EDUCATIONAL ALGAE BIOREACTOR

Group 7: Morley Bennett, Étienne-Nathan Balasingam, Clara Wang
Mentor: Yvan Gariepy, P Eng.

DECEMBER 13, 2024
Faculty of Agricultural and Environmental Sciences
Department of Bioresource Engineering
BREE 495: Engineering Design 3

Abstract

There is a desire in society to move towards sustainable (environmental/social/economic) practices. One notable means of achieving this is through the use of biosystems, and trained personnel are required to develop such systems at an industrial scale. Yet, there is little development in the post-secondary educational sector (such as CEGEP) for biosystems. This shortage and need for education and training is the motivation for this project. Our goal is to design an algae photobioreactor tailored for an educational setting, that has more variability and is more affordable than what is currently on the market. In a previous report, comparisons were made for various algae systems, for their capacity to showcase varying factors affecting algae growth and photobioreactor operation. It was determined that the air injection bubbler was the optimal design. In this report, a prototype based on the preliminary design was constructed and tested for 2 weeks. Proving to be successful in its ability to conduct various experiments, a financial analysis was calculated for its materials and capital costs.

Table of Contents

1. Introduction

Resource acquisition and product development are central to both society and the economy, significantly impacting the environment. Consequently, all facets of sustainability—environmental, social, and economic—are involved. There is a growing commitment to enhancing the overall sustainability of industries, which promises a better future. To achieve this, biosystems should be leveraged, as they align with the principles of a circular economy and efficient resource utilization. This applies to both product manufacturing and fuel production. The majority of the world's energy is dependent on fossil fuels, accounting for about 80% of annual global energy (Environmental and Energy Study Institute, 2021). However, fuels from natural petroleum deposits are being depleted and are expected to mostly run out within the 21st century (Shafiee & Topal, 2009). Thus, there is a growing need for alternative fuels sourced from organic materials.

Currently, there is a lack of education and exposure in post-secondary institutions, such as the CEGEP system, regarding biosystems and biofuels. Despite the growing desire to shift towards renewable resources and energy and away from petroleum, there is very little information on the actual functioning of biofuel systems in school curriculums. Science students are exposed to notions, and engineering technologists only learn about general mechanical and electrical systems. The growth of sustainable industries utilizing biosystems will require educated personnel, and currently, there is a notable lack of such individuals.

Microalgae is a very promising source of bioproducts, including biofuels and other commodities such as cosmetics or pharmaceuticals, because of their relatively high oil content (~30-50%) and rapid biomass production compared to terrestrial crops (Chisti, 2007; Khan et al., 2018). Although demand for algal bioproducts is growing, there are very few training technologies available for the developing industry. There are some programs and courses (mainly offered online) designed to expose students in K-12 education to the fundamentals of algae and how it can be a solution to global food and environmental challenges (Levine et al., 2021). For example, the Algae Technology Educational Consortium (ATEC) created by the Algae Foundation includes a community college certificate program focused on algae cultivation, or BioFuelNet Canada and Biomass Canada which offers online certificates on advanced biofuels, but they only gloss over algae as a feedstock because of how underdeveloped the industry is in Canada (BioFuelNet Canada, 2017; BioMass Canada, 2021; Levine et al., 2021).

There are practically no photobioreactors (PBRs) designed for educational purposes currently on the market, students typically have to build their own prototypes for projects. Educational PBRs have different needs from scientific-based research or industrial-scale production PBRs, focusing more on monitorability, variable factors, hands-on learning, and affordability. WOOFAA (2016) a company based in Hong Kong, has an educational microalgae PBR priced at around 3100 CAD$ (converted from 18000 HK$). However, the main goal expressed by its product description seemed to be focused on the carbon sequestration abilities of algae, not culture cultivation.

The ultimate goal of this project is to establish a functional biosystem designed to educate and train the next generation of biosystem professionals at the post-secondary level, such as engineering technologists (Engtechs) in CEGEP. The proposed PBR will achieve successful algae cultures, where environmental factors are adjustable, and changes in growth rate and chemical composition can be monitored, allowing for useful applications in experiments to determine optimal growing conditions.

But why did we choose algae? For educational purposes, a system must be practical to use, easy to store and maintain, and compliant with educational timeframes. Algae are simple to cultivate and typically do not die off easily. Algae systems can be cleaned and stored with relative ease, and new cultures can be initiated quickly. This allows for new cultures to be started at the beginning of a semester and the system can be cleaned out and stored during school breaks. Furthermore, algae exhibit rapid growth, which enables effective biomass production from the start to the end of a semester. Not only are algae practical for educational use, but they also serve as a representative model for systems involving water treatment, biofuels, and other bioproducts.

In the first report, we proposed a rough design for our photobioreactor after identifying the variables that would be necessary for it to make it functional and rigorously comparing various types of bioreactors to determine the most suitable type for an educational setting. In this report, we constructed a prototype of the proposed design with changes made due to the limitations of material, cost, and time. After being built, the prototype was tested by trial running for 2 weeks to validate its feasibility for being able to run various experiments with varying factors, its stability for running an experiment for an allocated time, and its ability to yield sufficient results on time. The photographic data collected was analyzed and graphed through MATLAB, using image reading functions of saturation. The cost of total materials was calculated not only for the prototype but also for an official design for actual commercialization.

2. Summary of Previous Report

2.1 Initial Design Considerations

In our last report, we conducted a critical analysis and comparison of the pros and cons of various PBR design options as a means to determine their strengths and weaknesses.

(Images of the various bioreactor types can be found in Appendix A)

There are two main categories of algae PBR designs: open systems and closed systems. Open systems are left exposed to the surrounding environment, while closed systems are mostly enclosed (Koller, 2015). Open systems have low operational and capital costs but are limited by environmental factors like contamination, low productivity rates and high space requirements, making them suitable for large-scale operations in favourable climates. The main advantage of an open system is its simplicity and unique ability to imitate algal growth in their given environment harvesting natural energy from sunlight alone (Xu et al., 2009). Closed PBRs offer better control, consistency, and productivity, as well as minimized contamination risks and far smaller space requirements, but it does come at a higher cost. The industry is increasingly favouring closed photobioreactors over open systems because of their advantages (Yen et al., 2019).

Open Systems

Open Ponds:

Essentially a natural pond with a mechanical rotating mixer. Simple, extremely low-cost design with minimal energy requirements, commonly used in biomass production where climate allows for it. However, the design suffers from poor mixing, low productivity, and high vulnerability to contamination and environmental factors (Gupta et al., 2015; Qin et al., 2019; Yen et al., 2019).

Cascade Systems:

Utilizes gravity and turbulent flow for mixing with inclined platforms, leading to better biomass density. While capital and operational costs are low, they are slightly higher than open ponds due to the need for water pumping. (Borowitzka & Moheimani, 2012; Masojídek et al., 2015)

Raceway Ponds:

A modified version of the open pond design that features paddle-based mixing, improving productivity. They share drawbacks with simple ponds, such as high space requirements, and require more energy to power the paddles, but the continuous operation and moderate mixing rates, make them more productive (Borowitzka & Moheimani, 2012; Yen et al., 2019).

Closed Systems

Flat Plate:

Composed of vertical translucent plates illuminated from both sides, with aeration from spargers at the tank's bottom. Although they require substantial space compared to other closed designs, they offer a large illumination surface area with significant biomass yield. However, they are prone to biofouling, making maintenance challenging. (Gupta et al., 2015; Masojídek et al., 2015; Yen et al., 2019)

Tubular:

Consists of transparent tubing arranged in any given orientation such as horizontal, inclined, spiral etc., that utilizes airflow for mixing. Although they offer good light penetration and biomass yields, their small tube sizes make cleaning challenging, and they also require considerable space. Their scalability makes them popular for biomass production but they require great amounts of energy for cooling and face photoinhibition from excessive light and oxygen (Masojídek et al., 2015; Xu et al., 2009; Yen et al., 2019).

Stirred Tank:

Consists of a glass vessel that experiences mechanical mixing, such as impellers or magnetic stirrers. While effective for mass and nutrient transfer, they have high operational costs due to energy requirements and generate high shear stress, which can reduce cell productivity. This is why they are mainly used in laboratory production (Gupta et al., 2015; Koller, 2015).

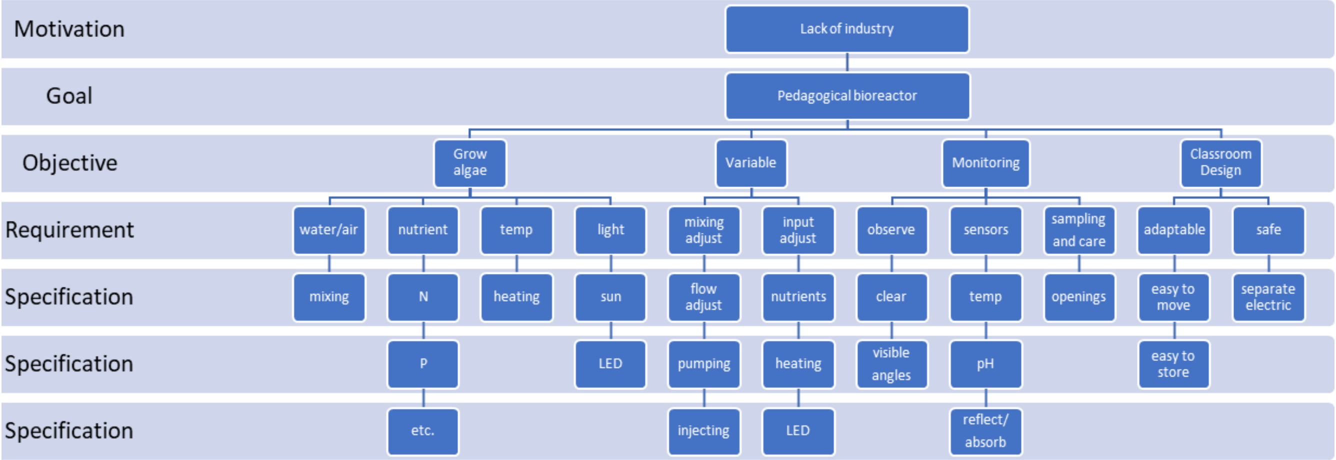
Bubble Column:

Consists of a tall column that uses air bubbles released through a sparger for mixing. Their design is simple, requiring no internal components other than the sparger, which facilitates easy sterilization and cleaning. This results in lower capital and operating costs compared to other closed photobioreactors. They provide optimal mixing rates with minimal shear stress on cells, making them highly productive. These systems are widely used in various commercial applications, including algae and baker's yeast production and wastewater treatment (Gupta et al., 2015; Xu et al., 2009; Yen et al., 2019).

2.2 Comparative Design Selection Process

In the previous report, this section compared all of the prior-mentioned photobioreactor designs to ascertain which if any may prove to be the best suited for education. Firstly, we defined our motivation, goal, and objectives, before identifying the requirements and specifications to achieve those goals and objectives (Fig. 1). Secondly, a form of design criteria was put forth to help ascertain which system is best suited for our educational needs. Those criteria were separated into four broad categories including technical design parameters, economic and environmental parameters, and finally socio-educational parameters.

Figure 1. *Criteria Overview*



Technical Constraints

These parameters outline all of the structural and mechanical needs that the system must adhere to, to properly be used in an educational setting. The first technical design constraint to consider is the ease with which this system may be effectively cleaned and sterilized. This will firstly ensure that no contamination may affect the algae growth so that any comparisons being made will be free of outside interference. However, this will more importantly ensure that this system is easy to use for the staff and students alike and will ensure that the device will remain presentable for quite some time. The second technical design factor being considered in this report will be its mixing capabilities. Firstly, adequate mixing will be required to ensure adequate algae growth rates as proper mass and energy transfer will be required for the cells to survive. Secondly, the mixing device must be something that is controllable and easy to showcase to students. The final technical constraint that must be considered is the size of the design, for this device must be easily stored when not in use and must be easy to transport from classroom to classroom. Therefore, the photobioreactor should be as small as possible.

Economic and environmental constraints

This section takes into account all design factors that can affect the affordability of this device for not only the schoolboard itself but for the planet as well. Firstly, the energy input needed to run this machine must be as low as possible to ensure that the operational cost and electrical usage remain as low as possible. Secondly, the capital cost of acquiring said device must be reasonable for any schoolboard to even consider using it. As many school boards are working on tight budgets that can’t afford high-end photobioreactors.

Educational and social design constraints

These design constraints deal specifically with the factors required to ensure that this tool may adequately educate students on the inner workings of a functional photobioreactor. Firstly, this algae growth system must be commonly used in the industry today otherwise, there would be no reason to teach technicians about its functioning. Secondly, this system must in some way allow students the opportunity to visualize the interior of the device as algae is being produced. In essence, the algae growth and mixing device must be visible at all times. Thirdly, the device must be able to run the same experiment repeatedly over multiple years whilst maintaining similar results. The final factor considered in this regard is whether this particular PBR system has been used for educational purposes in the past. As even though this final constraint isn't essential, it does provide some insight into what systems have been shown to function in this regard.

With all constraints considered, a comprehensive comparison could take place by evaluating each design against one another. To do so, a Pugh chart (Table 1) was created with the common bubble column used as the baseline due to its past use in the industry (WOOFAA, 2016).

Table 1. *Weighted Pugh chart for PBR system selection*

Weighted Criteria Matrix For PBR design

Tags	Prioritization Criteria	Value	Baseline Bubbler	Open pond		Cascade System		Raceway		Flat Plate		Tubular		Stirred Tank	
SOC	***Use in the Industry***	*1*	0	*1*	1	*0*	0	*0*	0	*-1*	-1	*-1*	-1	*-1*	-1
SOC	***Use in education***	2	0	-1	-2	-1	-2	-1	-2	-1	-2	-1	-2	-1	-2
SOC	***Visibility for Students***	2	0	-1	-2	0	0	-1	-2	0	0	0	0	0	0
SOC	***Repeatability***	1	0	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0
TECH	***Ease of Cleaning***	2	0	0	0	0	0	0	0	-1	-2	-1	0	-1	-2
ENV ECO	***Energy Requirements***	2	0	1	2	1	2	1	2	0	0	-1	-1	-1	-2
Tech	***Mixing capabilities***	1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
ECO	***Captial cost***	2	0	1	2	0	0	0	0	-1	-2	-1	-1	-1	-2
TECH	***Space Requirements***	2	0	-1	-2	-1	-2	-1	-2	-1	-2	-1	-2	0	0
	Totals		0	**-3**		**-4**		**-6**		**-10**		**-8**		**-10**	

Note. Each tag represents the specific design parameter being considered namely social (SOC) technical (TECH) environmental (ENV) and finally economic (ECO). Each criterion was given a weight ranging from 1 to 2 depending on its suggested importance. For each criterion, a system was given either a -1; 0 or 1 to display that it is either worse, equal to, or better than the baseline bubbler.

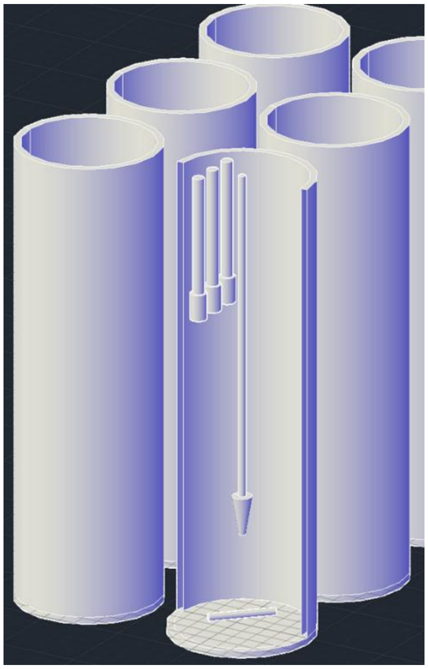
System design selection

After this rather extensive review, the bubbler system proved to be by far the most optimal design as it clearly outperforms in almost all design considerations. It offers visibility, low space requirements, low energy use, good growth rates and is already used in education. Taking all of this into consideration, our project went ahead with building a prototype bubbler PBR.

