Vertical Farming: Creating an Accessible and Sustainable Future

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Abstract

Vertical farming is becoming an increasingly prominent industry in today's world of sustainability. With decreasing land availability, agriculturalists are looking to build farms upward to maximize efficient use of space. However, vertical farming is expensive and inaccessible to many people due to the dominance of urban lifestyles. This project explores the roles of the engineering and design process in manufacturing more accessible vertical farms in the US through sustainable practices. The vertical farming industry is becoming increasingly advanced through the use of methods such as controlled environment agriculture and technology to optimize growth factors such as lighting through data capture, real-time feedback, and automated farming systems. This paper considers many factors that will contribute to reducing the carbon footprint of vertical farms, making them more sustainable and accessible to the general public. This experiment uses easily accessible materials to design and create a practical at home hydroponic garden for growers in the United States, applying sustainable practices and technologies to enhance the farming process. The vertical garden, which will produce lettuce and strawberries, will generate a significantly lower carbon footprint than a conventional farm while still effectively producing edible food. This paper analyzes the cost and resource efficiency of an at-home vertical farm system and how this compares to conventional soil methods. The experiment considers factors in cost and environmental effects such as water and land usage, and it discusses how vertical farming will become more prominent in the future.

1. Introduction

1.1 Vertical farming

The depletion of available farming land is causing a crisis in the farming industry. With factors such as climate change and urban sprawl, the amount of farmland available is rapidly declining. In today's economy, vertical farming is becoming an increasingly prominent solution to this issue. Building upwards rather than outwards has proven a more efficient use of space and resources. However, it can be expensive and difficult to start up a vertical farm, making it inaccessible for many growers. This paper explores the roles of design practices in manufacturing more accessible and sustainable vertical farms as well as analyzing the process of designing and constructing a practical at-home farm.

Vertical farming, defined as "the practice of growing plants in vertically stacked layers, vertically inclined surfaces and/or integrated other structures," (Bustamante, 2018) has recently emerged as an industry with the effects of climate change on conventional farms. With extensive amounts of soil degradation and a reduction of available land, agriculturalists have found a space-effective solution: growing crops vertically instead of horizontally. These systems will help deal with massive population growth and urbanization. Since the world population is expected to reach 9.7 billion in 2050 with 80% of people living in cities (United Nations, 2023), vertical farming will act as a catalyst to re-develop the network of food production and distribution throughout cities (Jürkenbeck et al., 2019). The expansion of this industry in urban settings will play a large role in the future of agriculture and sustainability.

These farms use water efficient hydro agriculture techniques, mainly hydroponic, aquaponic, and aeroponic farming, which are all independent of soil (Sharma et al., 2019). Thus, most vertical farms are located indoors, as this allows for an artificial environment. Through a form of farming called Controlled Environmental Agriculture, or CEA, plants grow within a controlled environment with regulated temperature, lighting, and humidity to provide optimal conditions to these crops (Bustamante, 2018). The regulated environment of these farms provides defense from hazards such as diseases and chemicals as well as drastically reducing emissions, water usage, and space.

Since the vertical farming industry is expensive, engineers and agriculturalists are searching for methods to reduce startup prices as well as achieve sustainable goals. In fact, these two obstacles go hand in hand with each other. Engineers have found that the most prominent limiting factors in the adoption of vertical farms are lighting and energy costs. Because large scale vertical farming requires an artificial environment, costs of energy used for factors such as LED grow lights and temperature control considerably exceed energy prices generated by traditional farms (Dutia, 2014). Improvements in the efficiency of energy use are the clearest way to increase the implementation of vertical farming.

Additionally, agricultural technology, or AgTech, is making vertical farming smarter and more efficient. The use of technology such as sensors and data collectors in indoor farming systems to focus on the optimization of crop growth will help save costs and resources, reducing waste and the environmental impact of these systems. One field of technology that will have a significant impact on vertical farming systems is internet of things technologies, devices with sensors and processing ability that are able to connect and exchange data over a communication network. Automation of farming systems has the potential to drastically increase productivity while reducing environmental effects and social costs (Dutia, 2014). Although this process enables farms to be more productive and reduces risks such as diseases, the cost of initial investment in these technologies is high. However, as this technology develops, the cost of implementation will decrease, making AgTech more available to smaller farms and rural areas. This paper will consider the benefits of AgTech in comparison to the costs of integrating this technology into vertical farms.

A major step in developing the vertical farming industry is utilizing more sustainable practices, since as mentioned earlier, much of the costs are related to operation and energy use. Vertical farming could develop jointly with renewable energy, as solar energy and other green power sources can be far cheaper alternatives to electricity. These options should play a role in the designs of future vertical farms, contributing to cheaper and more accessible systems.

In this project, an original at-home hydroponic vertical farm is designed using accessible materials and sustainable practices. To help address the issue of the inaccessibility of vertical farming, this paper shares the process of designing and manufacturing a feasible hydroponic farm for anyone to build. It presents an easy design method to construct a vertical farm with autonomous aspects to produce fresh crops for gardeners looking to save space and water. This paper explores the benefits and drawbacks of constructing and implementing an at-home vertical farm as well as comparing the costs to those of a conventional garden.

While agricultural technology and renewable energy present areas of improvement in the future of large-scale vertical farming, this simple process of creating an at-home vertical farm serves as a practical solution for growers looking to save resources. Although the current cost of integrating a vertical farm will likely exceed the inexpensive costs of buying produce at a grocery store, as vertical farms develop, the cost efficiency will potentially surpass that of grocery shopping in the future.

1.2 Hydroponics

One of the main motives for the development of vertical farms is to accommodate urban life. With the decrease in land availability for soil methods, vertical farming brings agriculture to the heart of urban society. The ability of these systems to be integrated into already existing spaces such as unused buildings and warehouses allows them to be easily incorporated into urban life (Bustamante, 2018). Providing access to fresh produce in cities generates multiple benefits, contributing to both accessibility and sustainability. Primarily, the localization of food production drastically reduces costs of transportation as well as minimizing energy and pollution output (Kalantari et al., 2017). Furthermore, the integration of vertical farms into existing infrastructure combined with the optimization of spacing helps save immense amounts of land (Kalantari et al., 2017). This proposes a practical solution to saving land in cities, which is important to a society experiencing a land shortage.

