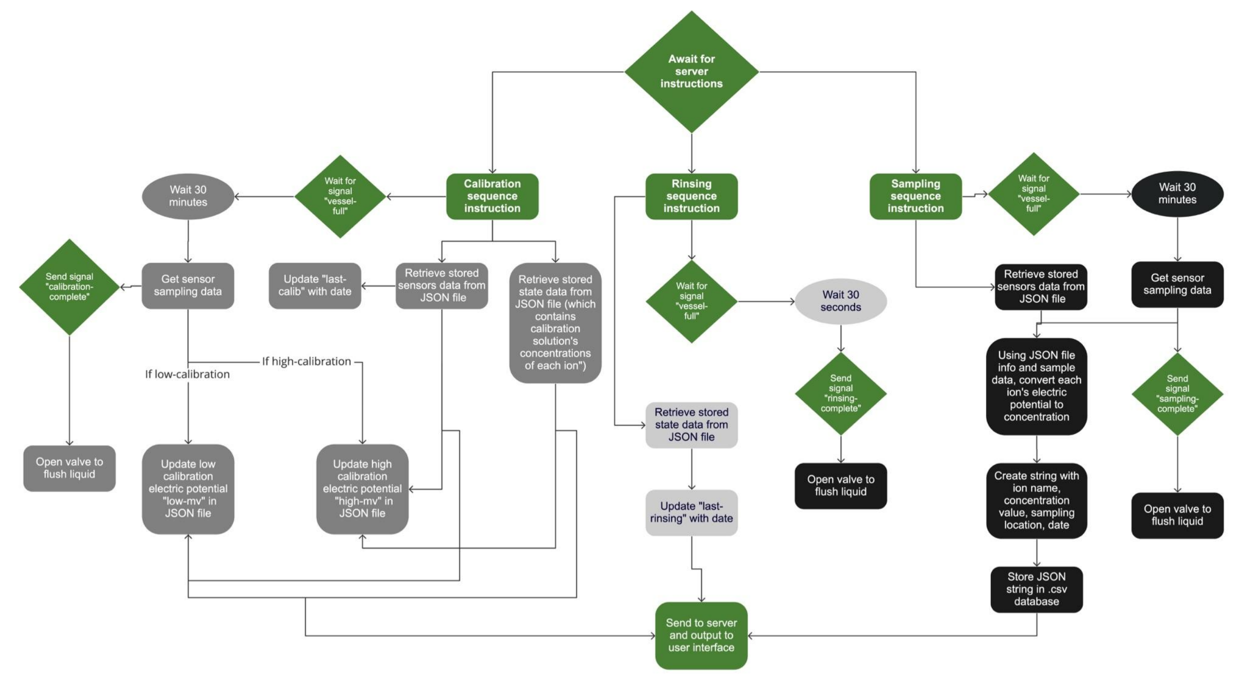


Figure 15. ALNA logic flowchart

3.1.10 Hardware

Two control boxes are required for the system. One is called the dosing box which is responsible for controlling the input. The other is the ALNA control box which houses the sensor interface and relay for controlling the output. The selection of specific items will be discussed in the following sections.

Pertaining to the criteria of ease of sourcing, all hardware parts are obtained from ABRA Electronics located in Saint-Laurent, Quebec.

3.1.10.1 Computers

Two single-board computers are needed for the two control boxes. The computers are expected to handle three to four-channel relays and communicate with at least six sensors. A specific software is to be developed for the ALNA to present data and do remote control of the pumps, solenoid valve, and sensors in the system.

Based on the requirements, a Raspberry Pi board is the most suitable. Since RPi allows for different operational softwares (OS) to be installed, it allows for much more complicated software development using the popular languages such as C++ and Python (Teja, 2021). The powerfulness of a RPi is also crucial in the role of web server control. The newer model of RPi such as RPi 3B+ supports wireless LAN, enabling real time communication with the presence of a router. The RPi 3B+ also has an extended 40-pin header, giving freedom of add-ons to choose for the sensor interface and relays (Raspberry Pi 3 Model B+, n.d.). Compared with the newest model RPi 4, RPi 3B+ is a much more economical choice and RPi 4 could be an overkill.

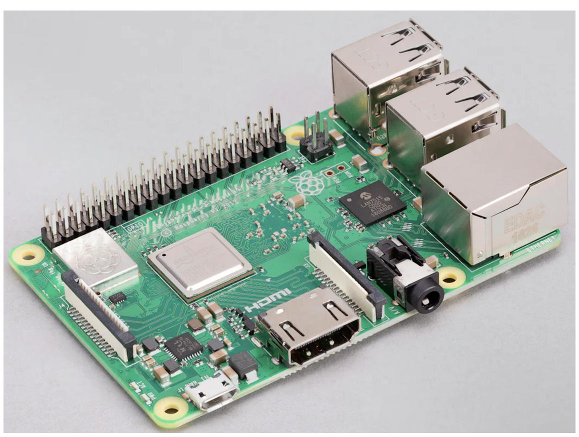


Figure 17. Raspberry Pi 3 Model B+.

Furthermore, we decided to install the Raspbian OS on both RPis since it is Linux-based, and more flexible in terms of what can be programmed in it. There is also the ease of managing applications with the built-in store and while being one of the most widely used OS, we could find extensive troubleshooting information available on the internet (*Latest Open Tech From Seeed*, 2019).

3.1.10.2 Power Supply and Power Jack

The two control boxes each need a power supply. In the ALNA control box, a solenoid valve (12V) controls the output and a RPi (5V) needs to be powered. In the dosing box, 4 peristaltic pumps (12V) and a RPi (5V) need to be powered. Giving thought to the installation location, both power supplies should be able to handle an input voltage of 120V, and preferably have a wall adapter.

For the ALNA control box, an output of 12V 5A should ensure a steady operation of the electronics. For the dosing box, to guarantee a smooth functioning of the peristaltic pumps, a power supply providing higher current should be considered, thus an output of 12V 10A is desired.