2.3 Initial Design Concept

This section presents the initial design from our previous report, seen in Fig 2. It briefly goes over the components of the preliminary design.

Figure 2. *Overview of vessel set-up initial design*



Vessels

The initially designed bioreactor from our previous report was composed of 4 to 6 bubbler columns placed on a single platform. Where all vessels have the same base design, and the capacity to have factors varied independently. All vessels' material will be transparent allowing for good exposure to external light and good visibility (acrylic plastic or glass). The vessels will be kept at a smaller size (~2-3L and ~4 in diameter) unlike what is normally seen in the industry. This is to ensure that they may be easily transported, cleaned and stored, and sufficient to run multiple short educational experiments. The top of these vessels will be open to ensure that gas may flow freely out of the vessel.

Lighting

The main light source is LEDs that are set up on the outside of the cylinder, its position can be adjusted, whether from the side or mounted on top. They have an adjustable control system to vary light factors (such as wavelength, intensity, and duration) so that many various experiments could occur without the need for significant alterations.

Mixing

Mixing occurs through the injection of gas through a nozzle tip. Various types of nozzles could also be implemented to showcase the different types of bubbling. The nozzle is to be attached to a pipe that can be inserted to any depth and point in the reactor from above. It should also be noted that the vessel's flat bottom will also allow for the use of stir bars which could come to showcase a varying mixing mechanism. Bubbling may also not provide enough desired mixing (possibly from low gas volume or pressure). Therefore, stir bar compatibility will allow for an alternate mixing method. For this, the bottom of the column will be flat. This design may allow for improper mixing at the bottom corner edge, however, stir bar compatibility is esteemed more important as it avoids compromising mixing as a whole.

Heating

Heating is implemented with a controller that receives thermocouple readings which will allow for temperature control and regulation. This temperature regulation and data acquisition from the thermocouples would also provide the students with another variable to conduct experiments.

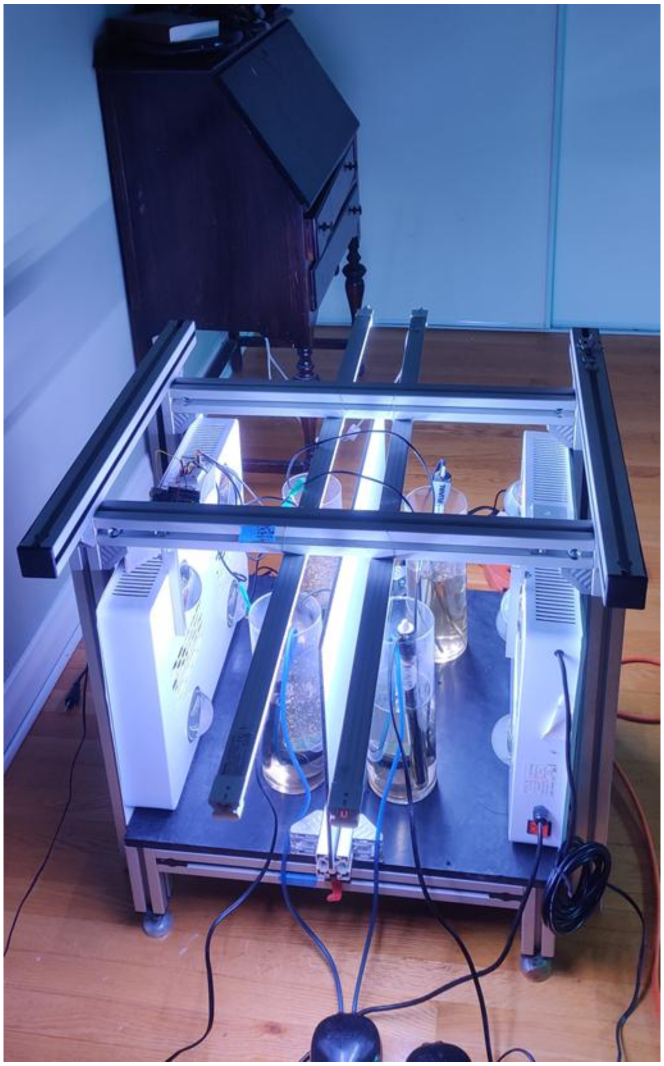
Sensors

Sensors used will depend to some degree on availability especially in regards to the prototype. Thermocouples are expected to be viable. EC, ISE, and pH are unsure options that require further confirmation, primarily due to their complexities regarding reading drift problems. Spectroscopy may depend on algae fouling. Some measurements may be better done on removed samples. Therefore, much is to be determined before selecting sensors hence, the sensors and data testing equipment will be further determined with the prototype.

3. Prototype Overview

3.1 Prototype Design

Figure 3. *Prototype setup in action*



The frame holding everything together was made of extruded aluminum. This provided ample strength to support the weight of all components. Extruded aluminum is also practical as it is designed to work with standardized brackets, and positioning is adjustable. This adaptability proved beneficial as it allowed for proper fitting and adjustability.

The base platform was made with extrusion aluminum and a composite board. This board material is typical for lab bench tops. It was easy to clean and not overly thermally conductive (as the platform should not be a giant fin). The 1.5 cm board was 60 by 60 cm providing ample space for placing vessels and working.

The frame and platform were made with 4.5 by 4.5 cm extrusion aluminum. It was easy to place the whole setup on a classroom table (minimum table width of 60 cm). The overall base dimensions for the frame and platform were: Length: 73.7 cm, Width: 60 cm, Height: 71 cm. At the top of the frame, there was an overhang widthwise, making the top width 66.8 cm, or 119.5 cm due to the lightbars (as positioned in Figure 3). However, that was at the top and did not affect the table space required. Furthermore, for full view and access, the setup should not be touching a wall.

The divider was a panel collated on both sides with metal painted white. The double metal layer panel allowed no light to pass through and the white reflected light back to the vessels on the same side as the respective light source.

The lighting was provided by one or multiple light sources. The divider, blocking light from crossing, allowed for different light conditions from one side to the other. Lighting could also be provided from above as the frame allowed for mounting the lights on the sides or top. Lighting was done using different types of light to vary conditions.

Panels were used, each with four "bulbs" covering LED pads. Light bars were also used, these had double LED rows running lengthwise.

Heating was provided by aquarium heaters. The heaters were supposed to be self-regulating. They worked at maintaining a mostly constant temperature. However, more calibration could be done to equalize the temperature across vessels.

Vessels containing the algae solution were made of clear colourless glass. The shape was a simple cylinder

Sampling should be possible for all points, skimming from the floating surface, extracting from throughout the column, removal from the sides, and sediment retrieval from the bottom. Sampling capacity also relates to general internal access and thus ease of cleaning and care.

Aeration was accomplished using aquarium air pumps and nozzles. For the release of air into the water the flow was controlled by the nozzles. For this, different spargers were tried. A simple sparger was made using a brush sponge, however the flow was not the best. A consistent cloud of small bubbles was desired. For this aquarium sparger stones were used. The stones floated. Having hooks or brackets at the bottoms of the vessels to hold the stones would not be practical for maintaining the ease of cleaning for the vessels and would provide more surface for algae to grow on. Different methods were tried for attaching the stones to weights. Finally, corrosion-resistant metal wire was used to hold the stones to weights, also made of corrosion-resistant metal. This provided an easy-to-remove and clean option. For the pumps, consistency was a slight difficulty as not all pumps functioned the same. Nonetheless, this was still a proof of concept as the malfunctioning demonstrated the flexibility of the system. When a component did not work it could be simply and easily replaced or compensated for.

The Aeration also provided mixing. However, this naturally implies different mixing with different aeration. Not all vessels needed to be run with the same aeration, thus mixing was variable.

For pH sampling, a pool testing kit was used. The test used phenol red as an indicator of pH level, with a colour comparison.

For data sampling, a photo spectroscope would be desirable, however, the equipment was not available. A simple alternative to this was photo analysis. This is also inexpensive and rapid. For this, a lightbox was made (Figure 4). This would allow for consistent photos. The vessels (one at a time) would be removed from the bioreactor and placed in the lightbox, photographed, and then replaced. The photos were taken using a cellphone camera. After cropping, a MATLAB (reference to appendix B for code) code was used to evaluate the cropped photos based on RGB values. The evaluated data could then be shown graphically or in some other form if desired.

Figure 4. *Lightbox with vessel inside*

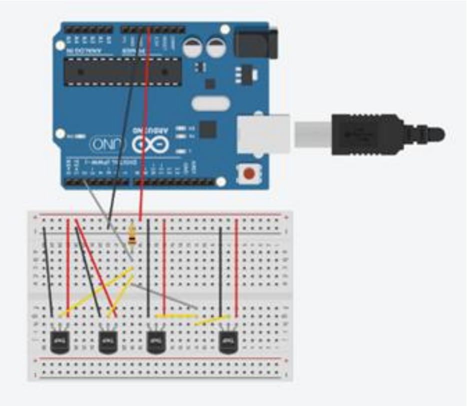
Nutrients could be as variable as made to be. For the prototype trials, already nutrient-rich water from a pond with farm runoff was used. The exact content of the water is unknown as it was not analyzed. This was not considered a problem as the trials were simply for proof of concept. To mitigate any experimental error from this, the trials were done starting all samples with the same start solution.

Species could be selected by the user. For the prototype trials, locally sourced wild species were used. This was also done for responsibility. The algae species were taken from the local environment. Thus, any waste during or after an experiment could be disposed of without importing any new invasive threat. It is advised that experiments be done taking into consideration regarding disposal of live organisms.

Temperature Sensors

To monitor temperature, four DS18B20 sensors were placed in each vessel. These sensors were wired to an Arduino as seen in figure 5.

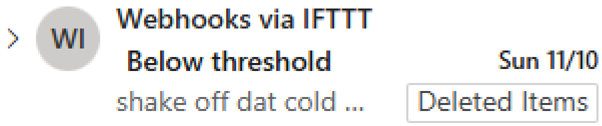
Figure 5. *Graphic representation of wiring for DS18B20 sensors*



The power supply (red wire) and ground (black wire) for each sensor were connected to the Arduino power and ground. The control pin for each sensor (yellow wire) was connected to the control pin on the Arduino in series with the power source through a 10KΩ resistor.

The Arduino would then record the temperature and send the results to thingspeak.com through the code found in Appendix C. Using the react function on thingspeak.com, if temperatures would ever be above 28°C or below 20°C a MATLAB code would analyze the recorded temperatures and would send data to IFTTT.com. IFTTT.com would then send a warning email to our email accounts declaring that there is an issue with the temperature as seen in Figure 6.

Figure 6. *Email sent from IFTTT*



Webhooks via IFTTT

Below threshold

Sun 11/10

shake off dat cold ...

Note. This email is what would be sent to our accounts if ever temperatures dipped below 20°C

3.2 Testing

It should be noted that the following experiments were done for testing, validation, and proof of concept. No exact outcome was set as a goal. They simply demonstrate how effects can be produced, observed, monitored, and evaluated.

Experiments started with equal solutions.

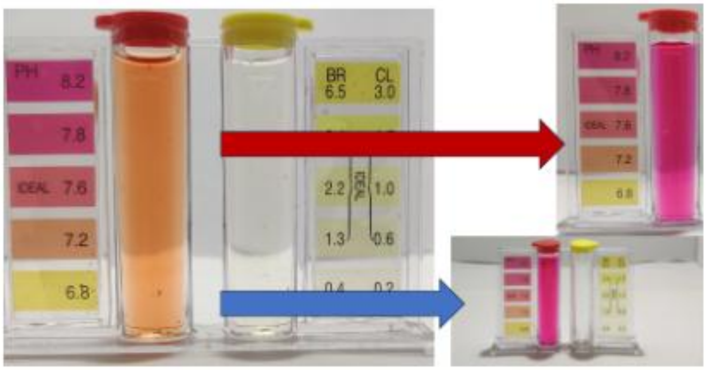
A large amount of nutrient water and algae seed solution were mixed in a large pot, and then even amounts (1300 mL) were added to each vessel. (NOTE: This was done to keep the starting value equal. For experiments on nutrients, and species... would not need to be done the same)

For data sampling, the vessels were placed in the lightbox and photographed.

An experiment was done using an equal starting solution. The lighting was set differently across the divider. On one side there was red light (620-630nm). On the other side of the divider, there was a light of mixed red and blue (630:430nm = 1:2).

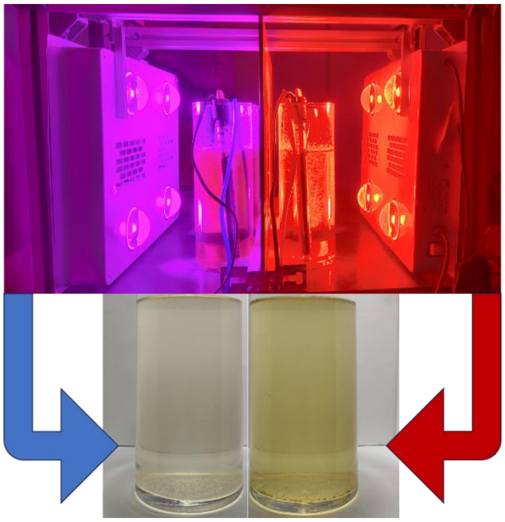
The results of this experiment (Figure 7&8) indicated a noticeable change in pH, with a general increase. More interestingly, we observed the adverse effects of light intensity on colour. The red light was less harsh than the blue. The short wavelength of blue light carries more energy per photon, which could have stimulated more pigment growth. However, too much of a good thing is never good, the excessive exposure led to the destruction and damage of the algal cells.

Figure 7. *PH results*



Note. Results from the first experiment pH change.