This experiment uses a hydroponic system, one of the most widespread types of irrigation used in vertical farming (Al-Kodmany, 2018). Hydroponics systems are used to create the perfect artificial micro-climate for plants to grow, as environmental factors can be controlled. In a hydroponic system, agronomists control environmental conditions such as temperature, humidity, and exposure to nutrients solutions of macro and micronutrients that provides the ideal pH to the plants (Asao, 2012). There are many ways to utilize a hydroponic system, but this project uses a vertical form of a drip, or substrate, system in which a nutrient rich solution is pumped to the top of a tower and the solution drips down to individual plants (Sheikh, 2006). An example of a vertical drip system is shown in *Diagram 1* below (Peters, 2023).

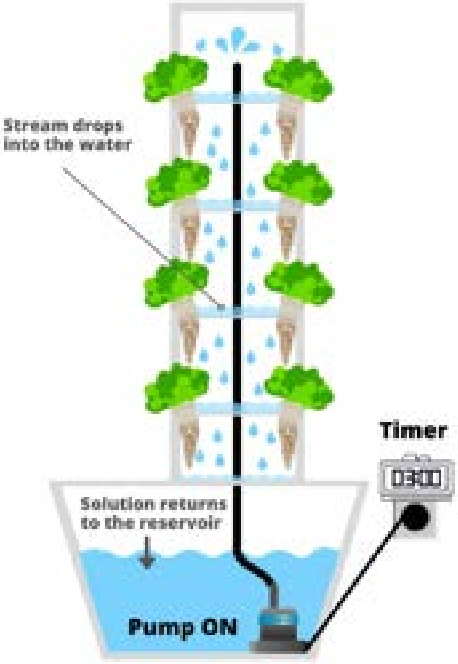


Diagram 1: Example of a vertical hydroponic drip system in a grow tower.

Additionally, this experiment uses rockwool cubes, a common medium for plant propagation in drip systems. These are dense cubes made with the fibers of basalt rock and chalk, which support the plant's growth and retain more water and oxygen than other soil mediums, providing a higher nutrient quality (Sheikh, 2006). Out of the many different types of hydroponic systems, drip systems are one of the more low-cost and simple methods, and strawberries are a typical crop grown in this system (Wootton-Beard, 2019). This makes it an optimal choice for this project, as its simplicity makes this method an accessible option for the general public.

Hydroponics serve as one of the most efficient methods of water consumption in farming. A closed loop hydroponic system can save up to 95% of the water used by traditional agriculture methods (Kalantari et al., 2017). Vertical farming through hydroponics is more efficient because it can support the cultivation of multiple crops simultaneously, sometimes up to eight types in a year. On the other hand, soil techniques can produce a maximum of three per year because this process can only occur for different plants at specific times of the year due to environmental factors (Kalantari et al., 2017). In total, for producing lettuce, one of the crops being planted in this experiment, hydroponic irrigation can use 1/20th of the water a conventional farm would use because the crops can be spaced out in a way not possible with soil methods. Additionally, the crop yields for hydroponically grown produce are much higher than the yields from soil methods. For instance, the average yield of lettuce through hydroponics is 21,000 pounds per acre, more than double the yield for soil methods at 9,000 pounds (Sardare & Admane, 2013). This study compares the amount of water and energy usage of an at-home hydroponic farm to the resource usage by conventional farming methods, analyzing whether these statistics hold true not just for commercial but also at-home vertical farming.

1.3 Agricultural Technology

Hydroponics can be used in conjunction with technology to provide optimal growing conditions to the plants. These systems often integrate forms of AgTech such as sensors that track growing process and conditions, automated rack systems, and smart heating and cooling systems to maintain the ideal climate. The main types of AgTech observed in vertical farming are precision agriculture, smart farming, and digital agriculture (Siregar et al., 2022). Precision agriculture concentrates on optimizing conditions for crop growth to save resources and reduce waste, improving efficiency and increasing yields with the same amount of input (Thompson et al., 2019). This type of agricultural technology utilizes machine learning to perceive methods in which the environment of the crops can be improved to maximize productivity. Smart farming applies intelligent technological advancements in agriculture by utilizing modern technologies such as Internet of Things (IoT) platforms to optimize farming systems (Siregar et al., 2022). This method focuses on data collection and analysis to ensure that the system is operated in a way to produce the best results. Lastly, digital farming applies precision and data farming to improve operational accuracy (Siregar et al., 2022).This method uses the data captured by smart farming technologies to form a strategic plan of action, enhancing production and reducing risks. All the methods of AgTech mentioned will enable farms to be more efficient and productive, allow for consistency in produce yield, reduce risks and recurrent costs, and make agricultural processes more environmentally friendly and climate resistant.

However, AgTech is still a developing sector and requires high costs of initial investment as well as further research to reach a level of substantial efficiency and sustainability (Dutia, 2014). These systems can be expensive to implement, and most of the existing agricultural technology is used by private companies and is inaccessible to the public. As the AgTech sector expands, funds are needed for research and development in this area, which are financed primarily by private investors (Dutia, 2014). There is much room for improvement in this field, and many companies are beginning to invest in AgTech research.

The hydroponic system in this experiment uses humidity and pH sensors: simple and affordable technology to track basic environmental factors and create a semi-autonomous system. It applies a process of data collection to automatically control the frequency of pumping water to the plants as well as reading pH levels to alert users when pH adjusters are needed. The electrical components of this vertical farm will be further elaborated on in Section 2.4.