To conclude, a 12V 5A power supply with a wall adapter is needed for the ALNA control box and a 12V 10A power supply with a wall adapter is needed for the dosing box. Both power supplies (if having a barrel connector output) should be paired with power jacks of the same size. They are shown in the following figures.

Figure 18. Chassis Mount DC Power Jack 2.1mm I.D. (Retrieved from ABRA Electronics)

Figure 19. 12VDC 10A Power Supply Wall Adapter (Retrieved from ABRA Electronics)

3.1.10.3 Power Converters

As stated in the power supply section, the RPi requires 5V input voltage, which is different from the rest of the electronics, thus power converters are needed for both boxes, specifically step-down voltage converters. The input and output voltage range of the step-down should include 12V and 5V respectively. It should also be made sure that the output power is enough for the performance of the boxes.

Furthermore, as a consideration to the skill requirements of the technicians, a step-down with volt and ammeter could be much easier to install and inspect with negligible extra capital input. As shown in Figure x6, the two screens display the amperage and voltage respectively. It is also capable of adjusting amperage and voltage limit.

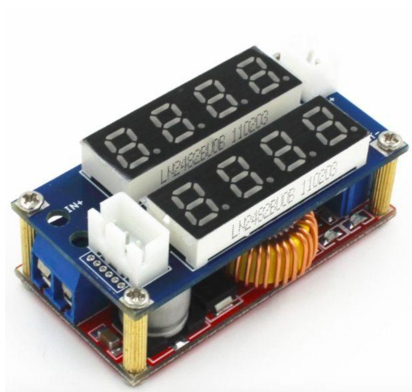


Figure 20. Step Down Voltage Converter with Volt and Ammeter (Retrieved from ABRA Electronics)

3.1.10.4 Relays

The ALNA control box needs a three-channel relay for the solenoid valve responsible for the system output, the level sensor in ALNA, and an extra channel leaving room for future add-ons. The dosing box needs a four-channel relay for the four peristaltic pumps.

Both relay boards should be compatible with the RPi 3B+. Boards with indication LEDs are preferred.

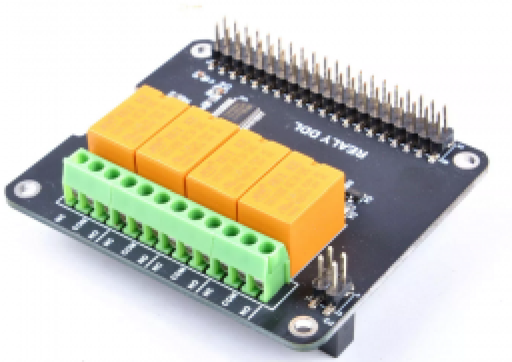


Figure 21. 4-Channel Relay HAT Module Board (Retrieved from ABRA Electronics)

3.1.10.5 Sensor Interface

There are six sensors in total, all of which are from Atlas Scientific, with male Bayonet Neill-Concelman (BNC) connectors. To allow the RPi to read multiple sensors with ease, RPi expansion boards will be needed. The expansion board should be compatible with BNC connectors and preferably stackable on RPi.

Whitebox T3 MkII (shown in Figure x8) made by the company Whitebox Labs was chosen. Each board has 3 BNC ports, is compatible with all Atlas Scientific EZO devices, comes fully assembled, and is stackable to allow connection with more sensors (Whitebox T3 MkII, n.d.). Moreover, the board has specific ports for Atlas Scientific circuits that enhance the sensor accuracy. It also has built-in electrical isolation, preventing interference with readings due to unwanted electrical noise.

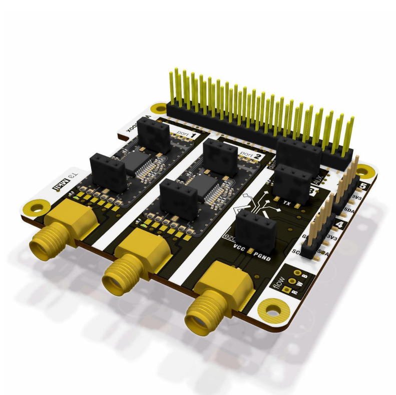


Figure 22. Whitebox T3 for Raspberry Pi (Retrieved from WhiteboxLabs)

3.1.11 Integrated system

In light of the sections above, a high-level description of the overall system will allow us to delve into the functional units built with all the vetted and selected components. Figure 23 below details all the main components of the ALNA system, save for the dosing box and other electronics, in an ideal agencing, which does not necessarily correspond to the reality of the site at Mirabel, QC. It is also to be noted that the visual below does not reflect the actual drilled hole positions on the ALNA chamber.

Almost all of the components are sourced from off-the-shelf industrial supplier e.g. McMaster-Carr and ABRA Electronics. The only 3D-printed component is the vessel insert. The tank sizes vary depending on the solution stored, while the peristaltic pumps are controlled by the dosing box not visible here. The external solution input and effluent output holes are drilled directly into the stainless steel beaker, while the smooth finish of it allows for flushing without requiring a slope at the bottom. Lastly, the tubing used for our system is UV-resistant and very durable.