Figure 8. *Results from Experiment 1*



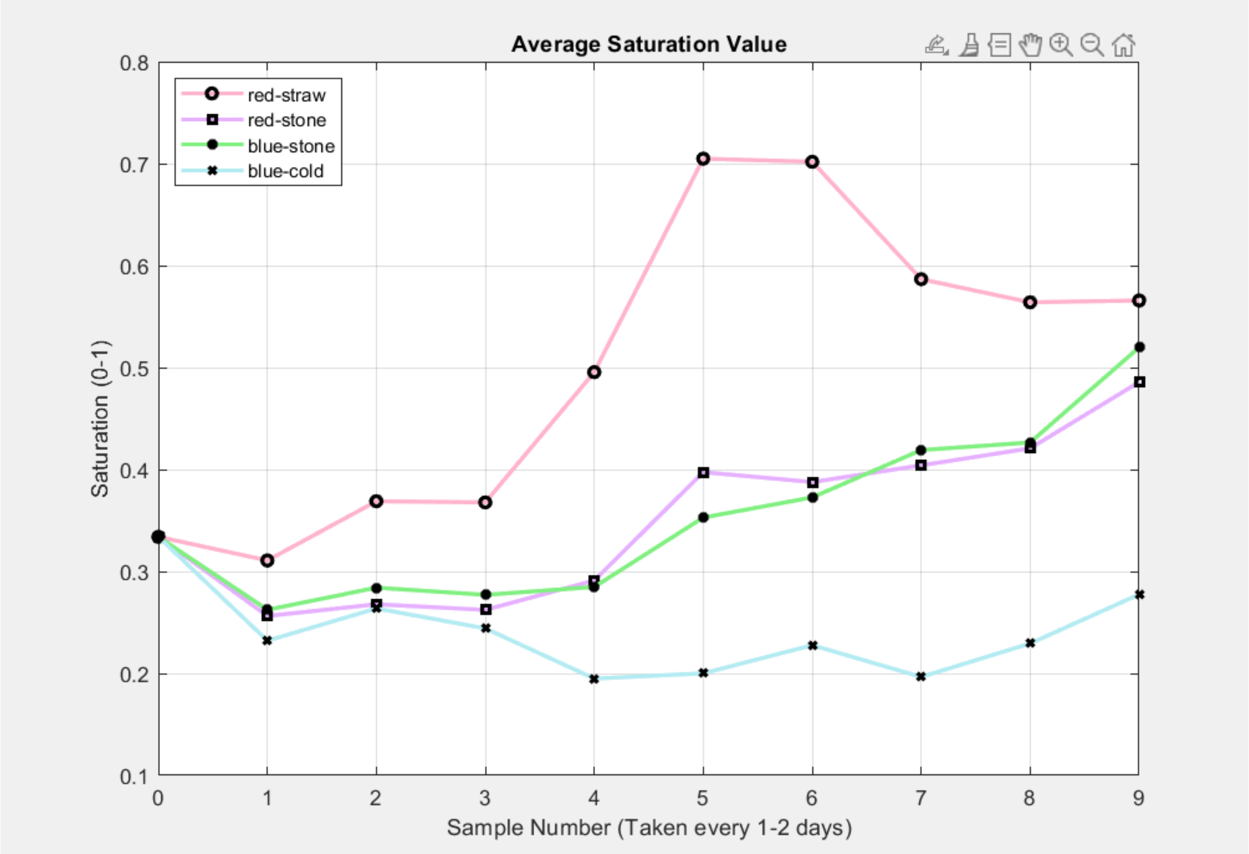
Note. Colour alterations from lighting experiment

Another experiment was done, using a different solution, yet also using an equal starting solution (as explained above). The experiment was done using light bars mounted under the top of the frame. The vessels were set up with the following conditions. Red-straw: had a heater and a straw as a nozzle providing straight pipe aeration. Red-stone: had a heater and a sparger stone. Blue-stone: had a heater and a sparger stone (note this is the same as Red-stone). Blue-cold: had a sparger stone and no heater. (Note that the Red and Blue in the names have no reference to conditions, this was simply a naming convention)

For the first half of the experiment, there seemed to be a brown algae growing better, this may have been the lag phase for the next species as after that a green alga began to grow.

This experiment had pump inconsistencies after which all aeration was stopped. This coincided with the green algae beginning to take eminence. Thus there may be a correlation between the aeration and that specific algae species. Furthermore, among the vessels with heaters, the like vessels, with sparger stones, both did similar to each other yet different from the one with a straw (See Figure 9). This relation to aeration is not certain and further experimentation would be needed to validate the concept. There was a clear stunting effect with the cold vessel as expected. Regardless of what were the causes for each outcome, the system worked to demonstrate growth monitoring. Also, in the experiment time (over the course of 12 days), not all vessels experienced a full growth curve. The reason for this may be uncertain (possibly time), however, this again highlights the benefit of multiple vessels. Biological organisms do not always behave as desired. Living systems can do strange things. Thus, having multiple vessels is a benefit, so if not all vessels work, there is still a chance that at least one will. The laboratory principle of not putting all eggs in the same basket.

Figure 9. *Graph of plotted growth monitoring values, MATLAB RGB processing.*



Note. The plot shows the colour concentration along the time of the four vessels. This is correlated to growth. The dip at the beginning may be due to settling or die off. The cold vessel (avg 20.3 ℃) had lower growth and no great change. The vessels with heaters (avg 26.5 ℃) all experienced visible growth. The vessels with similar conditions had similar overlapping curves. Only one vessel, the one that had a straw, presents a full growth curve with phases, lag, growth, plateau, and decrease.

3.3 Conclusion After Using Prototype

The adaptability of the design proved practical as it was flexible for component alterations. Extrusion aluminum is practical for natural factors, sizableness and versatility. It is also easy to keep clean. Glass vessels are good as they are clear and easy to clean. LED lights are great as they consume reasonable amount of energy and can vary intensity and colour with ease.

The experiments showed that the system is capable of running trials with variations of parameters while keeping some factors constant. The system is monitorable and capable of providing qualitative and quantitative data results. The system is inexpensive to operate. To use, it is simple enough and has a practical approach design.

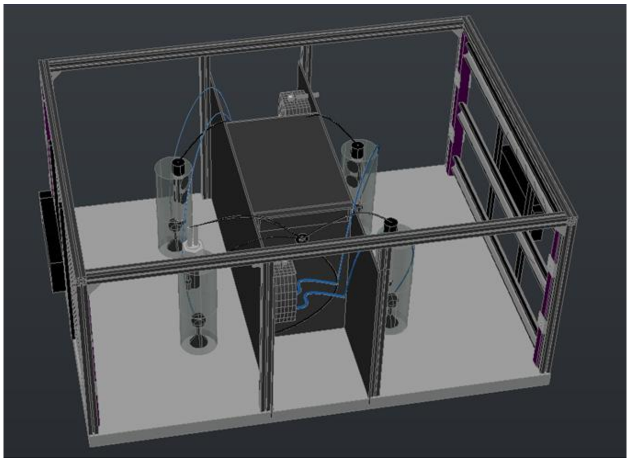
4. Final design

This section will review our final design concept by considering the goals and constraints that came to guide our material selection. It will begin by reviewing the overall design concept, followed by a detailed review of parameter selection and will finalize with an overview of the costs and capabilities of this system.

4.1 Overview of Design Concept

The overall concept used for the final design will closely resemble that of the prototype. Two rows of vessels will be placed on either end of a dividing wall between two light sources (as seen in Fig 10). Each vessel will be composed of its own monitors and control variables to ensure that each vessel can be controlled separately. The main goal of this design is not for the optimal functioning of a single experiment but rather to provide a device that may showcase a multitude of varying experiments with little to no physical alterations needed. Therefore, this design aims to give the user the ability to decide what they want to teach to the students by either performing a multitude of tests or one single test with control vessels.

Figure 10. *Overview of the final design*

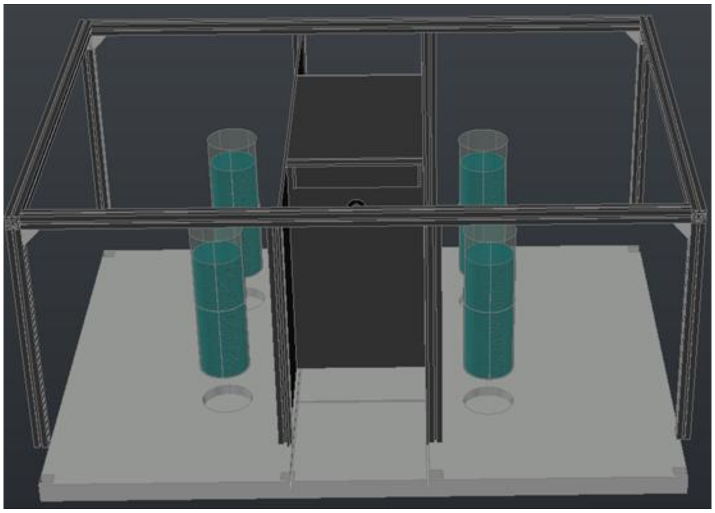


Note. This figure is an overview of the final design's exterior
with all pumps, vessels, lights and sensors.

4.2 Frame design

For this project, the frame had to be easy to store, easy to move, and easy to adapt to new designs. To meet these criteria, a frame such as seen in Fig 11 was implemented.

Figure 11. *Mainframe overview*



Note. This figure showcases the major components required for the frame: the extrusion aluminum skeleton, the plastic laminate baseboard, the electric box in the center and all indentations required.

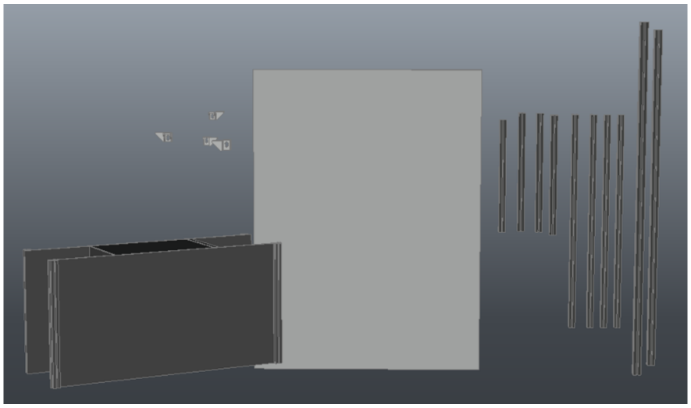
4.2.1 Baseboard

The baseboard will be composed of a 48x36x1.5 in plastic laminate material. This size was selected as it had to be large enough to house all components whilst being small enough to easily fit on a bench-top table. This would also make for easy access as students could reach across and through the system frame. This material was selected as it is resistant to scratches and water damage, it's resistant to both heat and electricity, and is easy to clean (Ashter, 2013). Therefore, this specific board was selected as it meets our base criteria of being resistant to water damage whilst also supporting our safety criteria of being non-conductive with incorporated safety edges. When it comes to preparing the board for this design, indents will be grooved for all frame components and vessels as this will reduce the risk of sliding. The reason we chose to not connect the vessels or frame to the board directly is that we wanted the client to be able to easily separate any of these three components to ease the transportation of the apparatus. This way if ever the machine cannot pass through some tight spaces, one could simply remove the skeleton from the frame and bring each piece in individually. This is clearly not as easy as transporting the whole apparatus in one piece however, this will make it possible to bring the machine through tight places that it normally shouldn't pass through.

4.2.2 Skeleton Frame

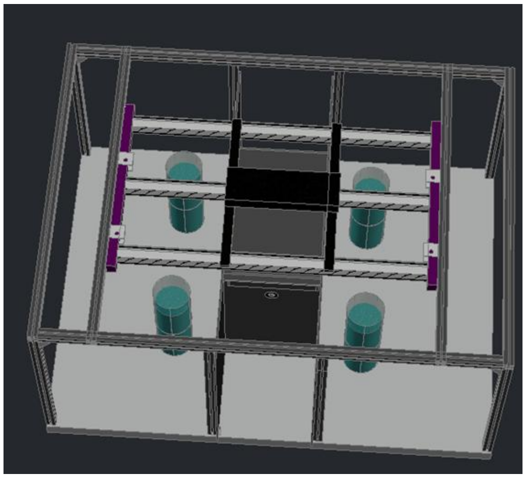
The extrusion aluminum skeleton will be responsible for connecting all frame components and will be the mount used to keep the LEDs upright. Each bar will be connected perpendicularly with the help of internal fasteners. Each corner will also be strengthened through the use of triangular supports. The reason we selected extrusion aluminum is due to its strength, durability, relatively low weight and cost, and ease of manipulation (Stojanovic et al., 2018). One of the main reasons we selected extrusion aluminum for our design is due to how easily it may be assembled or disassembled. The reason easy assembly was so important for this design is to fit specification 4.1.2 easy storage as one could simply remove a few bolts and wind up with a frame as seen in Figure 12 which throughout a school would be easy to find storage for. The other major benefit of selecting extrusion aluminum for the frame is in how one could come to implement new designs by simply adding or removing parts which would fit requirement 4.1 (adaptable). A good example of this application could be seen in Figure 13 in which a single light source could be mounted on top of the frame instead of on the sides by simply adding two more bars to the frame.

Figure 12. *Disassembled Frame*



Note. This figure showcases how the frame can be disassembled for storage including the extra bars for top-mount

Figure 13. *Top Mounted Light*

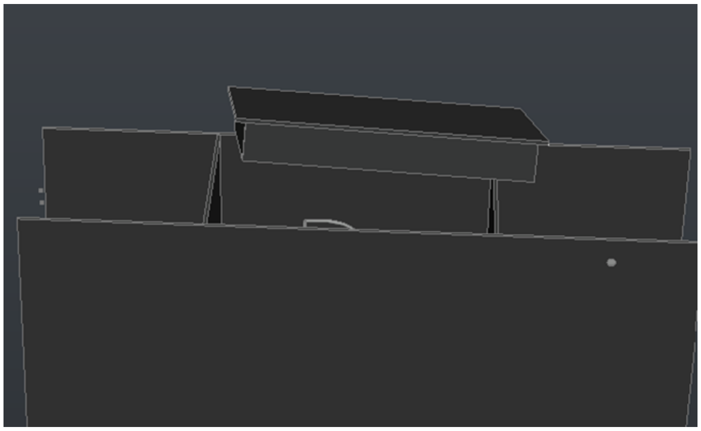


Note. This image displays how the frame may be altered to only use one LED.

4.2.3 Electric Box

The electric box was implemented into the frame (as seen in Figure 11) to ensure the security of the students, as this design involves an Arduino and multiple power supplies next to litres of water. The electric box will be made from a 4x4ft sheet of 0.19in aluminum as this material can be easily welded to the frame and has been proven to reduce energy consumption from lighting (Kondzior & Butarewicz, 2021). The exterior of the box will be created out of multiple cuts from the 4x4ft sheet of aluminum (as seen in Appendix D). The box will be placed between the two divider walls with an aluminum lid for cover (as seen in Figure 14) and will have two small holes drilled into the sides for the wires to pass through. Each hole drilled into the sidewalls will be filled with a grommet to limit the free space available for water to pass through. The exterior walls of the box were designed to be taller than the vessels to ensure that even if a vessel were to tip over, no large amount of water may make it to the box. Though this design for the exterior will effectively make the electric box rather water-resistant, it should be noted that water may still infiltrate through the grommets therefore, the inside of the box must also be designed with water resistance in mind.

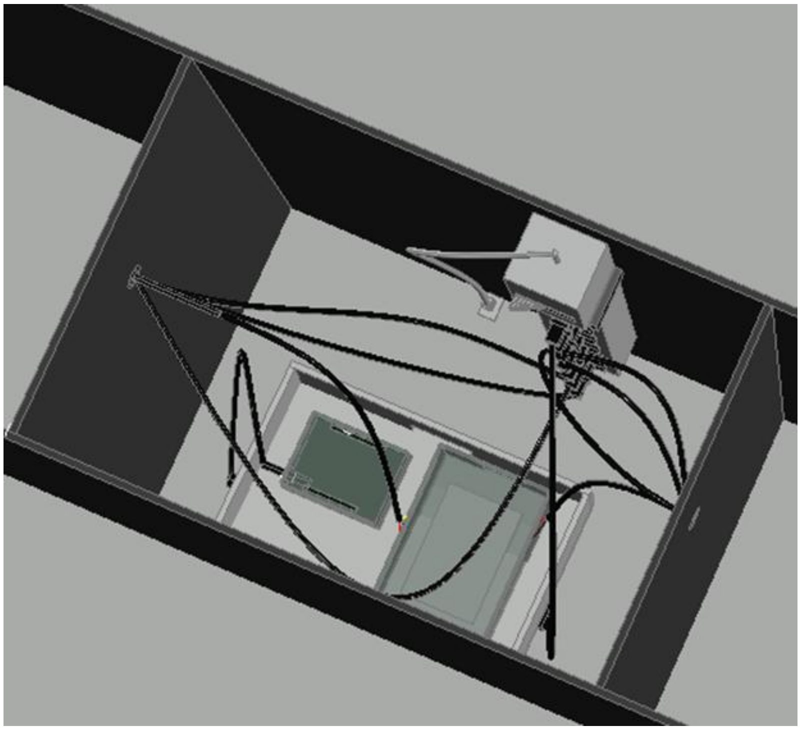
Figure 14. *Front view of electric box*



Note. This image is a front view of the electric box with the lid slightly raised.