2. Methodology

2.1. Design Overview

This project uses a hands-on approach to addressing the issue of accessibility in vertical farming, experimenting with a unique grow tower design. The specific model was designed to maximize efficiency while using inexpensive and accessible materials, and to fabricate a straightforward design that will minimize maintenance costs. It has a focus on prioritizing sustainable materials and processes to produce an environmentally safe model that could be replicated easily.

This design takes inspiration from various commercial vertical farm designs. One type of model, a vertical grow tower, appeared to be the best choice because of its space efficiency. An example of this design is the Tower Garden FLEX Growing System by Tower Farm, shown below. The dimensions of this tower are 52” height with the basin’s width and length of 30”, while being able to hold up to 20 plants (*The Tower Garden FLEX Vertical Garden*, 2023).
In this experiment, the tower design features two distinct sides to allow growers to produce two products simultaneously, allotting separation inside the tower for different hydroponic solutions. The total structure is approximately 45” tall with a length of 12” and a width of 24”, able to hold ten gallons of water, five on each side of the system, and nine plants, divided into five on one side and four on the other. Since hydroponic vertical farming favors leafy greens (Bustamante, 2018), I chose romaine lettuce as the main output to be grown in the tower. Hydroponic grown lettuce can be harvested at a much faster rate than conventionally grown lettuce, fully grown after 35 to 40 days of production (Sharma et al., 2019). Additionally, this project will use seascape strawberries as the second output to test how a non-leafy green will grow hydroponically, and the fruit’s small size will be suitable for the system.

However, the addition of a second plant is not necessary if a grower would only like to produce one type of plant. This project experiments with a slightly more complicated design to support the growth of two types of plants, but a simpler version is feasible by eliminating the second output and not having to divide the system into two separate sides. The environment that these plants were grown in is a warmer climate with a moderate humidity, typically with an average of 70-80°F in the summer and 55-65°F in the winter (*NOAA National Centers for Environmental Information*, 2023).

2.2 Materials

The construction of this vertical farm tower is split into two main parts: assembling the structure and integrating the technology components, then putting these two components together for the final product. Additionally, the last part following these two parts of the project includes growing and incorporating the plants involved in the experiment. For the assembly of the tower itself, the materials featured can be easily obtained at any home improvement or hardware store in the United States. The framework of the tower uses four Home Depot 2-gallon buckets (Home Depot SKU #150679) with lids (Home Depot SKU #150679) and two 5-gallon buckets (Home Depot / SKU #672358) with lids (Home Depot SKU #723222) for the basin, which are all composed of recycled plastics. To divide each of the bucket layers into half, allowing for the growth of two plants in the system, I use one 12x24” plexiglass sheet (Home Depot SKU #241610) per layer. I also used an extra sheet to support the bottom of the tower on top of the basin. A scoring knife (Home Depot SKU #241610) and a straight edge are required to cut these into the desired shape. To create holes in the buckets to hold the plants and allow for drainage as well as make space for the water pipe, I use a variable speed reversible electric drill, along with the following size drill bits: a 3” circular drill attachment to hold the plants (Home Depot SKU #229544), ¾” for the water pipe, and 1/16” for drainage holes. Super glue and caulk with a caulking gun are necessary to secure and waterproof the plexiglass dividers. Lastly, a sharpie and pliers are needed to mark appropriate places to drill and for removing the bucket handles, respectively.

This system harnesses a very simple understanding of agricultural technology and the basic electronics involved. Inside the vertical tower, two different 12V submersible pumps (Vansuna, Item Number 40Q-1206) are used— one for each side of the system. The main software is an Arduino Uno R3, which I used to perform the simple functions necessary to maintain the vertical farm. The AgTech components used to create a self-sufficient system are a DHT11 humidity and temperature sensor (BOJACK, Amazon ASIN: B09TKTZMSL) and a pH electrode probe (KETOTEK, Amazon ASIN: B07RRTZ8LF). To control the voltage running to the Arduino and the pumps, an AC110V relay (HiLetgo, Model Number 3-01-0341) is used with a wire connector. Additionally, a breadboard and jumper wires are necessary to connect the system as well as a power supply to generate power for the system.

In addition, to maintain the hydroponic environment, a general A&B hydroponic solution is necessary as well as hydroponic pH acid and base adjusters to support a stable pH. This hydroponic solution provides an adequate foundation of nutrients including Nitrogen, Calcium, and Iron for the roots. The plants are grown in 3” hydroponic cups (xGarden, Amazon ASIN: B07W9H8ZRH) which are incorporated into the grow tower.

In this experiment, the lettuce and strawberry were bought as seedlings and transplanted into the hydroponic system rather than germinated on their own, as this tests the plants’ main growth after undergoing germination. The lettuce used in the system is romaine lettuce, which favors cooler temperatures, and seascape strawberries because they can produce fruits any time of the year. These plants were purchased during the process of constructing the system, and their growth was maintained until the system was functioning and able to support the plants.

2.3 Tower Construction

The initial step in constructing this vertical farm design is to fabricate the structure of the tower itself. First, the handles of the buckets were removed using pliers. With a sharpie, a straight line was marked on the 2-gallon buckets to indicate where the divider will be. The locations of the divider as well as where all the holes in the bucket should be drilled were marked following the pattern shown below in *Diagram 2*.