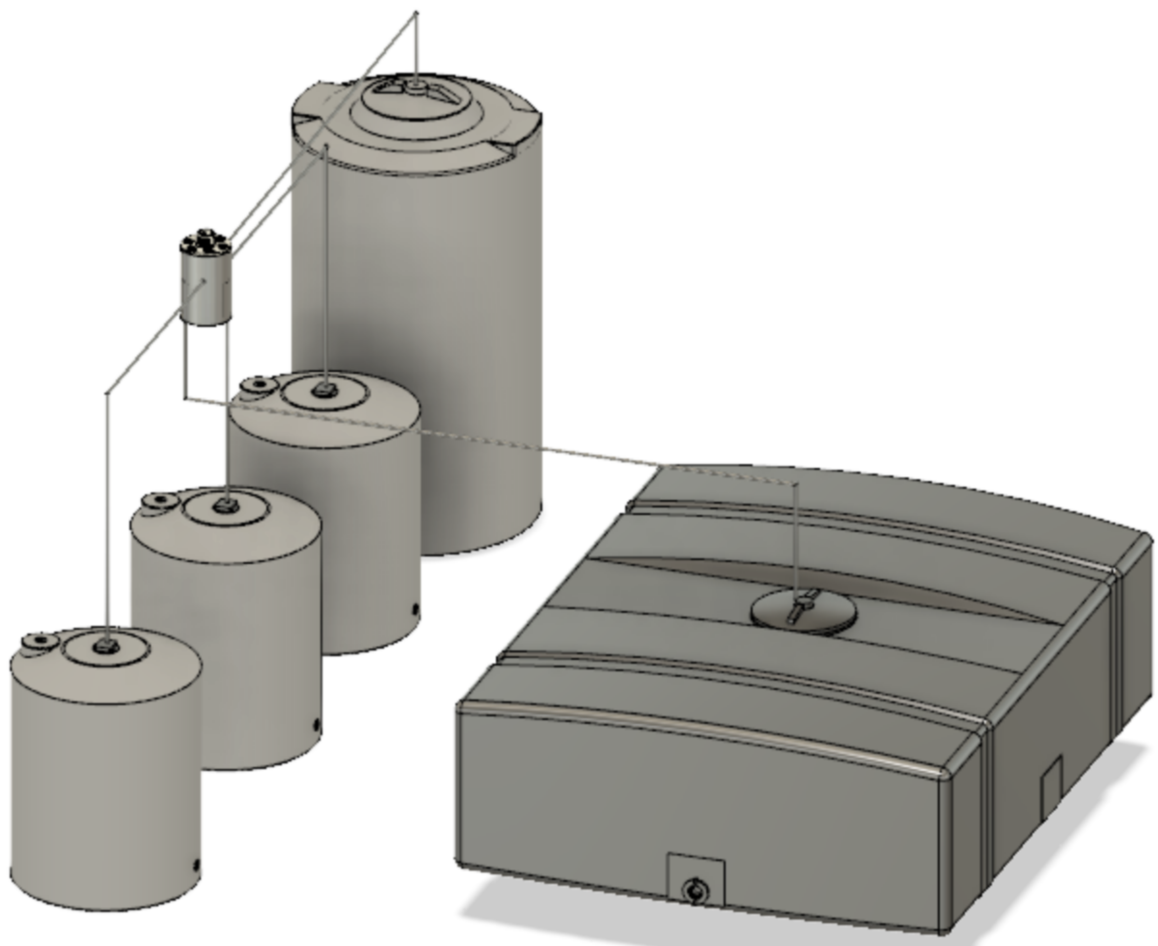


Figure 23. High-level rendering of the ALNA system.

3.1.11.1 ALNA Vessel

The chamber that was opted for is a corrosion-resistant (ANSI/NSF complient) stainless-steel beaker sourced off the shelf from McMaster-Carr with a 2-day delivery time. It presents the advantage of having a volume of 1.216L once the insert is put in. Holes are drilled (i) at the bottom (1) for effluents, which would pass through a barbed fitting tube of the appropriate size (1/2” OD), and (ii) on the sides for the inputs (1/2”). The holes upstream have been drilled into the beaker in order to simplify the design, otherwise the design would have had to incorporate an upstream chamber with four connectors and then be linked to a single hole in the beaker.

For the vessel insert, there was no alternative found except for very costly, polluting, and complex injection moulding, so this element is a very tailored piece of the ALNA system as per the design selection procedure laid out for it earlier. It is SLA-printed in its final form despite unsatisfactory corrosion resistance (like all of the other alternatives), and the team recommended to Circulus that they try and coat it with beeswax provided it does not interfere with the probes' regular operation. The probe holes were sized large enough for different sensors to be put in, depending on company needs, with the help of grommets in both holding planes to keep them stable and firmly attached.

Figure 24 below presents the built prototype with the inserts embedded, on a stand provided by Circulus AgTech, as well as the rendering of the final vessel to be delivered to Circulus AgTech pending print of the final system-sized insert.