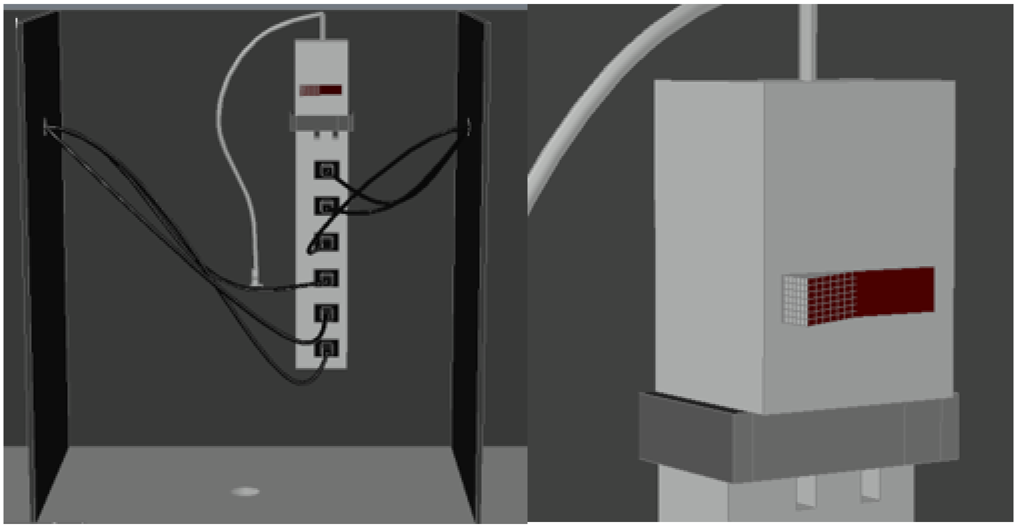
The inside of the electric box will be as presented in Figure 15. Inside the box, there will be an Arduino, a breadboard, a power block, and a 12V DC power adapter. The power block will be held upright by a metal brace (as seen in Fig 1) that will be welded to the wall this way it may be simply dropped into position or lifted out. The power block was kept upright on the wall in case any large amount of water may find its way into the box and begin pooling at the bottom. For this very reason, a hole would be drilled into the center of the baseboard to act as both a drain for any potential water and as an inlet for a power cord. It should be noted that the plug end of the power cord will be connected to the power block and therefore suspended away from the drainage hole.

Figure 15. *Internal View of Power Box*



Note. This image showcases how all elements will be placed within the power box. The only piece missing from this image is the 12V DC adapter which is placed directly below the Arduino platform.

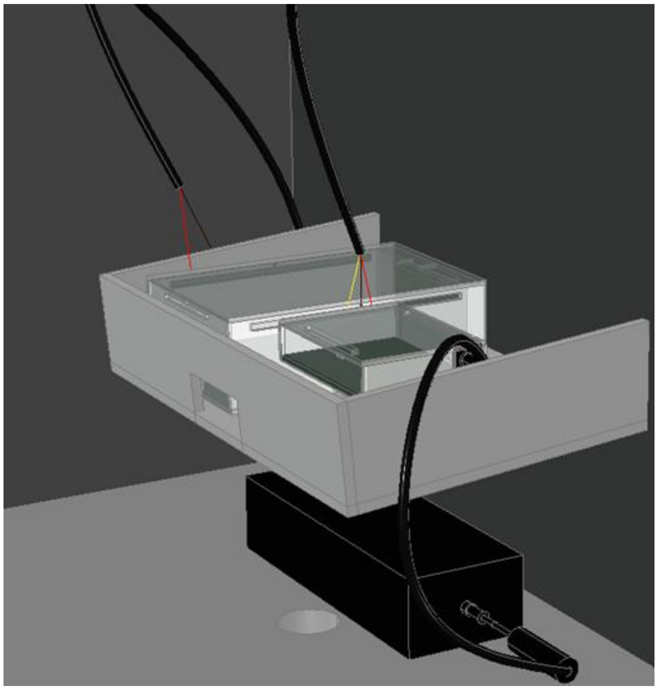
Figure 16. *Display of power block wall*



Note. On the left-hand side is a view of the wall as a whole whereas the right-hand side displays the frame that will be used.

The Arduino and breadboard will be placed as seen in Figure 17. These were placed inside plastic cases on a sloped platform welded onto the back wall to protect them from water damage, at least as much as possible. The platform will also have a small hole in the front to act as a drainage point should ever large pools of water gather within the box. The DC power adapter may be left along the bottom of the box as it is already rather resistant to water damage.

Figure 17. *View of Arduino platform*



Note. This image demonstrates how the Arduino, breadboard and DC power adapter will be placed within the electric box.

Though this design is not completely waterproof, the electric box was not designed to incur litres upon litres of water. Generally, even if someone were to drop an entire vessel along the top of the box most of the water should come to trickle off the sides.

4.2.4 Vessel Selection

For this design, four 4x12 in glass cylinders were selected to be used as vessels. Each vessel had to be large enough to grow manageable amounts of algae whilst incorporating all sensors and tech required for growth. These vessels also had to be small enough to ensure that quick algae species could pass through their entire growth cycle within any given semester as light availability may very well be the limiting factor in most experiments. One of the main reasons glass was selected as the vessel material was longevity as light penetrance will often come to degrade with time (Koller, 2015). This is often seen with plastics under constant illumination and also with glass due to glass corrosion however, the latter may be avoided if the glass is commonly cleaned and maintained (Koller, 2015) which would be rather easy with vessels this size.

Considering the length of this section, some images were left within Appendix D including the exact dimensions of the frame.

4.3 control variables

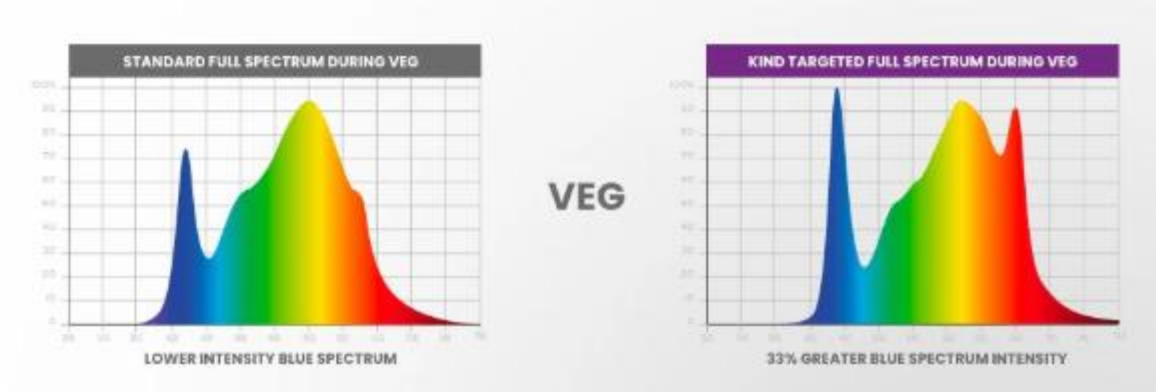
This section will review all variables that students may come to control in their experiments: lighting, heating, mixing, pH and feeding.

4.3.1 Lighting

The intensity of light needed for growth varies widely from species to species therefore, the lighting should account for this by offering a wide range of lighting intensities. On the lower end, most species need at least 200 µmoles (Hancke et al., 2018; Kondzior & Butarewicz, 2021). A general high value of intensity to cause photoinhibition would be 1000 µmoles as this has been shown to kill most species (Rodrigues et al., 2000). Therefore, the light should be able to reach intensities that are approximately 1000 µmoles if possible. The wavelengths should also be adaptable, as optimal wavelengths differ from species to species, (Singh & Singh, 2015). Therefore, the lighting should offer a full spectrum and potentially a combination of both blue and red light as many species come to benefit the most from these wavelengths (Satthong et al., 2019; Bialevich et al., 2022).

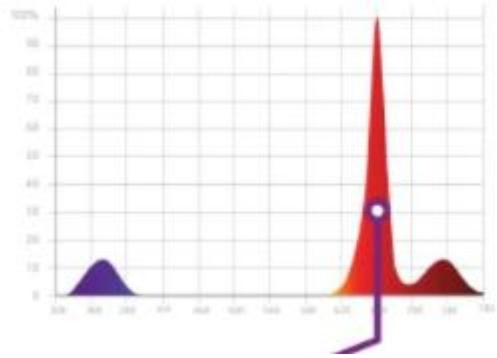
Therefore, for the lighting of this system, the KIND LED X330 was selected. This system offers multiple variable controls such as light intensities ranging from 841µmols to 0 with a built-in dimmer control. This would give students the opportunity to use intensities that could either be too low for growth or far too intense for growth (at least for many species) and anything in between. It also comes with a built-in timer which could be useful for experiments meant to mimic seasonal shifts or for experiments on optimizing growth with low energy costs. The KIND LED also offers two separate wavelength controls that each operate on their own dimmer. The first wavelength offered is a full-spectrum wavelength with emphasis placed on the blue spectrum as seen in Figure 18. The second wavelength is a combination of both the UV and IR spectrum as seen in figure 19.

Figure 18. *Full spectrum comparison*



Note. This image portrays the full spectrum wavelength covered by both the KIND LED (right) and what they (KIND) claim to be the normal full light spectrum (left).

Figure 19. *IR and UV Spectrum*



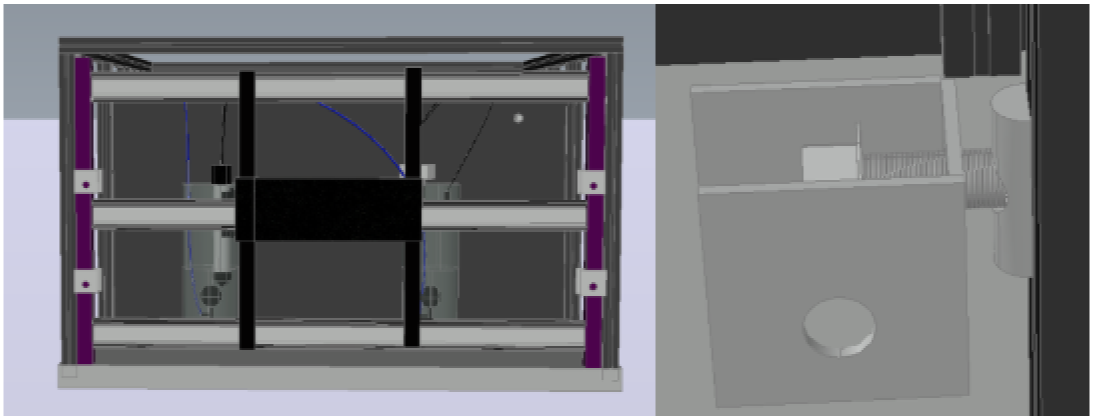
Note. This image displays the second light wavelength that can be emitted from the KIND LED.

For the final design, two KIND LEDs will be required on each end of the system for comparison. To maintain easy visibility of the system at all times and a low capital cost, these lights were not closed off into separate boxes which will bring about some bleeding of one LED’s lights into the other’s vessels. This decision was made after testing the prototype as though some bleeding most likely occurred, the effects on both samples were distinct and could showcase the difference in lighting to the students. Therefore, it should be emphasized that the lighting of this design is not intended for experimental research as the primary focus here is for education.

If lighting were not the focus of the experiment one could simply be placed above all four vessels to save on energy. It should also be mentioned that though this light offers many benefits on its own, schools could decide to use other forms of light sources such as the UTEX RGB-LED platform (Utex.org) if they wanted to test wavelengths that aren't offered by the KIND LED. This would be quite simple to do with this frame design as any new anchor or beam could be placed to hold the new light in place, with the only constraint being that the new light stays smaller than the external frame.

To connect the lights to the frame, two U-shaped brackets can be attached to the frame along any point using a T-nut and a bolt as shown in Figure 20. This will hold the light in place while also making it easy to remove.

Figure 20. *Representation of Light Brackets*



Note. The left-hand side of the image is a side view of the final design showcasing all four brackets used to anchor the light in place. The right-hand side showcases how the brackets may be attached to the extrusion aluminum through the use of a T-nut.

4.3.2 Heating

For this project, two separate heating designs were selected one for simplicity and the other for optimized control and learning.

The first option will utilize the 150W Aquael Platinum heater which is a standard aquarium heater. It benefits from including built-in temperature sensors to keep temperatures at a somewhat constant level with variations of only 0.4 ℃. With these heaters, the temperature can be controlled with a touch of a button ranging between 20 ℃ to 33 ℃. LEDs on the heater will also visually display the current and target temperatures. Another great benefit to these heaters is that they already include attachments for fish tank walls which will make installation rather trivial. Overall, this heater was selected due to its simplicity ensuring that any project could simply come to control the temperature with minimal effort.

The second option is far more complex however, it gives the user greater control over experimental temperatures. This option will utilize the 12V immersion cartridge heater, which on its own is a simple heater that can only be turned on or off. However, the benefit of this heater is that it can be connected and controlled by an Arduino through data provided by a DS18B20 temperature sensor. For this to function, there will need to be an Arduino, a breadboard, wires, a MOSFET, a 330Ω resistor, a 10KΩ resistor, and a power supply. The selected power supply had to possess a current strong enough to power both the heater and the Arduino (8.3A) and had to match the 12V needed by the heater. Therefore, the 12V PEGASUS ASTRO (10A) was selected. The wiring would be as shown in Appendix F.

Through this approach, students could set more specific temperature settings than the 1°C jumps seen with the Aquael heater. Students would also be able to develop codes to control temperature based on any external parameter they see fit. For example, a student could now create a seasonal representation of algal growth automatically making the temperature decrease after set periods of time. This design would also give students some basic knowledge of Arduino wiring and coding which while not the main objective of this design is still beneficial for the students.

Overall, the heating will be controlled through two designs. Four versions of the Aquael heater will be provided so that students have the option to ignore the wiring and coding whilst still running all four vessels. Option 2 will only be applicable to one vessel, as for one this is not a necessity and for two, the current needed to run multiple heaters from one Arduino could prove to be dangerous around water. Multiple Arduino set-ups could have been selected however, this would have greatly increased the cost and complexity of the final design and was therefore omitted.

4.3.3 Mixing

The main parameter to consider when selecting the bubbling system was power output as the pump had to be stronger than the hydrostatic pressure of the vessel. At maximum capacity, the vessels can contain 12in of water,

$$P = \rho * g * h$$

$\rho = 1000\text{kg/m}^3$ for water

$g = 9.81\text{m/s}^2$

$h_{max} = 0.3048\text{m}$

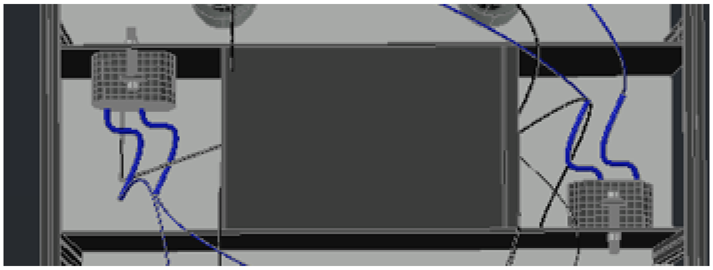
$$P = 1000\text{kg/m}^3 * 9.81\text{m/s}^2 * 0.3048\text{m} = 2.99\text{kpa}$$

Therefore, the pump has to generate a pressure output of 3Kpa (30 mBar) or more.