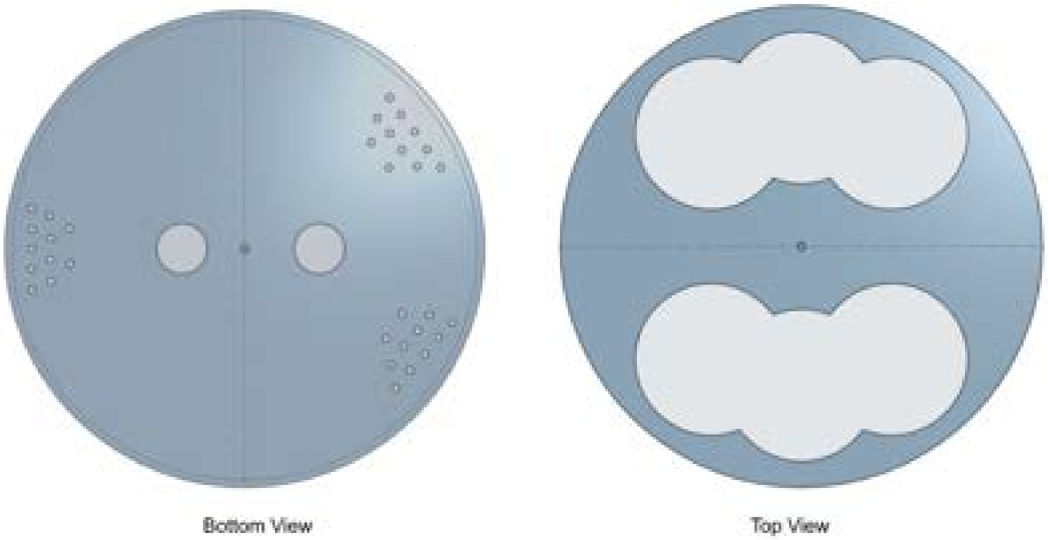
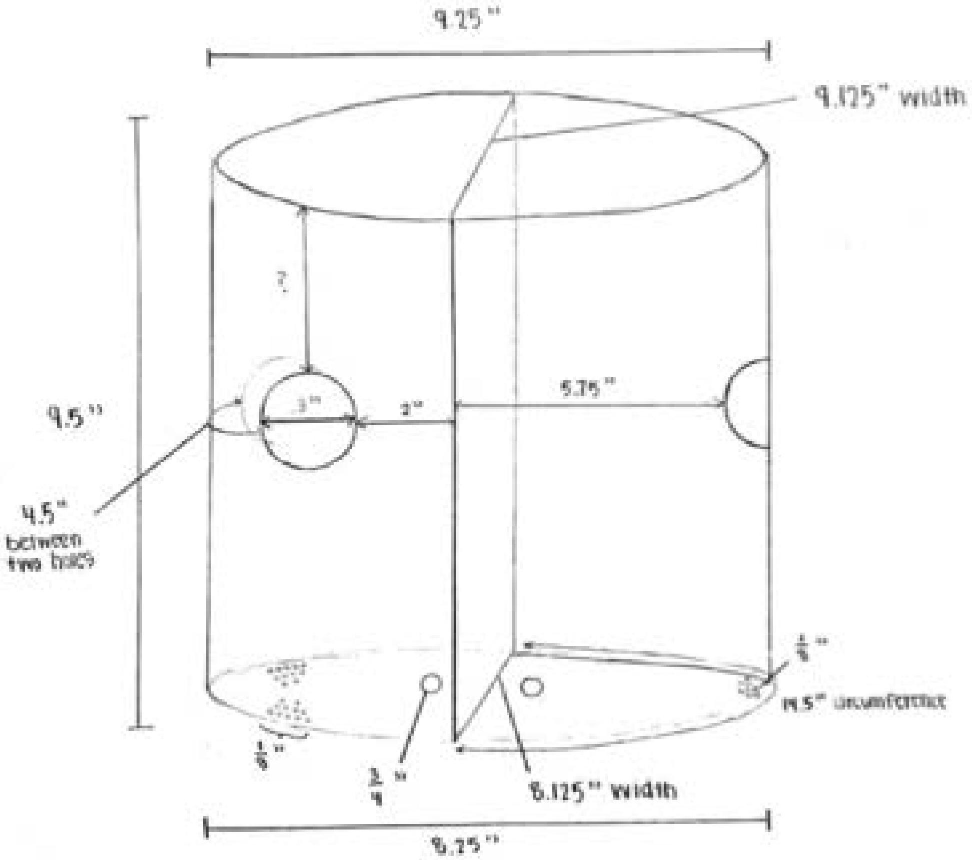


Diagram 2: 3D CAD model depicting placement of where to drill holes in each 2-gallon bucket for draining. The left shows the bottom view of the bucket with the ¾" and ⅛" holes, while the right image shows the top view of the 3" drainage holes in each bucket lid.

Then, using the 3" diameter circular drill attachment, three holes were drilled into the sides of each 2-gallon bucket, halfway up the bucket placed above where the three drainage spots are. These holes will serve to hold up the plants in the system. Using a ¾" and a ⅛" drill bit, a pattern of holes was drilled into the bottom of each bucket as shown in *Diagram 3*. The ¾" holes are for the water pump tubes to reach the top of the tower, while the ⅛" holes are for water to drain on the plants below. The ⅛" holes act as a good size for water flow because they do not drain too fast nor too slow. For the bucket lids, the 3" circular drill bit was used again to drill three holes into a shape that allows for water to drain from the bottom of the bucket on top regardless of what side it is on. The appropriate shape is pictured below in a more detailed modeling of the holes and dimensions of each layer shown in *Diagram 3*, and the arrangement of the drainage holes for the bucket lids in *Diagram 2*.



Bucket Dimensions
Height: 9.5 inches
Diameter: 9.25 inches (top), 8.25" (bottom)
Circumference: 29 inches

Diagram 3: Sketch of the dimensions for each of the three 2-gallon bucket layers as well as placement of holes to hold plants and for drainage.

With a sharpie, each plexiglass sheet was marked into a trapezoidal shape to fit the inside of the bucket with bases of 9.125” at the top narrowing down to 8.125” on the bottom, and a height of 9”. This specific shape is shown below in *Diagram 4*.