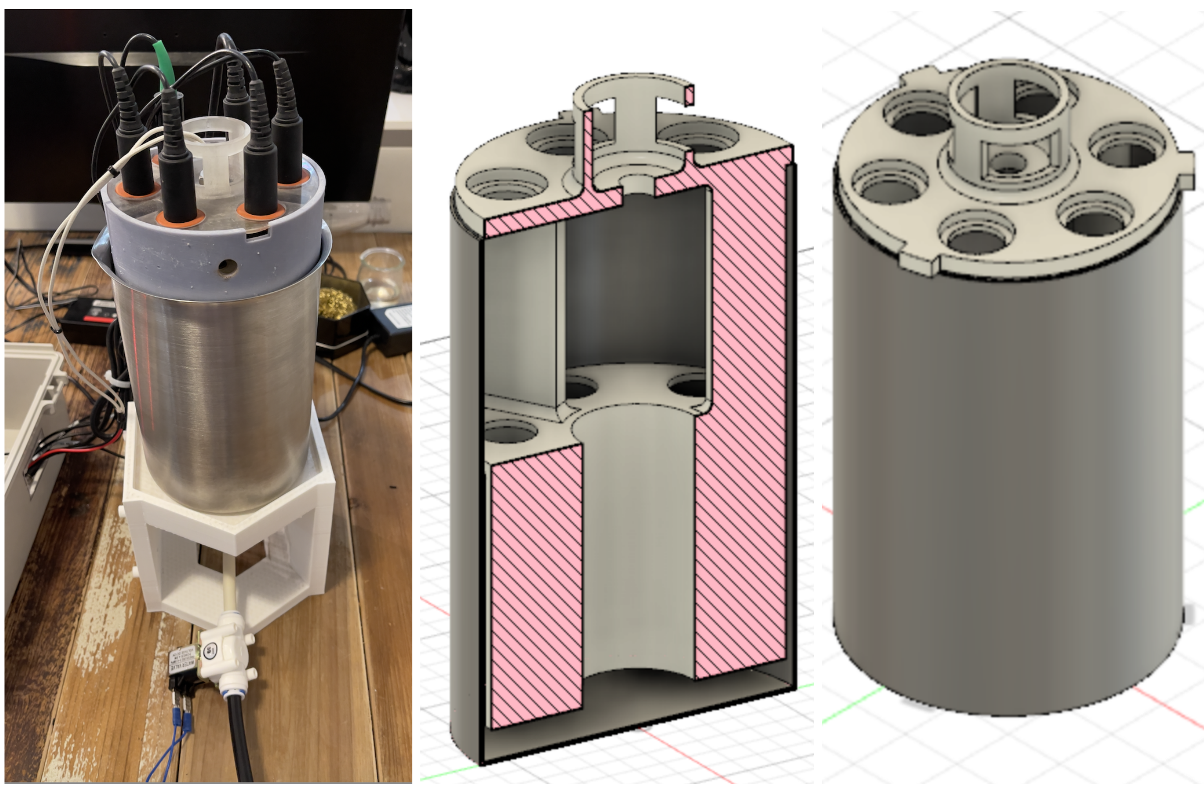


Figure 24. Smaller-scale ALNA Vessel prototype inside the final Steel Beaker (left). CAD rendering of the final design in sliced (center), and isometric (right) views.

3.1.11.2 Dosing Box

Figure 25. Dosing Box Exterior

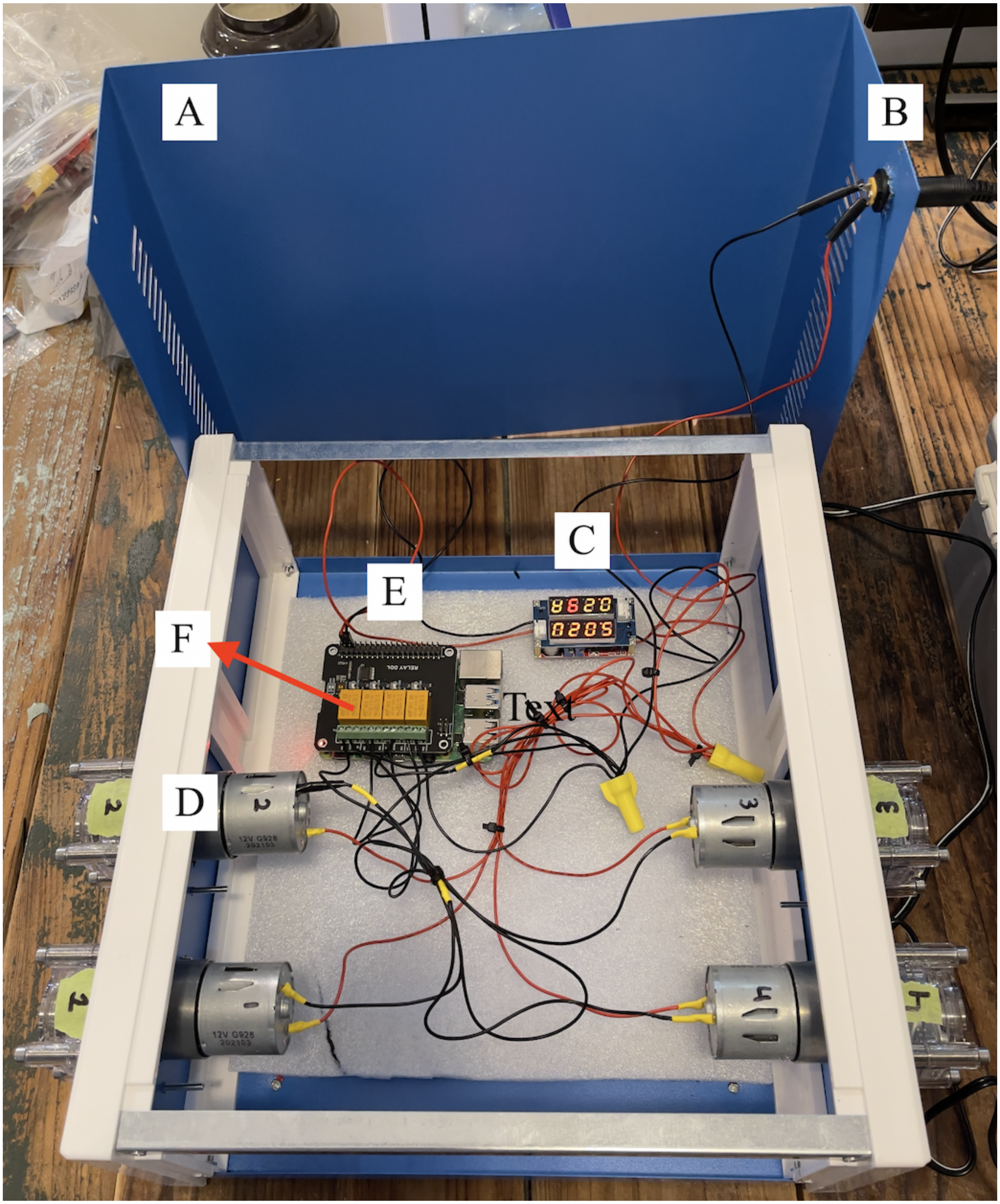


Figure 26. Dosing Box Interior

Figure 27. Blue Metal Enclosure Project Case (Retrieved from Amazon.ca)

As shown in Figure 25 and 27, the enclosure chosen as the dosing box is a metal project box with dimensions of 310mm * 285mm * 115mm (L*W*H). All sides of the project box are screwed on, two of which (as shown in figure 27) come off individually. In figure 27, it can be seen that the box has built-in aeration/ ventilation grids, though they are small enough to prevent high dust accumulation inside.

The box is modified to fit other components such as pumps and power supply. Two parallel sets of holes were drilled on the two individual panels in order to mount the peristaltic pumps. Another hole was drilled on the side of the box (Point B in figure 26) to install the barrel jack which the power supply plugs into.

As shown in Figure 26 point B, the power supply (12V 10A) is plugged in through a power jack. The power supply has a 2.1mm output male barrel connector and is plugged into a 2.1mm power jack mounted on the panel.