For the final design, the OxyMax200 was selected, with a pressure output of 200mbar well above the minimal requirements. The main benefits of selecting this pump stem from its variable controls. For one, the pump offers two hoses whose flow rate may be controlled separately. Secondly, the nozzle tips on each pump offer simple control over bubble size and can easily be connected to the bottom of the vessel through suction cups. By altering both flow rate and bubble size, students will control the energy dissipation of mixing. This device could educate students on what sizes and flow rates are optimal or most detrimental for algae growth as high energy mixing will damage cells whereas low energy mixing won't provide adequate heat mass transfer and lighting.

To operate all four vessels, two separate OxyMax pumps will be needed. Each pump will be fastened onto the divider walls by a bolt placed through a pre-drilled hole as seen in Figure 21.

Figure 21. *Display of pump set-up*



Note. This image illustrates where and how each pump will be placed on the final design. The blue wires are the aeration hoses that connect to each vessel.

4.3.4 pH Control

Although most algae species do well in a near-neutral pH range of around 6 to 8, some can thrive in pH as high as 10. High pH makes CO_2 less available, decreasing photosynthesis. While CO_2 injected through mixing can lower the water's pH, the absorption of carbon by algae through photosynthesis causes the pH to increase (Khan et al., 2018). Due to the relatively small scale of our bioreactor, the gas exchange done with the bubbling system should be sufficient to keep the pH within range. So, a pH probe and pH control system are unnecessary for our design. Additionally, as expressed by our mentor Yvan Gariepy, unlike some sensors such as thermocouples can easily adapt to any reactor, even submerged, and take continuous readings, pH sensors can go adrift in their readings if continuously left in solution. Prof Adamchuk suggested adding a bypass to avoid drift in readings, if we were to adopt a pH sensor for operation with the reactor.

With that in mind, the pH sensor in our design was chosen to not be attached to the main reactors, nor continuously kept in the solution for constant monitoring. The Milwaukee MW101 PRO pH Meter (214$) was selected for the final design for its accuracy and precision of ±0.02 pH, and broad pH range (0-14.00). Like most pH sensors it will require manual calibration, proper cleaning and storage. It has a 3-foot-long probe cable and excellent reviews from both professional and casual users. Alternatively, for a tighter budget, Milwaukee also offers some cheaper models like the MW100 PRO (124$) or pH54 (65$), and litmus paper (pH strips) starts at around 2$ for 80 strips, which are not very accurate or precise but could provide a rough idea of how pH levels shift as algae grow.

From the pH tests we conducted with a pool kit, the algae solution ended up being more alkaline by the end of the trial, likely due to carbon capturing. For the correction of pH for a longer experiment, nitrogen compounds like ammonium (NH_4^+) or nitrate (NO_3^-) can be added incrementally to raise or lower the pH, whilst also providing an essential nutrient for algae culture (Scherholz & Curtis, 2013). Another pH correction method that can be employed is the increased injection of air to increase mixing and subsequently gas exchange, to increase the CO_2 concentration in the solution (Gao, 2021).

4.4 Data Acquisition

To thoroughly educate students on algae growth, students will have to be able to measure the growth rate of the algae for comparison. When considering measuring the rate of algal growth multiple common approaches may be taken such as: using a spectrophotometer to measure chlorophyll content or optical density which is quick and non-destructive (Chirivella-Martorell et al., 2018), using a hemocytometer to count cell concentrations on a microscope which is cheap and easy but labour intensive (Seo et al., 2017), or using a scale for dry-weight which is simple, but inaccurate at lab-scale (Chioccioli et al., 2014).

Though there exist multiple approaches to measuring algal growth this device will not incorporate any. The main reason for this is that though this design could easily incorporate the tools needed for comparison such as scales, spectrophotometers, or hemocytometers, many institutions may already possess this technology or may have other innovative means of measuring growth. Therefore, by implementing these devices into the final design, we would simply be increasing the cost of the apparatus for tools that many institutions may already possess or may not want in the first place, therefore none will be provided.

That being said, should schools prefer to replicate the approach taken in this report they may reference the protocol presented above and the codes in Appendix B. This will be a practical resource as it is both rapid and inexpensive and can provide a standard code allowing for comparison of data between schools.

4.5 Material and Capital Costs Overview

This section will compile all materials needed for the final design including prices. It should be noted that a table in Appendix E comprises all material manufacturers (or distributors when relevant).

Table 2. *List of all items with cost*

Item	Unitary cost	Nb of units	Total cost
KIND LED	495$	2	990$
VESSEL	15$	4	60$
AQUAEL PLATINIUM HEATER	42$	4	168$
ARDUINO UNO	37$	1	37$
WIRES	10$	1	10$
BREADBOARD	5$	1	5$
DSB18 SENSOR	12$	1	12$
MOSFET	2$	1	2$
CARTRIDGE HEATER	22$	1	22$
BREADBOARD BOX	22$	1	22$
12V PEGASUS ASTRO	88$	1	88$
330Ω &10KΩ RESISTORS	6$	1	6$
ARUINO COVER	6$	1	6$
MILWAUKEE PRO PH METER	214$	1	214$
OXYMAX PUMP	52$	2	104$
EXTRUSION ALUMINUM	-	-	176.62$
WORKBENCH TOP	290$	1	290$
INTERNAL FASTENERS	5$	12	60$
CORNER BRACKET	3.36$	4	13.44$
LIGHT FIXTURE (BRACKET, NUTS AND BOLTS)	6.44$	4	25.76$

ALUMINUM SHEET	390$	1	390$
RUBBER GROMET	4.19	2	8.38$
TOTAL MATERIAL COST	-	-	2710.20

Note. This table includes the pricing of all items as of 2024/12/06. These are the values given to the products themselves and do not comprise the price of shipping or the labour costs required for implementation. These values also exclude the benefit of purchasing in bulk.

Overall, the cost of this device comes to a total of 2710.20$ (Canadian) which is rather average for the educational market. For example, when compared to other educational reactors on the market, this is 578$ cheaper than the STEM Educational Kit Microalgae Photobioreactor (Urbanclimo.com) but 1980$ more expensive than the UTEX deluxe package (utex.org).

4.6 List of Possible Experiments

Table 3

List of all potential experiments that may be easily implemented with this design.

Variable	Potential Experiments
Lighting	Intensity control from 841µmol - 0 allows: 1. testing optimal intensities 2. test intensities detrimental to algal growth 3. test minimal light requirements for certain species
	Light duration with built-in timers to test: 1. Seasonal effects on growth 2. Optimal lighting durations for maximal growth 3. Observe optimal growth rates/ energy consumption rate

	Wavelength growth comparison between full-spectrum and IR+UV with individual intensity controls to educate on: 1. The varying effects on the yield of each wavelength 2. The Benefits of alternating wavelength application throughout the growth cycle.
Bubbling	Bubble size to compare mixing types
	Flow-rate to compare energy dispersion rates for: 1. Too low: hindrance of growth 2. Too high: death of cells 3. Effects on pH.
Heating	Compare constant temperatures for 1. optimal growth vs minimal or maximal boundaries 2. optimal temperatures for maximal growth/unit energy
	Contrast constant temperature control with variable temperature control to compare: 1. Daily variations as seen in nature to constant control for optimal growth 2. Replicate seasonal temperature change to view the natural cycles of algae. 3. Optimal application for growth rate/unit energy
pH	Can experiment for optimal growth rates

	Can test experiments meant to hinder algae growth
Total	Overall, this device offers the easy variation and comparison of **18** tests through which students may be educated on: 1. What parameters can stunt or eliminate algae growth 2. How to design photobioreactors to optimize algae growth whilst minimizing costs 3. The natural behaviour of Algae in the environment

Note. All variables above may be controlled by the system itself except for pH however, the monitoring device will at the very least provide schools the opportunity to test this parameter through whichever means they see fit.

4.7 Closing Remarks on Final Design

In conclusion, the design showcased above incorporates the multitude of constraints set out to optimize its usefulness for educational institutions. For one, this design is adaptable and easy to move as the extrusion aluminum frame may be easily altered or removed from the baseboard which also makes this easy to store. Secondly, it offers a wide range of control over multiple variables including lighting, bubbling, and heating. Thirdly, it considers the economic and environmental costs of operation by offering a one-light model, an aluminum backboard, and the opportunity to automatically limit lighting and heating durations. Finally, it also considers the safety of the students through the inclusion of an electric box and safety edges along the baseboard.

The end-all goal of this project was to design a system that could be used as a teaching device on algal growth and photobioreactor functioning which overall, has been a major success. This final design could be used to instruct students on at least 18 different types of experiments that all pertain to growing or killing algae, the functioning of photobioreactors, or the natural growth cycle of algae. Though other educational photobioreactors can be found on the market (sometimes for lower prices) this device could prove to be rather competitive and innovative in this field. For one, this design is the only photobioreactor known on the market (as of 2024) that was specifically designed to operate multiple vessels at once which facilitates comparison and the engagement of multiple students. This device was also specifically designed to offer a multitude of variables that can be easily controlled which many other reactor designs fail to accomplish, at least to this degree.

The other major advantage of this design is its adaptability as the extrusion aluminium frame makes switching instruments quite easy. For example, incorporating any new LED is possible so long as it’s smaller than the frame length.

Overall, this design is not perfect, as other systems can prove to be more cost-effective or offer better control over specific system parameters however, when it comes to training students on variable selection, variable control and algae growth this design would be hard to rival.

Though we are quite content with what we have designed above, potential improvements can always be considered. For one, we would obviously want to construct and test this new design so that any potential flaws may be spotted and fixed. Secondly, the implementation of control systems over nutrient feeding rates and pH controls could offer greater testing capabilities for this machine. Secondly, the implementation of a pumping system could effectively replicate other photobioreactor designs such as the tubular design which would be interesting for comparison.

References

Aluminum Sheet - 3003, 5052, 6061. MetalsDepot®. (n.d.). https://www.metalsdepot.com/aluminum-products/aluminum-sheet

Aquael Platinium Heater 150W. Aquarium Depot. (n.d.). https://aquariumdepot.ca/products/aquael-platinium-heater-150w

Ashter, S. A. (2013). *Thermoforming of single and multilayer laminates: plastic films technologies, testing, and applications*. William Andrew.

Bialevich, V., Zachleder, V., & Bišová, K. (2022). The effect of variable light source and light intensity on the growth of three algal species. *Cells*, *11*(8), 1293.

BioFuelNet Canada. (2017). *Reseau BioFuelNet Canada*. BioFuelNet. https://biofuelnet.ca/advanced-biofuels-course/

BioMass Canada. (2021). *COURSE – BIOMASS CANADA*. Biofuelnet.ca. https://biomass.biofuelnet.ca/course/

Canada Robotix home page. Canada Robotix. (n.d.). https://www.canadarobotix.com/

Chioccioli, M., Hankamer, B., & Ross, I. L. (2014). Flow cytometry pulse width data enables rapid and sensitive estimation of biomass dry weight in the microalgae Chlamydomonas reinhardtii and Chlorella vulgaris. *PloS one*, *9*(5), e97269.

Chirivella-Martorell, J., Briz-Redón, Á., & Serrano-Aroca, Á. (2018). Modelling of biomass concentration, multi-wavelength absorption and discrimination method for seven important marine microalgae species. *Energies*, *11*(5), 1089.

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, *25*(3), 294–306. https://doi.org/10.1016/j.biotechadv.2007.02.001

Enclosure/case for Arduino Uno R3. Canada Robotix. (n.d.-b). https://www.canadarobotix.com/products/3029

Environmental and Energy Study Institute. (2021, July 22). *Fossil Fuels | EESI*. Eesi.org; Environmental and Energy Study Institute. https://www.eesi.org/topics/fossil-fuels/description

Gao, K. (2021). Approaches and involved principles to control pH/pCO2 stability in algal cultures. *Journal of Applied Phycology*, *33*(6), 3497–3505. https://doi.org/10.1007/s10811-021-02585-y

Glass cylinder vases D-4" with Multiple Heights. Glass Vases Depot. (n.d.). https://glassvasesdepot.com/glass-cylinder-vases-diameter-4-inch-16-height#height=89

Global industrial™ Workbench Top, plastic laminate safety edge. Global IndustrialTM. (n.d.). https://www.globalindustrial.ca/p/safety-edge-work-bench-top-plastic-60-w-x-36-d-x-1-5-8-thick

Gupta, P. L., Lee, S. M., & Choi, H. J. (2015). A mini review: photobioreactors for large scale algal cultivation. *World Journal of Microbiology and Biotechnology*, *31*, 1409-1417.

Hancke, K., Lund-Hansen, L. C., Lamare, M. L., Højlund Pedersen, S., King, M. D., Andersen, P., & Sorrell, B. K. (2018). Extreme low light requirement for algae growth underneath sea ice: A case study from Station Nord, NE Greenland. *Journal of Geophysical Research: Oceans*, *123*(2), 985-1000.

Immersion cartridge heater. DERNORD. (n.d.). https://www.dernord.com/products/immersion-cartridge-heater-cartridge-heating-element-12v-100w-200w-300w?srsltid=AfmBOort-RMahhd6BCtJJPyJPvVSxs_OcfoNpzCTVvxU16kO-iS1u4Sh

Item 1010. 80/20 Inc. (n.d.-b). https://8020.net/1010.html

Item 14200. 80/20 Inc. (n.d.-d). https://8020.net/14200.html

Item, 11-5518. 80/20 Inc. (n.d.-a). https://8020.net/11-5518.html

Khan, M. I., Shin, J. H., & Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microbial Cell Factories*, *17*(1). https://doi.org/10.1186/s12934-018-0879-x

"Kind Led X330 Grow Light w/ UV and IR." *LED Grow Lights Depot*, www.ledgrowlightsdepot.com/collections/adjustable-spectrum-led-grow-lights/products/kind-led-x330-grow-light?_pos=2&_fid=bb2133a33&_ss=c. Accessed 5 Dec. 2024.

Koller, M. (2015). Design of closed photobioreactors for algal cultivation. *Algal Biorefineries: Volume 2: Products and Refinery Design*, 133-186.

Kondzior, P., & Butarewicz, A. (2021). Influence of Walls in a Container on the Growth of the Chlorella Vulgaris Algae. *Journal of Ecological Engineering*, *22*(10), 98-108.

Levine, I. A., Gerk, C. L., Gómez, S. M., Nalley, J. O., & Nalley, M. M. (2021). The Algae Foundation® and Algae Technology Educational Consortium. *Journal of the World Aquaculture Society*, *52*(5), 1099–1117. https://doi.org/10.1111/jwas.12817

Masojídek, J., Sergejevová, M., Malapascua, J. R., & Kopecký, J. (2015). Thin-layer systems for mass cultivation of microalgae: flat panels and sloping cascades. *Algal Biorefineries: Volume 2: Products and Refinery Design*, 237-261.

Milwaukee pH54 Waterproof pH Tester. Milwaukee. Milwaukee PH54 PRO Waterproof 2-in-1 pH Tester with Thermometer and Replaceable Probe

OxyMax 200. OASE. (n.d). OxyMax 200 – OASE North America

Pegasus Astro 12V 10A Heavy Duty Power Supply. Telescopes Canada. (n.d.). Pegasus Astro 12V 10A Heavy Duty Power Supply

Piece 3871. 80/20 Inc. (n.d.). https://8020.net/3871.html

"Prime-Line 1 in. Chrome U Bracket 650-6419." *The Home Depot*, www.homedepot.com/p/Prime-Line-1-in-Chrome-U-Bracket-650-6419/203565788?MERCH=REC-_-rv_search_plp_rr-_-n%2Fa-_-0-_-n%2Fa-_-n%2Fa-_-n%2Fa-_-n%2Fa-_-n%2Fa.