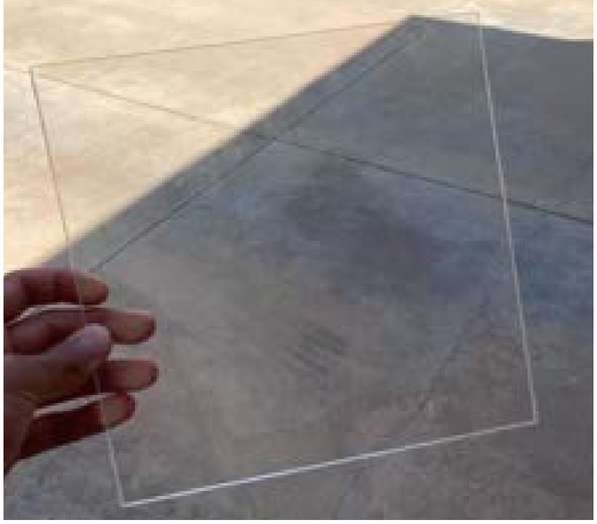


Diagram 4: Trapezoidal shape of plexiglass dividers

This specific sizing is necessary for the sides of the plastic sheet to perfectly line up with the inside of the bucket, ensuring that no water can leak through. Using a scoring knife on a straight edge, the outline of this shape was scored on both sides until flexible enough to snap. Then, each plexiglass divider was super glued into the bucket, subsequently being left to dry for 24 hours. Once the superglue was dried and the dividers in place, the edges of the dividers were caulked using a caulking gun to seal and waterproof the divider. Again, this was left to dry for 24 hours, and then tested to ensure that the dividers prevented water from traversing to the other side of the bucket.

With the last plastic sheet, an 8 x 12” rectangle was scored and snapped out of the middle, leaving a border to support the bottom of the tower while leaving space for the water to drain from the bottom layer into the basins. For the 5-gallon bucket lids, the drainage holes were cut in the same way as for the 2-gallon bucket lids, using the 3” circular saw attachment and drilling holes to line up with the drainage holes. The final layout should look roughly like the model shown below in *Diagram 5*.

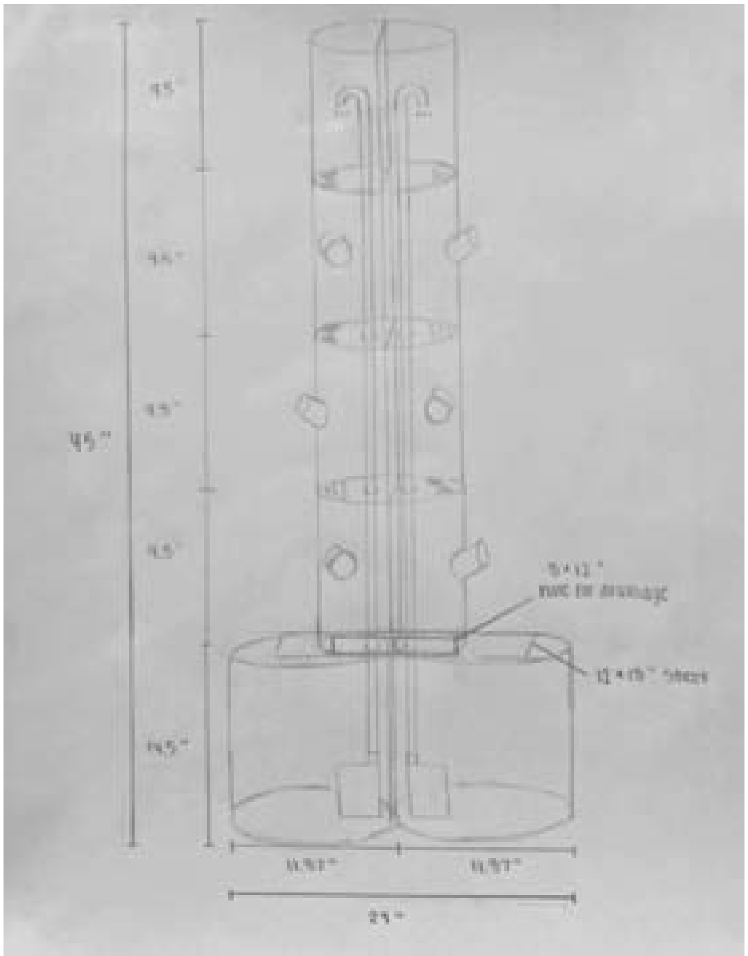


Diagram 5: Sketch of a basic model of the vertical farm structure.

To prepare the tower to support growing the plants, the 3” hydroponic cups were used . Slits were cut into the sides to make sure that they would fit stably inside of the 3” holes at an angle to let the plants grow both out of the tower and upward and were then super glued these into the holes. Duct tape was placed under each hydroponic cup to prevent water from spilling out of the system through the slits in the bottom of the cups. Once each individual layer was ready, each bucket was stacked on top of each other on top of the two basin buckets as shown in the diagram above. Then, hot glue was used to attach all these buckets in place, carefully lining up the layers so that it would drain property. An image of the final construction is shown in Section 2.5.

2.4 Electrical Components

Once finished fabricating the main structure, the electrical components of the system are prepared. The main objective of the electrical setup is to record the temperature, humidity, and pH of the system and control water given to the plants as well as monitoring a stable pH. In this electrical setup, the principal component is the Arduino R3 board, which uses C++ to run the program controlling the water pump and sensors. The first step in organizing this setup is drawing up a diagram of all the connections, which can be shown below in *Diagram 6*.