The wires then split into two paths; one is directly wired to the four pumps providing 12V. As shown in Point D in figure 26, pumps were mounted on the sides of the box. The pumps are numbered both inside and outside of the enclosure, so that they could be easily recognized.

The other path is connected to the step down with built-in ammeter and voltmeter and an LCD screen as shown in figure 26 point C. There are two screws on the step down to adjust the voltage and amperage limit. Here the voltage is adjusted to 5.02V, which will be fed to the RPi.

The RPi 3B+ is located in figure 26 Point E. On top of it is a four channel relay HAT module board. The relay channels are numbered from one to four, and are connected to pump one to four respectively.

3.2 Experimental Phase

The following section describes selected aspects of our implementation activities, as well workaround and methods used by the team to achieve their stated goals in building both the ALNA Vessel and the Dosing Box.

3.2.1 Printing Process & Manufacturing Errors

The challenging bit regarding the construction of the physical system pertained to 3D printed elements. As we opted for fast prototyping, FDM was the method to go though it presented numerous bottlenecks.

A first bottleneck concerned the vessel chamber, and was to be imputed on the Ender 3D v2 printing machine used by Mac 3D. The initial printing time for the chamber in PET for prototyping was 18 hours but failed twice, as per the Figures below.

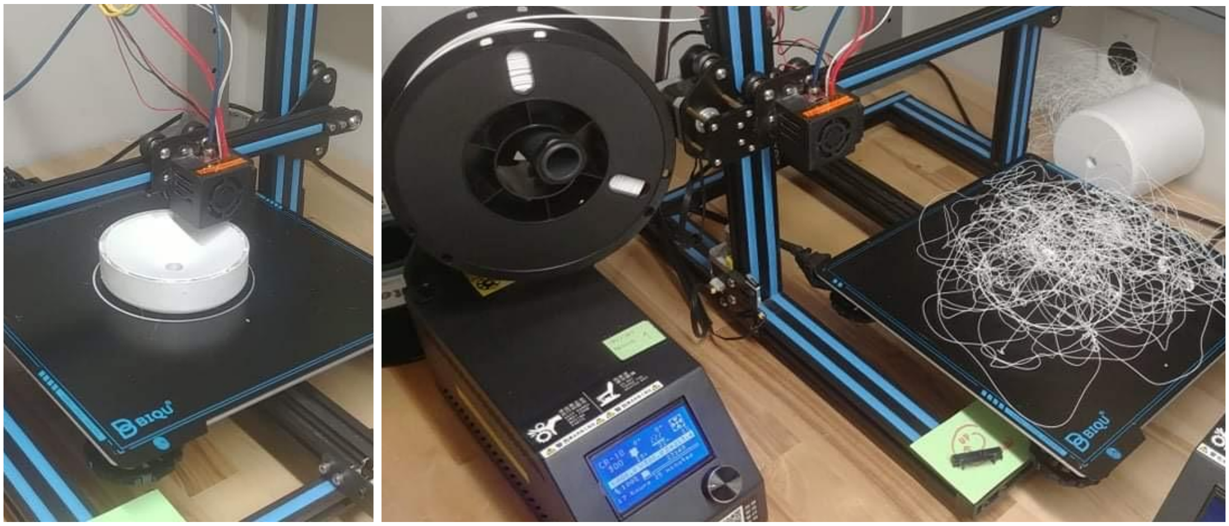


Figure 28. Printing phase and failure of the chamber printing.

What’s more, a combination of scheduling, commissioning, and printing issues led us to only having the prototype-sized insert by the due date, which thus hindered our ability to fully test the final design for functionality while operating. As can be seen in 3.1.11 Integrated System, the insert for the final system is supposed to be 1.04 times bigger than the prototype, and the timely completion was hindered by the fact that the insert was simply too big for a machine to print, and that the print’s structure would pose issues as Mac 3D only has access to FDM which would then require us to have significant structural support to build it. The initial print would have taken 2 days and 8 hours with more than half of the filament used being wasted in the form of structural support. We thus had to opt for a clever workaround i.e. slicing the insert into three parts; as of today, the final insert has been printed and is currently at Circulus AgTech’s industrial facilities, pending integration to the stainless-steel beaker.

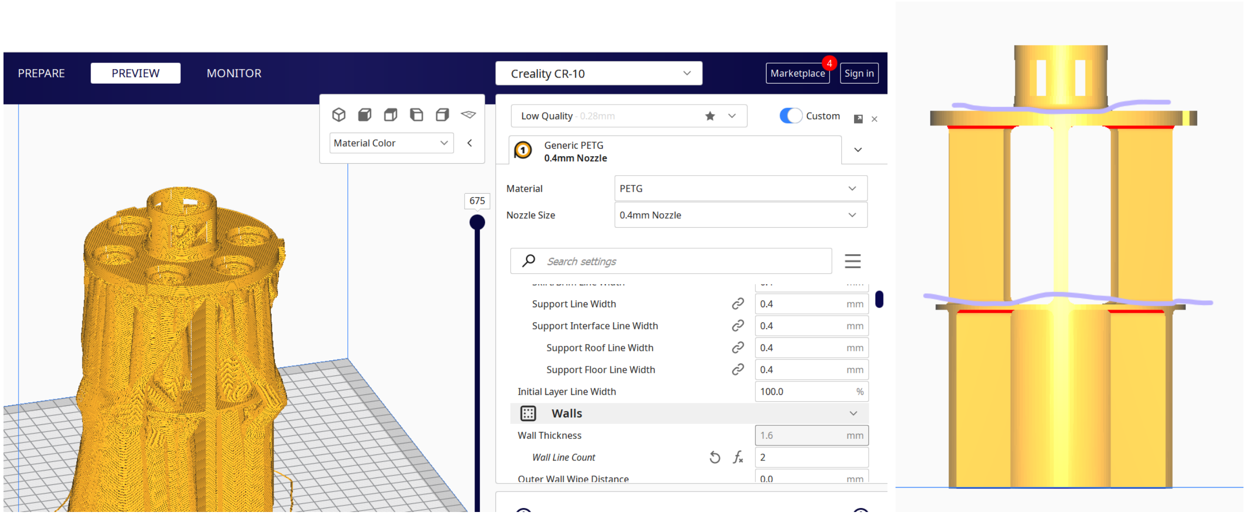


Figure 29. Initial prototype printing situation on Ultimaker Cura (left), and slicing workaround devised in conjunction with Mac 3D (right).