Protostax enclosure for breadboards. ProtoStax. (n.d.). https://www.protostax.com/products/protostax-for-breadboard?srsltid=AfmBOoridzOtSdlBhokUt7RkWpjlYEbGTofM8TUbR9J6ZArasmkV_XJR

Rubber grommets. Cabletiesandmore.ca - Cable Management . (n.d.). https://www.cabletiesandmore.ca/rubber-grommets?srsltid=AfmBOor1npV6NcUCUjSVC-japh-aQrW66KuEETEdpoi-nfvddwfMDXhL

Satthong, S., Saego, K., Kitrungloadjanaporn, P., Nuttavut, N., Amornsamankul, S., & Triampo, W. (2019). Modeling the effects of light sources on the growth of algae. *Advances in Difference Equations*, *2019*, 1-6.

Scherholz, M. L., & Curtis, W. R. (2013). Achieving pH control in microalgal cultures through fed-batch addition of stoichiometrically-balanced growth media. *BMC Biotechnology*, *13*(1). https://doi.org/10.1186/1472-6750-13-39

Seo, D., Oh, S., Lee, M., Hwang, Y., & Seo, S. (2017). A field-portable cell analyzer without a microscope and reagents. *Sensors*, *18*(1), 85.

Shafiee, S., & Topal, E. (2009). When will fossil fuel reserves be diminished? *Energy Policy*, *37*(1), 181–189. https://doi.org/10.1016/j.enpol.2008.08.016

Singh, S. P., & Singh, P. (2015). Effect of temperature and light on the growth of algae species: A review. *Renewable and sustainable energy reviews*, *50*, 431-444.

STEM Educational Kit Microalgae Photobioreactor. Urbanclimo.com (n.d). STEM Educational Kit Microalgae Photobioreactor | UrbanClimo.com CO2 Absorption Bioreactor

Stojanovic, B., Bukvic, M., & Epler, I. (2018). Application of aluminum and aluminum alloys in engineering. *Applied Engineering Letters: Journal of Engineering and Applied Sciences*.

UTEX Photobioreactors Deluxe Package. Utex.org. (n.d.). https://utex.org/products/utex-photobioreactor-deluxe-package?variant=30991466627162

UTEX RGB-LED Lighting Platform. Utex.org. (n.d). RGB-LED Lighting Platform | UTEX Culture Collection of Algae

WOOFAA Co. Ltd. (2016). *STEM Educational Kit Microalgae Photobioreactor* . UrbanClimo.com; UrbanCLIMO. https://www.urbanclimo.com/item/microalgae-stem-pbr/

Xu, L., Weathers, P. J., Xiong, X. R., & Liu, C. Z. (2009). Microalgal bioreactors: challenges and opportunities. *Engineering in life sciences*, *9*(3), 178-189.

Yen, H. W., Hu, I. C., Chen, C. Y., Nagarajan, D., & Chang, J. S. (2019). Design of photobioreactors for algal cultivation. In *Biofuels from algae* (pp. 225-256). Elsevier.

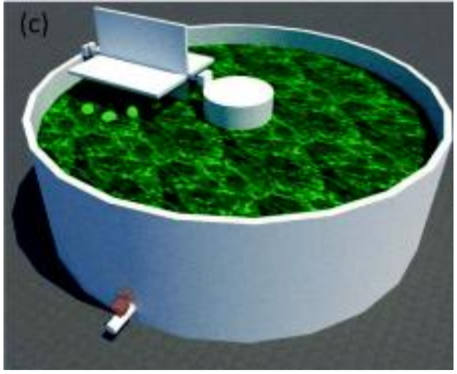
Appendix

Appendix A

Representations of all algae photobioreactor designs mentioned in this project.

Figure 22

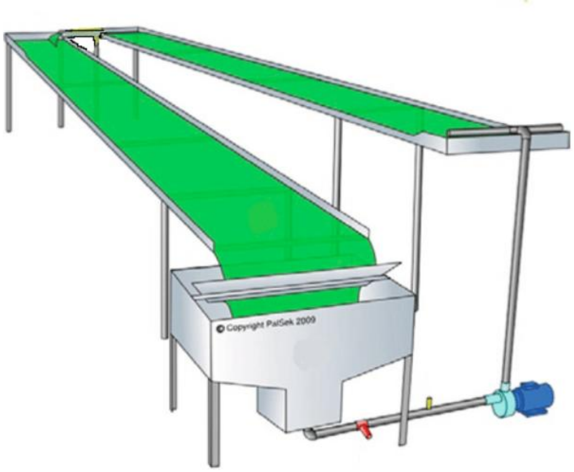
Simple pond



Note. Representation of a simple pond design from (Dos Santos et al., 2021)

Figure 23

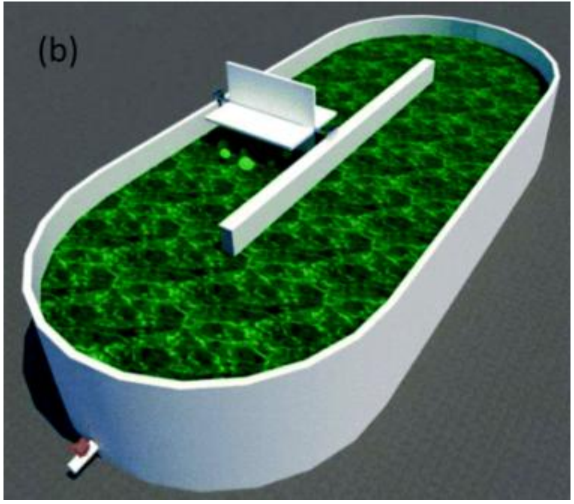
Cascade system



Note. Representation of a classic cascade system from (Dos Santos et al., 2021).

Figure 24

Raceway system



Note. Representation of a raceway system from (Dos Santos et al., 2021).

Figure 25

Flat plate design

Note. Representation of a flat plate design from (Masojídek & Torzillo, 2014).

Figure 26

Tubular design

Note. Representation of a tubular PBR design from (Masojídek & Torzillo, 2014).

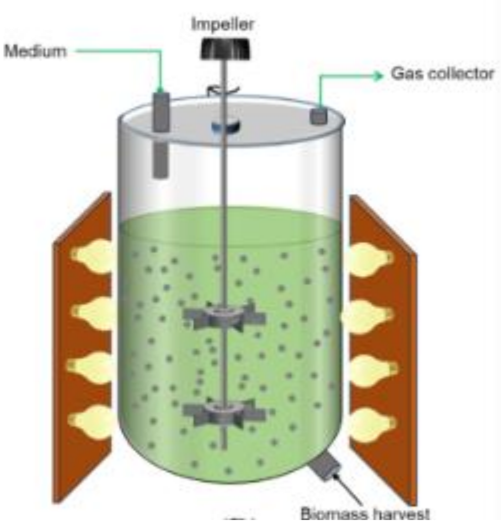
Figure 27

Bubbler system

Note. Representation of common bubbler design from (Masojídek & Torzillo, 2014).

Figure 28

Stirred Tank



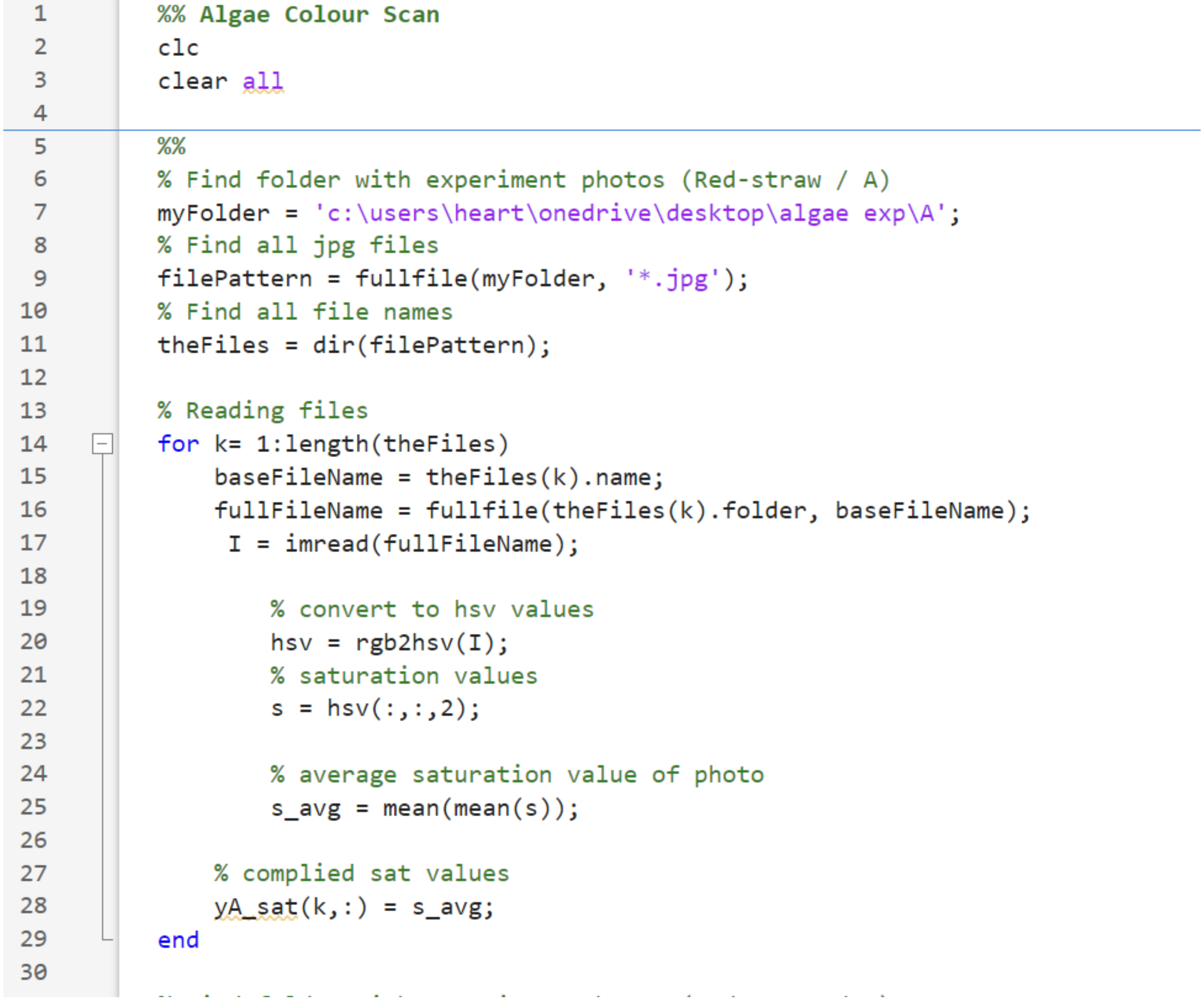
Note. Representation of a common stirred tank design from (Dos Santos et al., 2021).

Appendix B

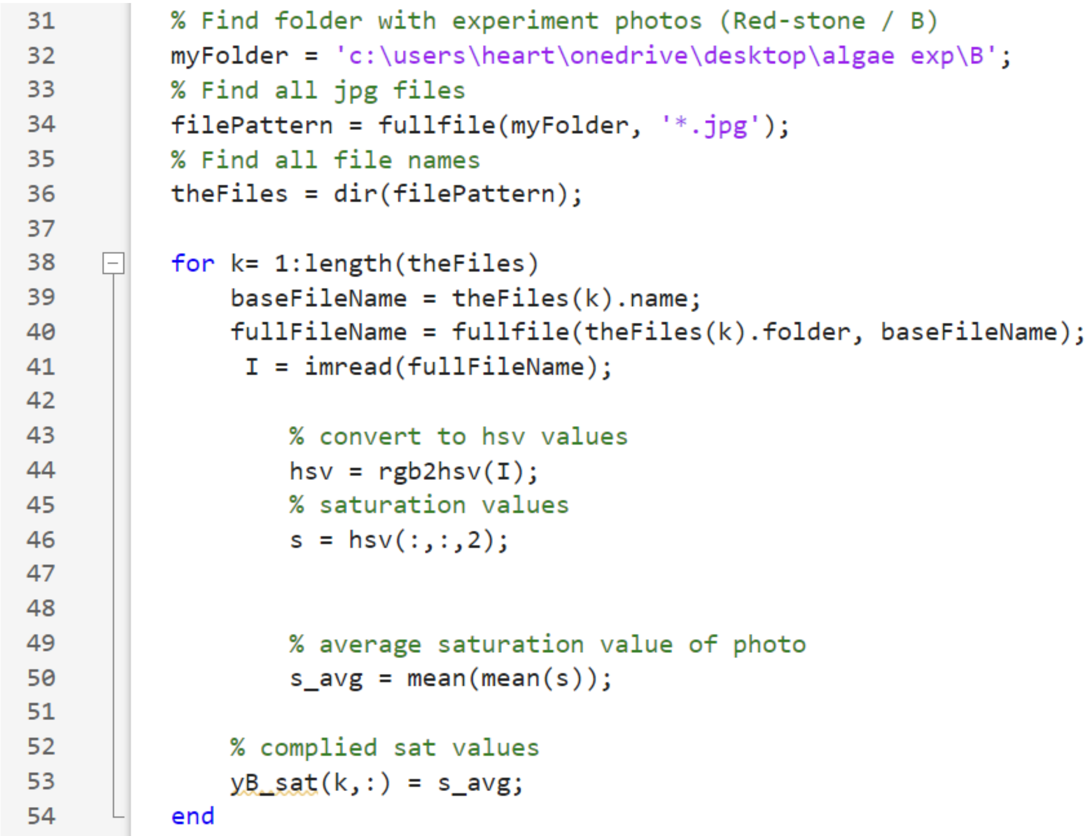
MATLAB Code for Testing Data

Figure 29

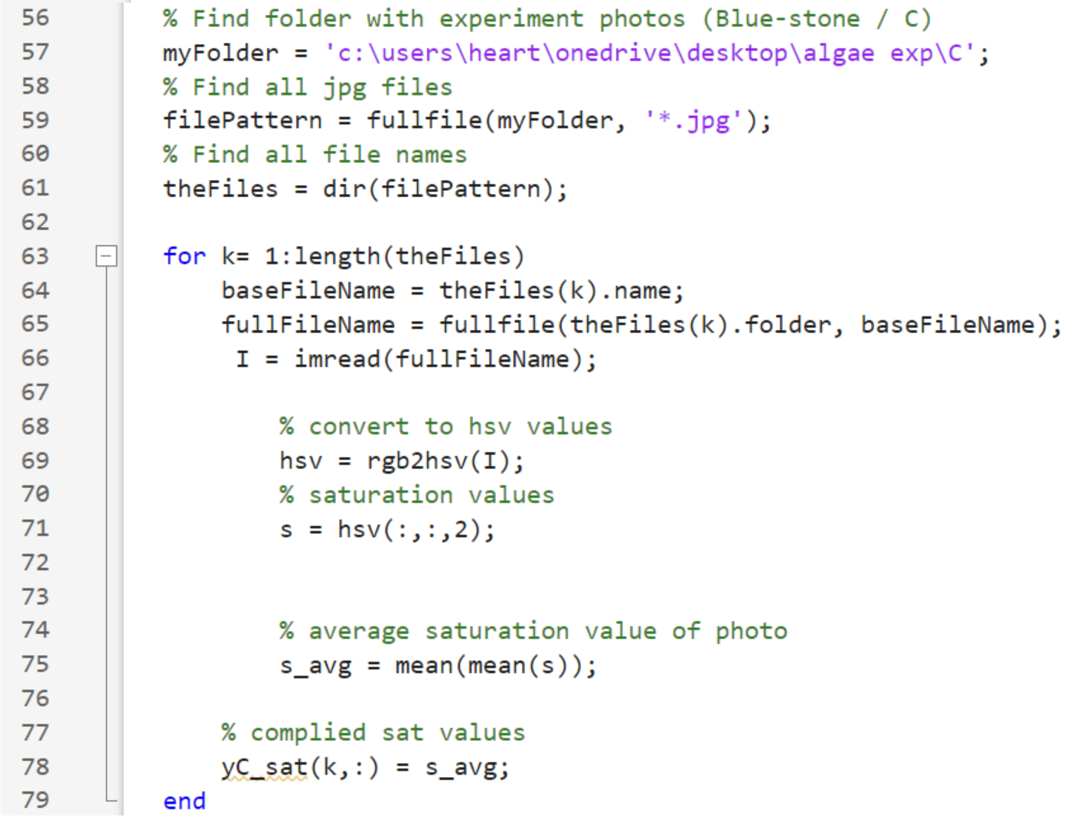
Matlab code used for the analysis of data