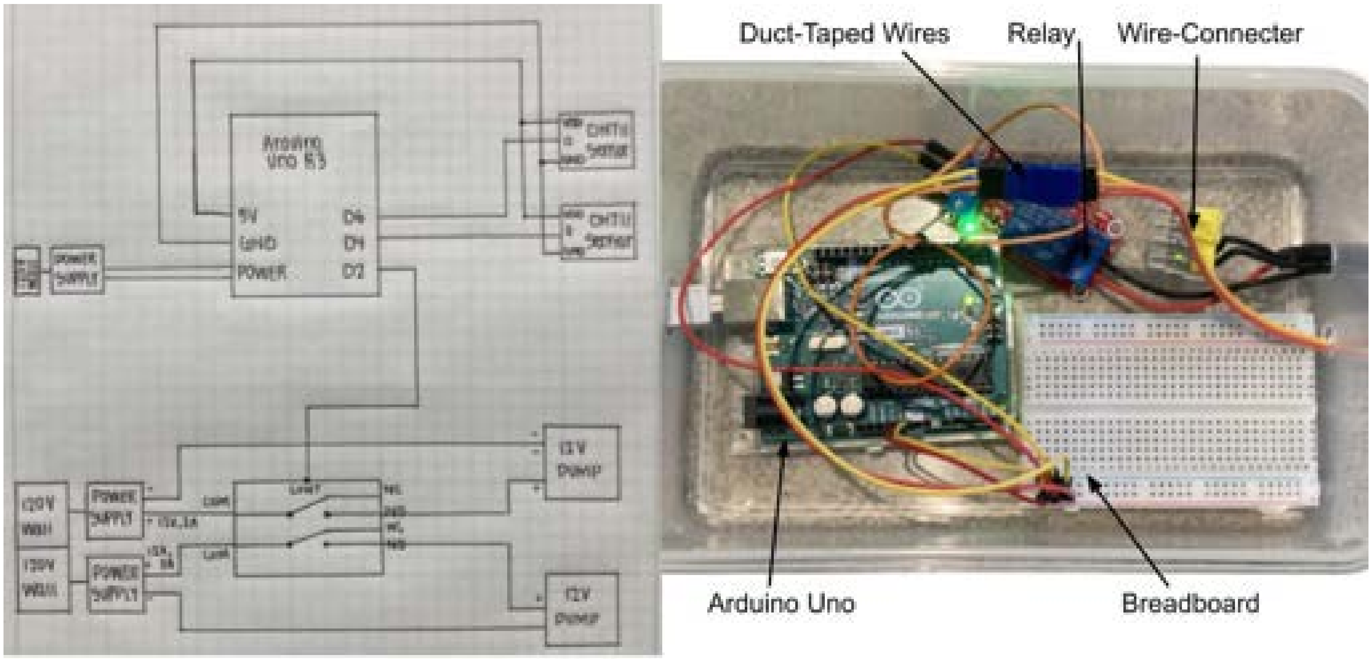


Diagram 6: Model of all the electrical connections comprising the agricultural technology used in the vertical farm and the placement of electrical components in the electrical box.

Then, the sensors and relay were tested to ensure compatibility with the Arduino. As shown in the diagram, the two DHT11 humidity and temperature sensors were connected to the Arduino, and the control from the pump was connected to the Arduino. The 5 volts and the ground on the Arduino were both connected to a breadboard to allow for multiple connections rather than limiting the power and ground use to just one wire. Since the wall provided 120V AC and the pumps required 12V DC, the power supply transformed the 120V AC to 12V DC. The ground wire from the power supply was connected directly to the pump, while the 12V wire was connected through the relay to control the current.

While programming the functions for the Arduino, it is important to download the DHT Sensor Library to be compatible with the DHT11 sensor being used, which drastically simplifies the program. The basic functions of the code are to read the temperature and humidity values from the DHT sensor, and to enter a conditional ‘if’ loop if the humidity drops below a certain number. 60% humidity was found to be an adequate number for this task, as the constant air humidity remained around 64% according to the DHT11 sensor while testing the program. If the humidity falls below 60%, the pump will turn on and water the plants for 60 seconds before turning off. Additionally, the program ensures that the plants will receive water even if the humidity sensors become flawed. To ensure daily watering, the code includes a daily counter in which the pump will turn on for 60 seconds every 24 hours. As explained in Section 3.1, while watering the plants, the pump will turn on in twenty second increments to control the amount of water in the top bucket, making sure it does not overflow. (See Appendix for code).

The placement of each electrical component in the system is subjective and can be altered. The humidity and temperature sensors were in the top bucket with plants. This layer is the driest and the plants located there will need water the most, so it makes sense to measure the humidity of this layer to determine when to turn the pump on. However, this placement requires longer wires for the sensors to reach the top of the tower. An alternative option is to keep them in the lowest layer to minimize the length of wire needed and lowering the threshold of the humidity level because this layer is more moist. The pH sensors are located in the basin where most of the water is stored, indicating when to change the pH of the water in the system.

2.5 Final Construction

Once both the tower construction and the setup of the electrical components and code were complete, these two elements were integrated together into the final product. To make sure that the structure was stable and would not fall because of wind, multiple large rocks, weighing a total of about 10 pounds on each side, were placed into the basin buckets to weigh the tower down. Then, the ½" tubing was attached to the pumps and placed in the basin while fitting through the holes in each layer to reach the top bucket to pump water. The DHT11 humidity sensors were placed in the second to top bucket, the highest bucket with plants and attached to the inside lining of the bucket with tape to measure the humidity in the driest layer. Both the wires from the humidity sensors and the pumps connected to the Arduino through holes in a plastic box to keep the Arduino, breadboard, and relay safe from water and natural occurrences. The setup of this electrical box is shown in the diagram below. The wires connecting the humidity sensors to the Arduino were taped to the outside of the structure to prevent them from disconnecting. The Arduino connected to a USB which was plugged into an extension cord that led to an outlet, shown in *Diagram 6*. The final construction of the grow tower is shown below in *Diagram 7*.

Diagram 7: Image of the final construction of the vertical grow tower.

2.6 Integrating the Plants

Once the structure is ready, the plants can be transplanted into the system. To transfer the lettuce and strawberries from soil to hydroponics, they were first taken out of their soil and the roots were soaked in water to make sure that none of the soil would alter the nutrient solution. Then, once this process was complete, the roots of the plants were placed into the rockwool cubes as shown below in *Diagram 8*. When the plants were securely positioned into the rockwool, they were placed into the hydroponic cups in the tower, making sure that the strawberries and lettuce were in the right spots on either side of the tower.

Diagram 8: Process of lettuce being placed into rockwool cubes while transplanting into the hydroponic system.