3.2.2 Software Integration

Figure 30. NodeRED dashboard that controls ALNA and dosing box system

The team faced a preliminary issue with the implementation and testing of the MQTT communication protocol in both dosing box and ALNA systems, which was resolved with the help of Mr. Debbagh. Furthermore, it was challenging to implement the float switch fail-safe activation in case the dosing box's pump automation failed which will have to be investigated further in order to find the most effective way of addressing it, i.e., if it should be activated every time the float switch notes the maximum liquid level, or if it should check whether the pumps have been deactivated and not react. This can induce a potential failure of the system if there is liquid still traveling through the tubing system.

3.2.3 Performance Testing

Mostly pertaining to the dosing box after assembly, the team conducted preliminary testing on all four peristaltic pumps for a duration of 1 minute each to make sure that power was supplied accurately, and that the relays were linked to the pumps correctly. Further testing of other components was postponed due to competing priorities within Circulus AgTech's CTO Office.

3.2.3.1 Dosing box

In the dosing box, corresponding pumps should be actuated at designated times for a set time interval. The vessel should be filled to a desired level as a result.

Actuation of the pump sequence and time interval was tested using a demo code which instructs the relay to turn on the pumps in sequence (from one to four) for the designated time interval, which is 2.43 minutes, with a wait time of ten seconds in between pumps.

Testing results showed that the relay is wired correctly with all pumps on normally open, which means that the pumps will only be turned on when instructed and will be turned off for when no signal is received. The sequence of pumps is in accordance with the sequence of the relay, meaning that relay number one is wired to pumps number one and so on. With little delay, pump one was actuated as desired and was turned off when the duration reached 2.43 minutes. The relay then waited for ten seconds to actuate the next pump.

More testing would have to be done with sample solutions to make sure the wait time is of an appropriate length and that the output valve is actuated accordingly.

3.2.3.2 ALNA

The sensors in the ALNA should work seamlessly with the dosing box, so that when sample solutions and calibration solutions are inputted in the vessel, the sensors would start taking and sending measurements. After completion of each solution, the output solenoid valve should be actuated to let out the liquid into the waste tank.

The flow of the ALNA was also tested using a demo code, where the ALNA control box signals the sensors after a solution has been filled in the vessel. When the readings reach a stable state, the output valve is actuated for the same time interval as input for the liquid to exit the vessel. The solenoid valve is closed when either the float sensor has indicated an empty vessel, or the time interval has been reached.

Further testing should be done to justify the criteria of when to start and terminate the output sequence. Now the output sequence will begin either when the readings are stable or when a set time interval of known measuring time has been reached. Similarly, the termination of the sequence as mentioned above, is signaled either by the float sensor or when a designated time interval that ensures all liquid will be out is reached.

3.3 Assembly and Maintenance Protocol

A noteworthy element of this section is that the electronics do not need any sort of regular maintenance, the rest of the elements pertaining to initial assembly and scheduler procedure with their associated protocols are laid out below.

3.3.1 Initial Assembly

3.3.1.1 Physical assembly

Grab vessel insert → screw in float switch → put in grommets → put in sensors → slide it into the vessel chamber → put in the barb fitting at the bottom → put the upstream solution tubes into their dedicated holes (no assigned hole) → **[OPTIONAL]** apply sealant or plumber’s tape before insertion → put the Vessel on the ALNA stand (provided by Circulus AgTech) → link the downstream barbed fitting to the effluent tank → plug in the sensors to the ALNA control box.

3.3.1.2 Hardware launch

At the time of finalized physical assembly, the ALNA electronics and Dosing box are to be plugged in, and will run seamlessly without any intervention; there is as such no need for an assembly/disassembly codex.

3.3.1.3 Software launch

<u>Technician Instructions for each Raspberry Pi:</u>

1. Download and launch Raspberry Pi Imager for your computer's OS → Connect microSD card to computer → On RPI Imager, select Raspbian OS to install and select the microSD card → click WRITE → (OPTIONAL) Once finished, eject SD card.
2. Check name of SD card (usually **boot**) → Create empty file in SD card folder named "ssh" with no extension → Create empty file in SD card folder "wpa_supplicant.conf" → Copy and paste "country=CA
   ctrl_interface=DIR=/var/run/wpa_supplicant GROUP=netdev
   update_config=1
   network={
   ssid="**NETWORK-NAME**"
   psk="**NETWORK-PASSWORD**"
   }" → SD card can be ejected and RPi can be accessed remotely with ssh.

3. Access Circulus AgTech git lab software package repository → Download corresponding software to RPi in repository → download all requirements that are present in the requirements.txt file → ready.

3.3.2 Maintenance Standard of Procedure

Every three weeks

Rinsing tank (max. 10 minutes)

Open cap at the top of the tank → bring in hose connected to city tap water → fill up to the tank's mouth → close and seal the cap.

Every month

Calibration tanks (max. 20 minutes)

Wash hands → open cap at the top of both tanks → bring in bottles containing the Circulus AgTech calibration solutions → fill up to the tanks' mouth → close and seal the cap → wash hands.

ALNA cleanup (max. 30 minutes)

Turn off all and disconnect electronics directly linked to the ALNA → Remove tubing seal and disconnect tubing → remove probes from the insert → remove the insert from the insert → unscrew the float switch → wipe all probes with a wet tissue → wash the insert with a pressure hose → dry the insert with paper tissue (by capillarity) → wipe the inside of the chamber with Clorox wipes → wipe chamber with regular tissue → re-assemble ALNA vessel as 3.3.1 Initial Assembly.

Every 2 months

Effluent tank (max. 30 minutes)

ALNA remains on, operator comes to empty the effluent tank - connect bit of UV-resistant tubing into the drain and into a third-party container → open drain into safe chemical disposal tank commissioned → wait until tank emptied at the drain-level → remove the tubing → wash hands.