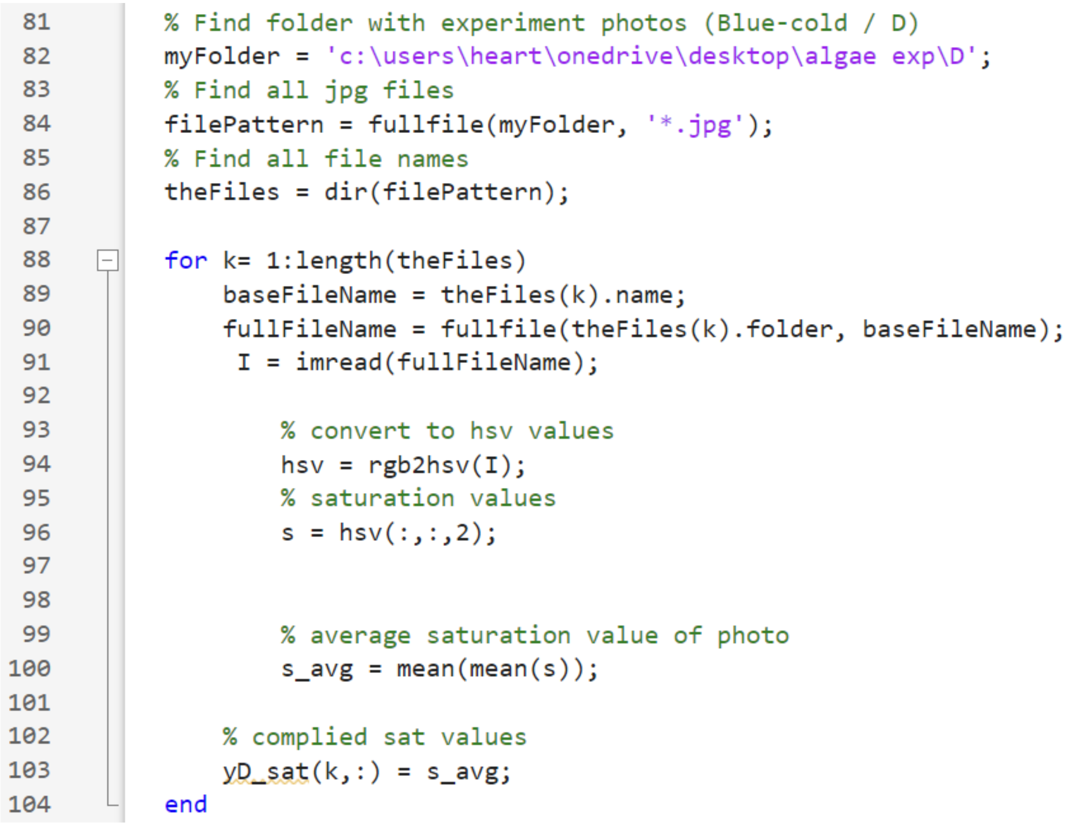
```
%% Algae Colour Scan
clc
clear all

%%
% Find folder with experiment photos (Red-straw / A)
myFolder = 'c:\users\heart\onedrive\desktop\algae exp\A';
% Find all jpg files
filePattern = fullfile(myFolder, '*.jpg');
% Find all file names
theFiles = dir(filePattern);

% Reading files
for k= 1:length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(theFiles(k).folder, baseFileName);
     I = imread(fullFileName);

        % convert to hsv values
        hsv = rgb2hsv(I);
        % saturation values
        s = hsv(:,:,2);

        % average saturation value of photo
        s_avg = mean(mean(s));

    % complied sat values
    yA_sat(k,:) = s_avg;
end

```



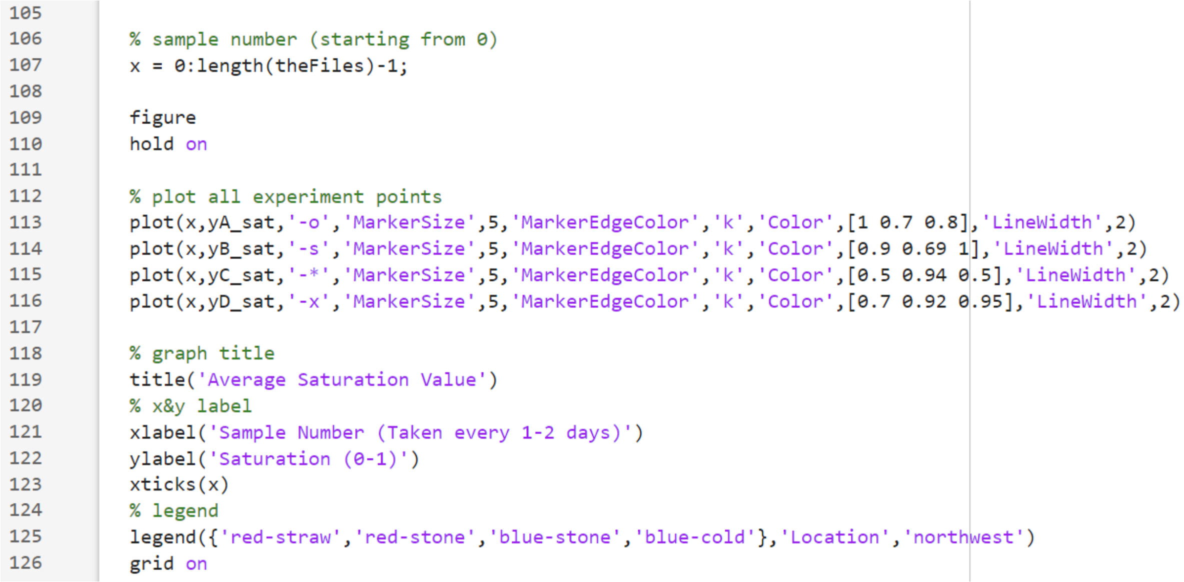
```
% Find folder with experiment photos (Red-stone / B)
myFolder = 'c:\users\heart\onedrive\desktop\algae exp\B';
% Find all jpg files
filePattern = fullfile(myFolder, '*.jpg');
% Find all file names
theFiles = dir(filePattern);

for k= 1:length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(theFiles(k).folder, baseFileName);
     I = imread(fullFileName);

        % convert to hsv values
        hsv = rgb2hsv(I);
        % saturation values
        s = hsv(:,:,2);


        % average saturation value of photo
        s_avg = mean(mean(s));

    % complied sat values
    yB_sat(k,:) = s_avg;
end
```



```
% Find folder with experiment photos (Blue-stone / C)
myFolder = 'c:\users\heart\onedrive\desktop\algae exp\C';
% Find all jpg files
filePattern = fullfile(myFolder, '*.jpg');
% Find all file names
theFiles = dir(filePattern);

for k= 1:length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(theFiles(k).folder, baseFileName);
     I = imread(fullFileName);

        % convert to hsv values
        hsv = rgb2hsv(I);
        % saturation values
        s = hsv(:,:,2);


        % average saturation value of photo
        s_avg = mean(mean(s));

    % complied sat values
    yC_sat(k,:) = s_avg;
end
```



```
% Find folder with experiment photos (Blue-cold / D)
myFolder = 'c:\users\heart\onedrive\desktop\algae exp\D';
% Find all jpg files
filePattern = fullfile(myFolder, '*.jpg');
% Find all file names
theFiles = dir(filePattern);

for k= 1:length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(theFiles(k).folder, baseFileName);
     I = imread(fullFileName);

        % convert to hsv values
        hsv = rgb2hsv(I);
        % saturation values
        s = hsv(:,:,2);


        % average saturation value of photo
        s_avg = mean(mean(s));

    % complied sat values
    yD_sat(k,:) = s_avg;
end
```



```

% sample number (starting from 0)
x = 0:length(theFiles)-1;

figure
hold on

% plot all experiment points
plot(x,yA_sat,'-o','MarkerSize',5,'MarkerEdgeColor','k','Color',[1 0.7 0.8],'LineWidth',2)
plot(x,yB_sat,'-s','MarkerSize',5,'MarkerEdgeColor','k','Color',[0.9 0.69 1],'LineWidth',2)
plot(x,yC_sat,'-*','MarkerSize',5,'MarkerEdgeColor','k','Color',[0.5 0.94 0.5],'LineWidth',2)
plot(x,yD_sat,'-x','MarkerSize',5,'MarkerEdgeColor','k','Color',[0.7 0.92 0.95],'LineWidth',2)

% graph title
title('Average Saturation Value')
% x&y label
xlabel('Sample Number (Taken every 1-2 days)')
ylabel('Saturation (0-1)')
xticks(x)
% legend
legend({'red-straw','red-stone','blue-stone','blue-cold'},'Location','northwest')
grid on
```

Appendix C

Codes for Temperature Measurement

This appendix contains all codes used for the DS18B20 sensors. The first code is what sent a warning to our emails whereas the second code is what would gather and send temperature data to Thingspeak.

Figure 30

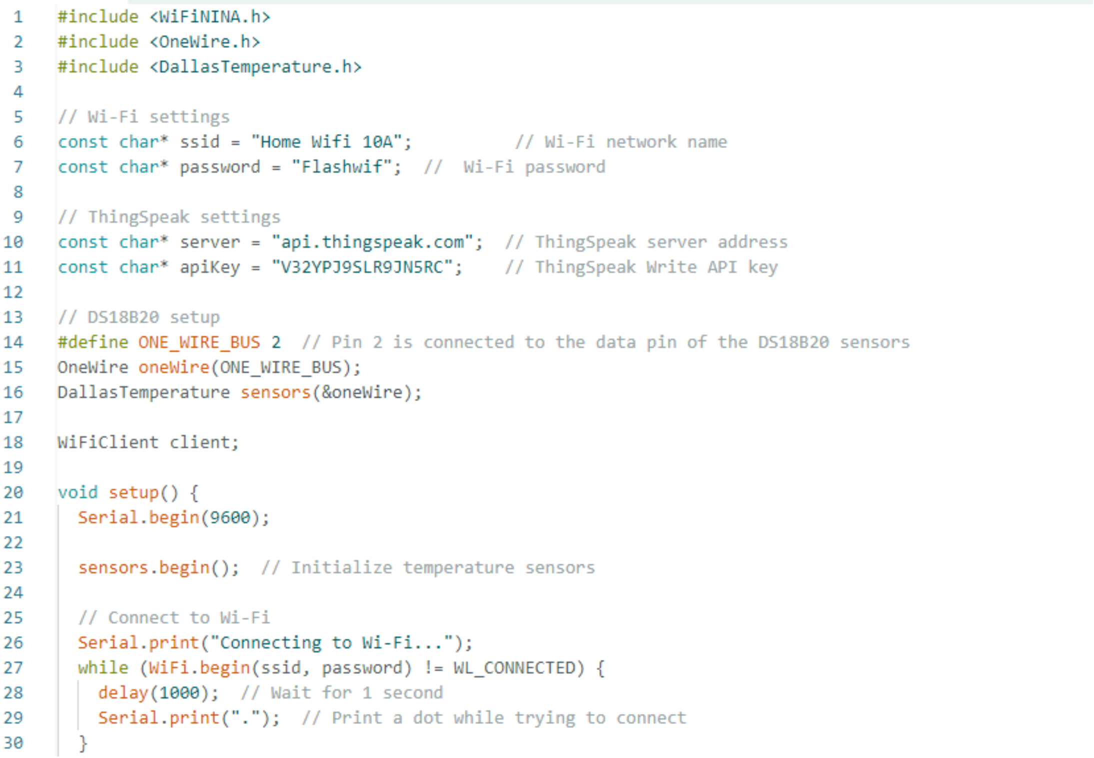
Thingspeak code

```matlab
% Define parameters
channelID = 2734182;                  % ThingSpeak ID
readAPIKey = 'OVR7VE33M71HVRAR';      % ThingSpeak Read API key
threshold = 20;                       % Temperature threshold
webhookURL = 'https://maker.ifttt.com/trigger/chill/with/key/MRu-WlebAd0923C4KRqRBkfYp_O_fuFQSZUwHiPCSG';

% getting temperature data
data = thingSpeakRead(channelID, 'Fields', [1, 2, 3, 4], 'NumPoints', 1, 'ReadKey', readAPIKey);

% setting trigger variable
alertTriggered = false;

% Loop through each field's temperature reading
for i = 1:4
    temperature = data(i);
    if temperature < threshold
        alertTriggered = true;
        % Display which field exceeded the threshold
        disp(['Alert triggered for Field ' num2str(i) '. Temperature: ' num2str(temperature) '°C']);
    end
end

% Trigger IFTTT webhook if any field's temperature exceeded the threshold
if alertTriggered
    % Send a request to the IFTTT webhook
    response = webwrite(webhookURL, 'value1', data(1), 'value2', data(2), 'value3', data(3), 'value4', data(4));
    disp('IFTTT webhook triggered with all temperature values.');
else
    disp('All temperatures are within safe limits.');
end
```

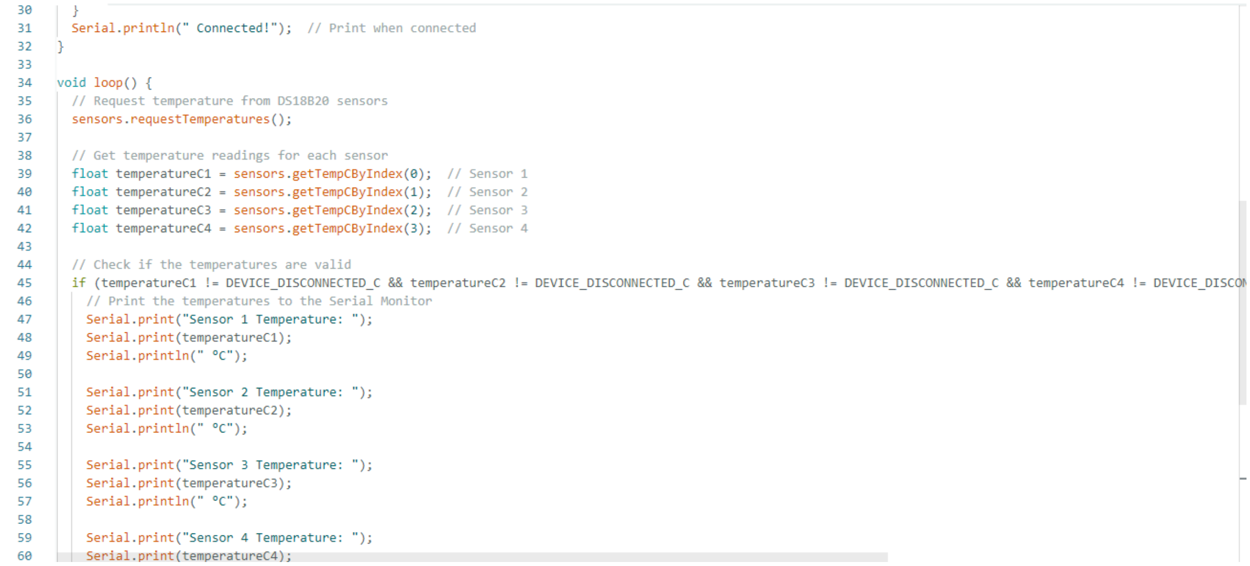
Note. This code sends a trigger to IFTT once the threshold has been passed. In this case, the threshold was set at below 20°. For the too-hot alert, the exact code was used with 28° set as the threshold as though this temperature is fine for algal growth it gave us an early system should ever the heaters set at 26° were to malfunction. Both the high and low thresholds could not be placed on the same code as Thingspeak needs two separate react functions to operate.