Once the plants were fixed in the rockwool cubes, they were integrated into the system via the hydroponic cups. The plants were placed into the cups at an upward angle, and extra rockwool was used to maintain their position and restrict movement. The vertical farm after the implementation of the lettuce is shown in *Diagram 9* below.

Diagram 9: Image of lettuce positioned in the hydroponic system.

3. Results/Analysis

3.1 Functionality

Overall, the vertical farm is a self-sustaining system, with the exception of having to replace the water and nutrient solution occasionally, most likely every two to three weeks. The system works by continuously recording the humidity of the top layer every minute. If the humidity reaches a level below 60% relative humidity, the pump will run for a minute. However, since the pump runs quicker than the water drains, it is programmed to run in twenty second increments and then wait for thirty seconds to let the water drain, then repeat until it has run for a total of a minute. This prevents overflowing of the top layer and limits the water pressure in the top bucket to minimize the chances of the divider detaching. Additionally, there is a daily timer set in the code to run the pump every 24 hours to make sure that if there is a problem with the humidity sensors that the plants still receive a sufficient amount of water. The pH sensors measure the pH of the water in the basin, and although they do not automatically re-adjust the pH, they show when the water requires any pH adjusters and growers can manually add base or acid solutions to maintain a constant pH. The automation of pH maintenance is an opportunity for improvement in the system; however, since there is little interaction between the water and outside factors, adjusting the pH should be an infrequent occurrence.

There are many possible ways to design and construct this at-home vertical farm, and the method chosen aims to find a balance between maximizing functionality while keeping it easy and accessible. One major potential change is choosing to only grow one type of plant rather than multiple, and this would greatly simplify the process because it would eliminate the need to have dividers inside of the buckets, and it would be easier to maintain a singular output. Additionally, it would be possible to reduce the use of technology and use a water pump with a set timer. Regardless, this outdoor design combines the essential sensors to maintain an autonomous system while minimizing costs of additional technology required in an indoor setting, utilizing natural sunlight to sustain plant growth. Further discussion considering potential changes to the experiment can be found in Section 4.2.

3.2 Cost Analysis

This paper outlines the cost of vertical farms and describes how to make this a more successful option for agriculturalists at home. Although it is a time-consuming process, the materials used in this experiment are quite easy to obtain, making it a project that any at-home grower can accomplish. After completing the fabrication of the system, the costs were analyzed and compared to that of a commercial vertical farm. The final costs associated with the materials used in constructing and applying technology to a single vertical farm grow tower are shown below in Table 1.

Table 1
Shows approximate fixed costs of materials to complete the vertical grow tower.

Item	Amount	Total Cost
2-Gallon Paint Bucket	4	$20.00
2-Gallon Paint Bucket Lid	4	$10.00
5-Gallon Bucket	2	$10.00
5-Gallon Bucket Lid	2	$6.00
Plexiglass Sheet 12 x 18”	5	$60.00
3” Circular Drill Attachment	1	$23.00
¾” Drill Bit	1	$12.00
Superglue	1	$8.00
Caulk	1	$13.00
Arduino Uno R3	1	$37.00
12V Submersible Pump	2	$51.00
DHT 11 Humidity & Temperature Sensor	2	$6.00
110V Relay	1	$7.00
Jumper Wires + Breadboard	1	$13.00
A&B General Hydroponic Nutrient Solution	1	$18.00
Hydroponics pH Sensor	1	$20.00
3” Hydroponic Cups (50 pack)	1	$13.00
Total	**42**	**$369.00**

Overall, the fixed costs of this at-home vertical farm is similar to commercial farms that are sold online. Although the majority of large-scale vertical farming companies have complex indoor factory systems and don’t sell simple designs to utilize domestically, smaller companies will sell grow tower systems similar to the one in this experiment for anywhere between $200 and $700. For instance, the FLEX Growing System by Tower Garden referenced in Section 2.1 sells for $670, while another commercial tower, HydroBuilder’s EXOTower 3-Tier Garden Tower, is marked at $220 (*ExoTower Hydroponic Garden Tower*, 2023). These costs vary due to obvious factors like size, but also because of differing levels of autonomy and resource efficiency. Since the inexpensive ones likely do not use the level of agriculture technology explored here, it concludes that this experiment is a relatively efficient and cheap way of producing your own vertical farming system.

Following the construction, the additional variable costs only include electricity and water. Even so, this design does not use LED lights and instead turns to natural lighting as the main source. This cuts down much of the costs of electricity that would be needed and makes this design a more appealing solution to growers who have access to natural lighting. The cost of electricity comes solely from the electricity used by the power supply. This power supply takes about 10 W of electricity per hour. The final electricity costs as well as other variable costs are shown in Table 2.

In a study produced by the University of Nevada, Reno, Chenin Treftz and Stanley Omaye conducted an experiment comparing the fixed and variable costs of growing strawberries through hydroponics versus soil. They concluded that the fixed costs of the hydroponic system was $593.80 while the variable costs associated with plant maintenance accumulated over a one-year period was $47.38, resulting in a total of $641.18 (Treftz & Omaye, 2016). This value ended up exceeding their one-year costs for conventional farming, which was $291.07, divided into $270.59 for fixed costs and $20.48 for variable costs (Treftz & Omaye, 2016). The hydroponic total mainly accounted for nutrient solution related costs, but it exceeded by more than double the amount. However, this total omits the cost of the plants themselves. In my experiment, the total one-year costs were much closer to their calculated amount by conventional farming. Below shows a table of the total variable costs associated with growing both strawberries and lettuce for one year.