Every 6 months

Replace all tubing and the four peristaltic pumps used.

3.4 Economic, Environmental, and Social Impacts

As per the OIQ, it is every engineer's duty to take into consideration any consequences of the actions on life, health, security and property towards the public while maintaining sustainable development.

3.4.1 Economic analysis

First, it is foreseeable that the system's implementation will result in a loss of jobs due to the introduction of automated sequences, remote control, and a maintenance schedule that only requires human input once a month - the estimated loss is at one Circulus AgTech operator per location, so three in total. Nonetheless, and rather than allowing for the loss of job opportunities, it could be seen as replacing a menial job by a technical one where IoT and quality assurance knowledge is remunerated, as the system will still require human oversight to gauge the system's operational status as well as assess the quality of the incoming liquid nutrient solution.

Second, there is a critical radius past which transporting manure to the system is done at a loss, mainly owed to transport costs. Thus, distance from various barns and farms where manure for suitable transformation, in sufficiently available quantity, and with a steady supply, iis essential in determining the location of the system.

Lastly, the system has to make economic sense for the client: as per Circulus AgTech's HR Payroll and Technical divisions' figures, the current design (incl. Labour costs) comes at a monthly operating cost of $170 with an initial Capital Expenditure of $679.40 (with taxes) against a monthly operational cost estimated at $70 for the proposed design, while the upfront expenditure at Year 0 is $3908.20 (with taxes); all of these figures include the taxes.

The high Capital Expenditure can however be imputed on the fact that the tanks alone cost $2590 (with taxes), and were out of both the scope and the financial calculations for the previous design. Moreover, and after having aligned with Circulus AgTech regarding their cost assumptions, it turns out that the electronics for the previous design were not included either, which the team has extrapolated at $557 (with taxes, the same as our current design). This in turn brings the capital expenditure for the previous design to $1236.40 while the capital expenditure for our design without the tanks comes down to $1319.02. This translates into a cost higher by less than $100 while the system is much more reliable, ergonomic, compact, and robust; this is an extremely satisfactory result as it would be amortized in one month as per the operational costs above if compared to the previous design; if we were to opt for a zero-based budgeting approach based on the operational costs, the system would save up $100 per month, and would thus pay for itself within forty months, which is more than its forecasted service life of 4 years.

Table 8 below highlights the list of parts that were required in order to assemble the ALNA system; detailed links and costs per part have not been included as they would constitute a breach of our Non-Disclosure Agreement with Circulus AgTech.

Item	Quantity	Supplier
Automated Liquid Nutrient Analysis (ALNA) System + Dosing Box (DB)		
DC-DC Step Down Voltage Converter with Volt and Ammeter	2	ABRA electronics
Raspberry Pi 3B+	2	ABRA

BBB-32GB-10 32GB MicroSD UHS-1/Class 10 Memory Card with SD Card Adapter	2	ABRA
13mm Chassis Mount DC Power Jack 2.1mm I.D.	2	ABRA
ALNA		
Stainless steel beaker	1	McMaster
3D-printed vessel insert	1	3D printer
Tight-Seal Moisture-Resistant Barbed Tube Fitting	1	McMaster
2/2 NC Solenoid Valve - Free Hanging (In-Line)	1	ABRA
Vertical float switch	1	ABRA
WAVE-11638 RPi Relay Board	1	ABRA
Whitebox T3 MkII for Raspberry Pi	1	Whitebox
12V 5A switching power supply	1	ABRA
EZO ORP Circuit	4	Atlas Scientific
Vernier BNC Ion-Selective Electrodes	4	Vernier
EZO Conductivity Circuit	1	Atlas Scientific
Vernier BNC EC probe	1	Vernier
EZO pH Circuit	1	Atlas Scientific
Vernier BNC pH probe	1	Vernier
Item	Quantity	Where to Buy
Dosing Box (DB)		
DC-1210.0 12VDC 10A Power Supply Wall Adapter	1	ABRA
4-Channel Relay HAT Module Board for Raspberry Pi4B, Pi3B/3B+	1	ABRA
Blue Metal Enclosure Project Case DIY Junction Box	1	Amazon
Peristaltic pump 12V 3A 500 ml/min	4	Amazon
Tank System		
Polyethylene Plastic Tank (vertical with drain, 22 gal)	2	McMaster
Polyethylene Plastic Tank (vertical with drain, 70 gal)	1	McMaster
Rectangular Plastic Tanks	1	McMaster

(polyethylene plastic, 200 gal)		
UV Resistant Soft Plastic Tubing (ID=1/4'', OD=3/8'', 25ft)	2	McMaster
TOTAL COST	**$ 3,398.92 ($1,147.05 without tanks) + applicable taxes**	

Table 8. List of parts required for the ALNA system.

Moreover, this low difference in terms of costs is also to be reinforced by the fact that the selected components - with the exception of the insert which constitutes a calculated risk and the peristaltic pumps and associated tubing which are expected to be changed once during the ALNA system's service life and every 6 months, respectively - have a very long service life that goes beyond the ALNA system's. Table 9 lays out a list of selected components and their lifespan for appreciation.

Part	**Lifetime**
Beaker	30 years
Water tank	30 years
Vessel insert	6 months
Calibration tank (x2) and Waste disposal tank	10 years (each)
Tubing	6 months
Peristaltic pump (x4)	300 operation hours (each)
Level Switch	20,000 operation hours

Table 9. Lifetime of selected parts of the ALNA. Hardware elements such as Raspberry Pi are not shown though they are expected to be operational for 4 years.

3.4.2 Environmental analysis

While the ALNA system aims to minimize liquid nutrient losses after analysis by design, thus rendering it a sustainable alternative to the previous design through its operation, the main source of environmental pollution stems from construction and server-side operation. Elements such as the electrical consumption are of minimal harm since the Province of Quebec is being supplied through hydroelectricity, however the procurement of petroleum-sourced materials for FDM and the tanking, tubing, and pumping system is the forecasted biggest source of pollution. These elements have not been quantified as per our timeframe but should be further explored in order to fully understand the environmental ramifications of implementing our new system. What's more, McMaster-Carr has not responded to our request regarding the tCO_2-equivalent emissions that are related to the components we have purchased. However, recycled materials are given priority provided that they meet the performance and durability requirements, thus ensuring quality compliance of our physical system.