Figure 31

Code for DS18B20 sensors



```
#include <WiFiNINA.h>
#include <OneWire.h>
#include <DallasTemperature.h>

// Wi-Fi settings
const char* ssid = "Home Wifi 10A";          // Wi-Fi network name
const char* password = "Flashwif";  //  Wi-Fi password

// ThingSpeak settings
const char* server = "api.thingspeak.com";  // ThingSpeak server address
const char* apiKey = "V32YPJ9SLR9JN5RC";    // ThingSpeak Write API key

// DS18B20 setup
#define ONE_WIRE_BUS 2  // Pin 2 is connected to the data pin of the DS18B20 sensors
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

WiFiClient client;

void setup() {
  Serial.begin(9600);

  sensors.begin();  // Initialize temperature sensors

  // Connect to Wi-Fi
  Serial.print("Connecting to Wi-Fi...");
  while (WiFi.begin(ssid, password) != WL_CONNECTED) {
    delay(1000);  // Wait for 1 second
    Serial.print(".");  // Print a dot while trying to connect
  }
```



```
  }
  Serial.println(" Connected!");  // Print when connected
}

void loop() {
  // Request temperature from DS18B20 sensors
  sensors.requestTemperatures();

  // Get temperature readings for each sensor
  float temperatureC1 = sensors.getTempCByIndex(0);  // Sensor 1
  float temperatureC2 = sensors.getTempCByIndex(1);  // Sensor 2
  float temperatureC3 = sensors.getTempCByIndex(2);  // Sensor 3
  float temperatureC4 = sensors.getTempCByIndex(3);  // Sensor 4

  // Check if the temperatures are valid
  if (temperatureC1 != DEVICE_DISCONNECTED_C && temperatureC2 != DEVICE_DISCONNECTED_C && temperatureC3 != DEVICE_DISCONNECTED_C && temperatureC4 != DEVICE_DISCON
    // Print the temperatures to the Serial Monitor
    Serial.print("Sensor 1 Temperature: ");
    Serial.print(temperatureC1);
    Serial.println(" °C");

    Serial.print("Sensor 2 Temperature: ");
    Serial.print(temperatureC2);
    Serial.println(" °C");

    Serial.print("Sensor 3 Temperature: ");
    Serial.print(temperatureC3);
    Serial.println(" °C");

    Serial.print("Sensor 4 Temperature: ");
    Serial.print(temperatureC4);
```

```
    Serial.print(temperatureC4);
    Serial.println(" °C");

    // Connect to ThingSpeak server
    if (client.connect(server, 80)) {
      // Formulate HTTP GET request for all four sensors
      String url = "GET /update?api_key=" + String(apiKey) + "&field1=" + String(temperatureC1) + "&field2=" + String(temperatureC2) + "&field3=" + String(tempe
      url += "Host: " + String(server) + "\r\n";
      url += "Connection: close\r\n\r\n";

      // Debug: Print the full URL being sent
      Serial.print("Sending data to ThingSpeak: ");
      Serial.println(url);

      client.print(url);  // Send the request

      client.stop();  // Close the connection
      Serial.println("Data sent to ThingSpeak");
    } else {
      Serial.println("Failed to connect to ThingSpeak");
    }
  } else {
    Serial.println("Error: Could not read temperature data from one or more sensors");
  }
```

Note. This code will collect data from each sensor and will send it to ThingSpeak.

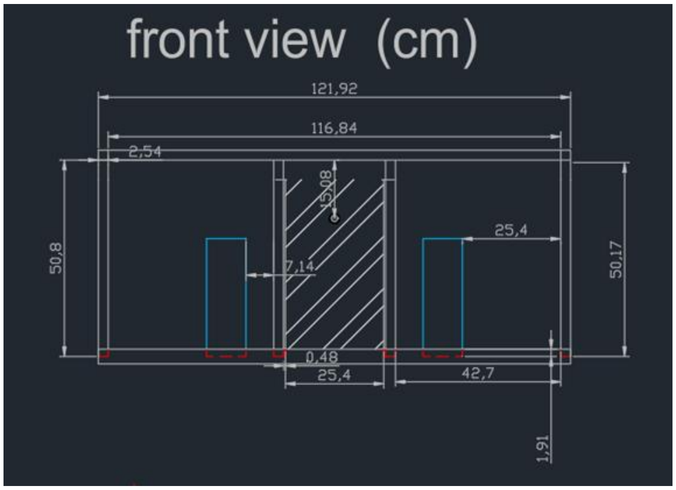
Appendix D

Frame dimensions

This section pertains all information that was not deemed immediately relevant for the reader to gain a basic understanding of the frame design.

Figure 32

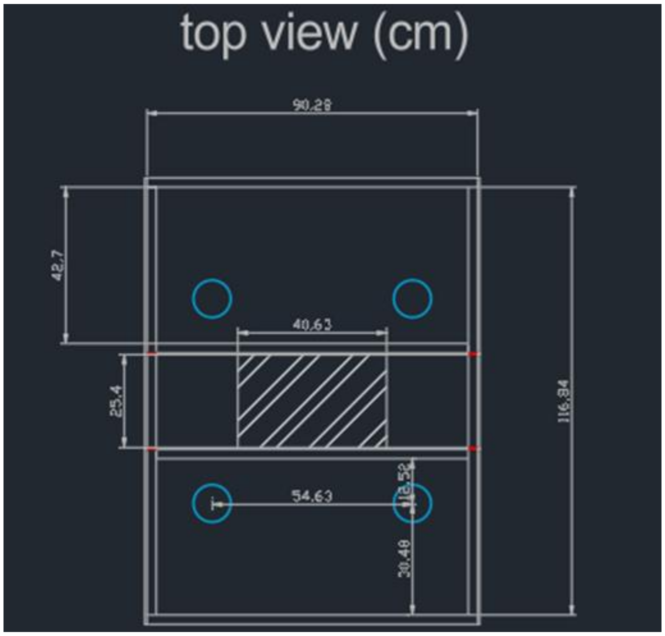
Front view



Note. This image represents the front view of the final design without the LEDs. All measurements are in cm.

Figure 33

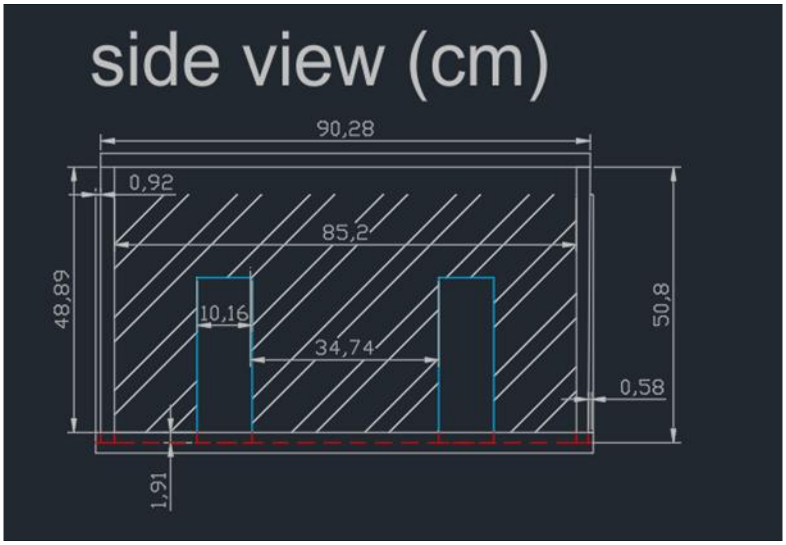
Top view of final design



Note. This image represents the top view of the frame for the final design. All measurements are in cm

Figure 34

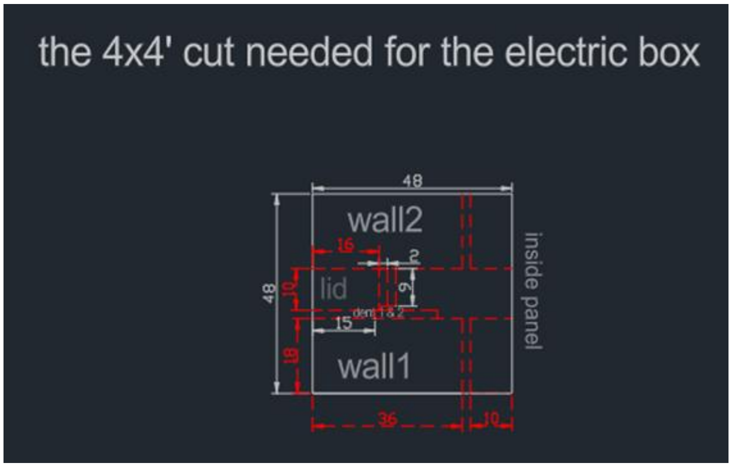
Side view of final design



Note. This image is the side view (where the lights would be mounted) of the final design. All measurements are in cm.

Figure 35

Section cut of aluminum sheet for electric box



Note. This image showcases how the sheet of aluminum may be cut to make the electric box. All dimensions are in inches.

Appendix E
Material Selection

Table 4

List of Extrusion Aluminum Bars.

1in extrusion aluminum	Length	Number	cost
X value	46in	2	37,38$
Y value	20in	8	78.32$
Z value (light)	902.8mm	4	60.92$
Total			176.62$

Table 5

List of Items and Manufacturer or Distributor

Item	Manufacturer/distributor
Lighting	
KIND LEDs	*LED Grow Lights Depot*, www.ledgrowlightsdepot.com/collections/adjustable-spectrum-led-grow-lights/products/kind-led-x330-grow-light?_pos=2&_fid=bb2133a33&_ss=c.
U Brackets	*The Home Depot*, www.homedepot.com/p/Prime-Line-1-in-Chrome-U-Bracket-650-6419/203565788?MERCH=REC-_-rv_search_plp_rr-_-n%2Fa-_-0-_-n%2Fa-_-n%2Fa-_-n%2Fa-_-n%2Fa-_-n%2Fa
Bolts	80/20 Inc. https://8020.net/11-5518.html
T-Nuts	80/20 Inc. https://8020.net/3871.html
Frame	
Vessels	Glass Vases Depot. https://glassvasesdepot.com/glass-cylinder-vases-diameter-4-inch-16-height#height=89
Workbench top	Global IndustrialTM. https://www.globalindustrial.ca/p/safety-edge-work-bench-top-plastic-60-w-x-36-d-x-1-5-8-thick

Extrusion aluminum	80/20 Inc.https://8020.net/1010.html
Internal fasteners	80/20 Inc. https://8020.net/14200.html
Corner Bracket	80/20 Inc. https://8020.net/14054.html
Aluminum sheet	MetalsDepot®. https://www.metalsdepot.com/aluminum-products/aluminum-sheet
Rubber Gromet	Cable Management. https://www.cabletiesandmore.ca/rubber-grommets?srsltid=AfmBOor1npV6NcUCUjSVC-japh-aQrW66KuEETEdpoi-nfvddwfMDXhL
Heating components	
Aquael Platinum heater	Aquarium Depot. https://aquariumdepot.ca/products/aquael-platinium-heater-150w
Arduino Uno, breadboard, Mosfet, resistors, DS18B20, and wires	Canada Robotix. https://www.canadarobotix.com/
Immersion cartridge heater	DERNORD. https://www.dernord.com/products/immersion-cartridge-heater-cartridge-heating-element-12v-100w-200w-300w?srsltid=AfmBOort-RMahhd6BCtJJPyJPvVSxs_OcfoNpzCTVvxU16kO-iS1u4Sh
Breadboard box	ProtoStax. https://www.protostax.com/products/protostax-for-breadboard?srsltid=AfmBOoridzOtSdlBhokUt7RkWpjlYEbGTofM8TUbR9J6ZArasmkV_XJR
Arduino cover	Canada Robotix. https://www.canadarobotix.com/products/3029
12V Pegasus Astro	Telescopes Canada. Pegasus Astro 12V 10A Heavy Duty Power Supply

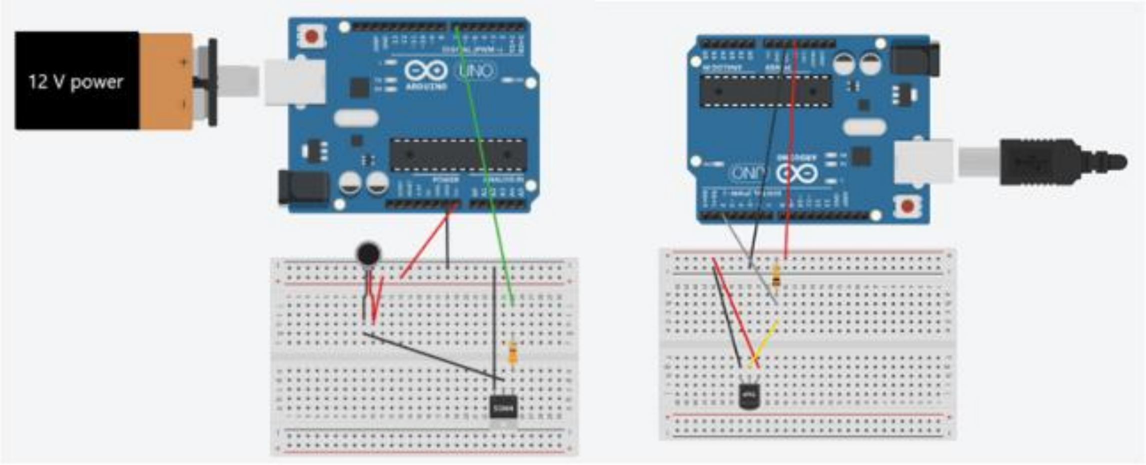
Other	
OXYMAX 200	OASE. OxyMax 200 – OASE North America
MILWAUKEE PRO PH METER	Milwaukee. Milwaukee PH54 PRO Waterproof 2-in-1 pH Tester with Thermometer and Replaceable Probe

Appendix F

Electrical Wiring for Heating Option 2

Figure 36

Wiring Display for option 2



Note. The left-hand side of the image showcases the wiring for the motor and Mosfet control. The image on the right showcases the wiring required for the DS18B20 temperature sensors. Both images will be on the same breadboard but for simplicity, they were placed separately on this image. The wiring for the temperature sensor will be as seen in the prototype and therefore will not be further reviewed in this section. The wiring for the heater would be as follows; The power supply would be connected to the breadboard via v_{in} which would then connect to the positive terminal on the heater. The heater's ground will be connected to the MOSFET whose own ground will be connected to the breadboard ground. The MOSFET's control pin will be connected to the Arduino through a 330Ω resistor. By implementing this wiring setup, the MOSFET will act as a switch that may open or close the heater's circuit which would effectively control the heater's power. Hence, a simple code could be used to power on or off the heater based on the temperature readings acquired from the DS18B20 sensor.