Table 2
Variable Costs Associated with Strawberry and Lettuce Growth for One Year

Item	Amount (frequency per year)	Cost
Romaine Lettuce Seedlings (6 seedlings)	4	$36.00
Seascape Strawberry Seedlings (25 seedlings)	2	$32.00
A&B General Hydroponic Nutrient Solution	3	$54.00
1” Rockwool Cubes (200 count)	1	$14.00
Electricity	87.6 kW	$21.90
Total	**10**	**$167.90**

Although this value exceeds the variable costs yielded by soil grown strawberries found by Treftz and Stanley’s experiment, the total costs disregarding the seedlings themselves is $78.00, leading to a total combined fixed and variable costs of $387.00. Despite the fact that this number is still quite a bit larger than the cost presented by Treftz and Stanley, the hydroponic farming method saved more resources and proved to be the more sustainable option. Continued research in optimizing the cost efficiency in vertical hydroponic farming will make it a cheaper alternative to conventional methods in the future.

3.3 Resource Comparison

Evidently, this vertical system can save a great deal of space compared to traditional farming methods. Although the implementation of the system exceeds costs of simply planting and maintaining produce in soil, this vertical growth tower exponentially saves space, which poses a garden alternative in a world where living space is rapidly decreasing and more suited to urban environments. While most types of lettuce and strawberries grown traditionally in soil need to be spaced 12-18 inches apart, this system can grow nine plants in a horizontal space of two square feet. Thus, this hydroponic system is around 1.5x more space efficient than conventional methods, as soil production would only support six plants in this amount of space.

Additionally, this system uses significantly less water than with soil farming methods. Treftz and Stanley's experiment indicated that the soil system used 30% more water than the hydroponic system while growing strawberries, requiring 520 gallons compared to the 320 gallons used by hydroponics (Treftz & Omaye, 2016). For the system built in this experiment, the vertical farm system holds 16 L of water total, 8 L on each side of the tower, or about 4.2 gallons. Assuming this water is replaced every two and a half weeks, or about 21 times a year, this system uses a total of 88.2 gallons of water a year to grow both lettuce and strawberries, which is about 17% of the water used for soil-grown strawberries in Treftz and Stanley's experiment. Compared to numbers stated earlier that hydroponic systems can save up to 95% of the water used through conventional methods, the 83% of water saved in this experiment does not quite match the efficiency but is still a tremendous amount of water saved. Without the benefits of a large corporation and indoor facilities to achieve the perfect isolated hydroponic system, this system does an adequate job of minimizing water use.

4.1 Discussion

These results show that it is possible to make vertical farming more accessible, but this specific design has yet to prove that the process of fabricating your own at-home vertical farm is cost efficient compared to commercially available models. However, this study proves that implementing this device into a home can greatly save resources compared to a homeowner who grows produce using traditional soil methods. As a domestic solution, this system can contribute to solving problems related to water usage that are generated by conventional mass farming. If more agriculturalists shift in the direction of hydroponic vertical farming, these methods can contribute to reducing the rapid decrease in fresh water supply as well as help areas in droughts recover by restricting the use of water used by soil farming.

Additionally, this study supports investment in the growing industry of agricultural technology. The sensors used in this system help to minimize water usage by tracking humidity, a simple function that saves great amounts of water. Although the technology applied in this project is cheap and accessible compared to the expensive technology used commercially through Controlled Environment Agriculture, this design takes steps towards implementing technology into vertical farm structures accessible for the public. As more people invest in and encourage the advancement of AgTech, this industry should see higher usage and profits. Emerging opportunities in AgTech motivate increasing numbers of investors and entrepreneurs to collaborate and generate environmental, social, and economic returns for the industry (Dutia, 2014). The development of AgTech will increase efficiency in the vertical farming sector and save an even greater amount of resources. Additionally, as the use of renewable energy sources rises, this industry could help vertical farming reach a higher level of sustainability.

4.2 Future Experimentation

This project could have been completed differently with other constraints. For example, if the goal had not been to create the most cheap and accessible design possible and favored results and technology, more technological elements could have been incorporated and an indoor system could be utilized to create an artificial environment for the plants. LED lights were not used because of the extra cost of energy use, but this addition to the system would potentially affect the plant quality, as LED lights are more commonly used commercially to produce high quality crops. I also could have altered the amount of plants being grown. With more space available, I could have chosen to use larger buckets to compose the tower, or I could have added another layer to the top of the tower to maximize space efficiency in comparison to the amount of land used. On the other hand, plant diversity could have been sacrificed and the experiment could focus on the cultivation of one specific plant. This change would have saved a considerable amount of time and resources, because dividing the buckets into two sides took a lot of time and effort. Overall, this particular design was a compromise between affordable and easy to use materials as well as agricultural technology and automation.

If someone were to replicate this experiment, designating one tower to a specific type of plant and using two different towers with their own distinct water reservoirs would be advised if choosing to grow multiple plants. This would make it much easier to prevent cross contamination between the two systems without the extra effort of dividing the layers in half. Fabricating the vertical farm in this way would be more cost effective as well as decreasing the chance of mixing between the two solutions. Additionally, in this experiment, the plants were purchased as seedlings early in the process of constructing the farm, and by the time they were integrated into the system they had already grown quite large. It would be possible to start with seeds and germinate them in the system to test for success in the plant's initial growth instead of testing if the hydroponic system can maintain the plant's growth. A further step up from this experiment would be to automatically maintain both the humidity and the pH of the system by connecting the pH meter to the Arduino and programming it to release pH adjusters into the system as needed. The level of automation used in the vertical farm could be expanded in multiple ways, and the accessibility of technology in the future will allow for more complexity in agricultural technology for everyday growers.

In essence, the vertical farming industry is becoming more prominent and accessible every day, as the need for space and resource-efficient systems become more apparent in today's society. As problems of soil depletion and decreasing land availability begin to plague society, more people will turn to these more efficient methods of farming. The industry is continuously developing to be cheaper and more accessible to the public, and this experiment that designs systems to meet the accessibility and sustainability needs of society will be one of many to come. Further experimentation is necessary to find a design that maximizes sustainability and output compared to initial costs.

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Appendix

The code to run the vertical farm in this experiment was created using C++ in the Arduino IDE application. A link to the exact code can be found here https://github.com/NoahJoshi/Vertical-Farm-Code.