Second, manure has to be transported on-site to produce the liquid fertilizer which would result in possible pollution since the freight is done by truck. Aside from the gaseous emission from the aforementioned trucks, greenhouse gas emissions from the manure itself - CH_4 in particular - is also a concern. Proper storage methods for manure i.e. maintaining it below 10°C during transportation to halt biogas production have been discussed with Circulus AgTech as part of our holistic problem-solving strategy; it was agreed upon that, as the scale of this project and the company grow, ventilation, air treatment, and eventual refrigeration during summer months will be put into effect if needed.

3.4.3 Social analysis

First, a lack of skills from technicians in IoT hardware and software matters is a concern. However, additional training on both the operation and functionalities of the NODE-Red software and Raspberry Pis should be able to offset this gap, while the software complexity should be minimized by providing training in JavaScript coding to relevant stakeholders.

Secondly, the complexity of the ALNA system could result in client alienation; there is thus a need to make the system easily accessible and understandable. To do so, a user manual comprising the physical and software systems' description and operation procedures is to be prepared. It is expected that potential future improvements of the system will revolve around the simplification of the user interface, given that Circulus AgTech plans on assigning a technical-level manpower to nutrient quality control.

3.5 Issues Faced During Design 3

From a high-level perspective, the major issue is inherent to our design. There is nothing like this system in the industry nor in research, so finding alternatives at the macro scale proved challenging though we managed to compare all subcomponents against alternatives, which makes our final design a still well thought-out one.

Distance

Although the issues mostly pertain to the engineering design and its associated implementation, the situation of our team also hindered project implementation. One of the team members, who happens to be the electronics expert, is out-of-country and therefore could not be present for the physical implementation, which resulted in more time having to be dedicated for the other members to understand what this part of the project consists in as well as building something tangible for it.

Client requirements

As per Dr. Mark Lefsrud, a fuzzy beginning will result in a fuzzy solution in terms of requirements and outcomes. It took numerous unfruitful meetings to understand what the client wanted in terms of system requirements to translate that into design criteria and requirements. In the case that we wouldn't get the desired information and data, we had to make relevant assumptions ourselves - for instance, the volume calculations for the tanks or the cost of electronics for the previous design.

Funding issues

This system comes at a price that is not sustainable for students to cover out-of-pocket, and as such the team had hoped that the funding promised by the Bioresource Engineering Student Society would help offset these costs. However, mismanagement on their side has led to the absence of communication in that regard until past the deadline at which the design had to be built. We thus could not afford to purchase the tank but Circulus AgTech has agreed to fund them though not before February 2022 e.g. after their 3rd round of seed funding.

Commissioning bottlenecks

While the team had high hopes in collaborating with Cube EUS for the vessel insert, their lack of responsiveness despite highlighting the time sensitiveness of the project (printing details needed a back-and-forth conversation, and the technician would not answer emails until 5 business days later) as well as the very high costs of printing as per the various quotes received has led to this potential work relationship fading away - it took 45 days for the technician to send a final quote. For the purposes of fast prototyping for the vertical chamber as well as the insert, Mac 3D was instead commissioned and worked tirelessly in order for us to have a prototype for both the insert and the chamber, though not without bottlenecks as per Section 3.4.1 Printing Process & Manufacturing Errors. Lastly, there was a nationwide shortage of Raspberry Pis which further postponed the implementation of our design, which ended up being offset by some of the team members scavenging their personal Raspberry Pis for the system to be implemented.

Scope creep

As previously described, the project initially solely consisted of the ALNA Vessel and its related hardware and software components. Circulus AgTech is a young startup whose Research & Development is - to use a euphemism - agile and ever-changing. As such, the needs of the company made it such that the tanking systems upstream and downstream were added as components to be designed by the team, with the dosing box that comes with it. This in turn added significant complexity to the project while not being allowed to have more time to work on it. However, these components were successfully integrated with the work we had been doing and as such, were well managed by the team.

4. CONCLUSIONS & RECOMMENDATIONS

Overall, the focus of this undertaking in the early stages was to devise a physical means of taking samples of liquid fertilizer by automating both the sampling, the analysis, and the revolving operations needed to obtain quality data points, all of this while making the system as robust, long-lasting, easy to build, and easy to acquire parts for.

Over the course of Design 3, it was expected from us to both build a prototype as well as functional model for our client, with both the upstream/downstream tank system, and an up-and-running ALNA vessel with its associated hardware and software. By using rigorous comparative matrices throughout the design and selection of every vital subcomponent, a stainless-steel beaker lodging the custom-made vessel insert was selected, alongside a Raspberry Pi-based hardware and NodeRED-based software suite for the dosing and the analysis, as well as food-grade polyethylene tanks for external solution holding. The future requirements for improvement will mostly concern the eventual scaling up of this vessel for other industrial use cases, as well as developing more corrosion-resistant alternatives for the 3D-printed probes insert; in that regard, injection moulding with the appropriate material was considered but vetted out because of cost and complexity considerations. Trying to obtain items in shortage, as well as coordinate the electronics building proved challenging, while numerous bottlenecks in acquiring the final probes insert were challenging aspects of the project. The final system’s probes insert is currently being printed by SLA, and it is expected that a full-scale demonstration of the system is planned for February 2022. We thus foresee the continuation of our partnership with Circulus AgTech beyond the scope of this course.

Elements the team wishes another team might be able to complete in the future and from which the basis of further refining and fine-tuning concern: (i) the Life-Cycle Assessment from a procurement and server-side operation standpoint, which was mentioned in the team members' midterm contributions, and (ii) the fluid transport considerations, such as the relevant impacts of tubing material, tubing diameter and pump strength can have on the laminar or turbulent flow of solutions and the respective long-term maintenance implications.

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