At-Home Vertical Farm and Automatic Irrigation System Implementation

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ABSTRACT

The world population is expected to reach nearly 10 billion people by 2050. Inequalities in food access will continue to be exacerbated without the intervention of advanced solutions. Vertical farming is a technology field which could allow for the expansion of food production by stacking garden spaces on top of one another. From an industrial perspective, this is a practical method for optimizing square footage of farms without interrupting native plant ecosystems or suburban and business properties. From a small-scale community perspective, vertical farms may also be implemented into homes enabling homeowners to become prosumers as they help to decentralize the global food chain. At Purdue University's DC Nanogrid House, a vertical farm (VF) has been constructed to investigate the feasibility and effectiveness of the agricultural technology.

While other papers focus on the commercial scale of VF and how it will determine future commercial and research farming, the goal of the present study is to develop an automated VF system for a residential application. Autonomous irrigation is installed and controlled via ESP-32 Micro Controller and capacitive soil moisture sensors, and high-efficiency LED lights are controlled based on the plants' needs. Methods for efficient power use, reduced water use, and other relevant topics will be discussed for the user's benefit. Readers should come away from this paper with an understanding of the benefits and disadvantages of VF and a plan for creating an at-home VF with an automatic irrigation system.

1. INTRODUCTION

1.1 Background and Motivation

By the year 2050, the population is projected to have reached 9.7 billion (U.N., 2022), and the planet's food supply will need to grow by 70% to accommodate that number of people (Krishnan *et al.,* 2020). Vertical farming (VF) is a potential solution that would provide food to the growing global population through maximization of the amount of food to be produced per area of land (Beacham et al., 2019). Additionally, VF is often cited as more environmentally friendly when compared to traditional farming techniques (Vatistas *et al.,* 2022).

VF systems can generally be broken down into two groups: horizontally stacked systems and vertical growing surfaces (Beacham *et al.,* 2019). Horizontally stacked systems (Figure 1) allow plants to grow on shelves that are stacked on top of one another. This is beneficial because it is an efficient way to increase production for commercial plant growth, especially among green leafy vegetables and herbs.

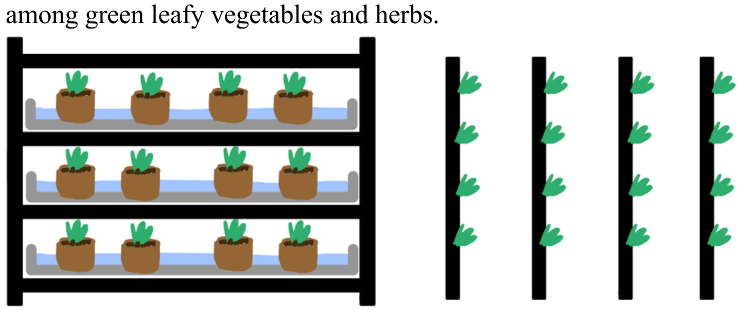

Figure 1: Horizontally stacked VF (left) and vertical growing wall (right).

Plants that are positioned to grow from a wall are known as vertical growing surfaces (Figure 1). Vertical growing walls can often be incorporated within buildings to reduce the amount of CO_2 in the air (Shao *et al.,* 2021) or improve visual appearance of the space (Timur and Karaca, 2013). This garden configuration can be used for food production, or, for the visual benefit of the community, it can be used to display flowers or leafy plants. Colorado State University's Michael Smith Natural Resources Building, located in Fort Collins, Colorado, exemplifies a VF in an academic building setting in Figure 2.

Figure 2: Vertical growing surface implemented into an academic building.

VF systems can be further divided into categories of growth methods: soil and hydroponics. These methods provide water and nutrients to the plants. Growing plants in soil is common, but hydroponics, a method by which roots are exposed to a nutrient-dense fluid, is also popular. Data has shown that hydroponics can produce ten times the yield of traditional farming, but it requires 80% more energy (Beacham *et al.,* 2019). The VF system discussed in this paper used the soil-grown method because reduced energy use was more favorable than plant yield. Furthermore, the goal of this study was to investigate the feasibility of an at-home VF for average households in the United States. This prevented the use of hydroponics because it requires high amounts of maintenance for details such as water temperature and pH levels (Nalwade *et al.,* 2017). This was considered out of scope for this project's budget and timeline.

The scientific community is primarily interested in VF's potential role in solving the global food crisis and reducing negative impacts on the environment during food processing. For reference, traditional farmland currently has the ability to produce 51.9 bushels of soybeans, a critical crop in the United States, per harvested acre (United States Department of Agriculture, 2022). A comprehensive review of current VF literature revealed that VF can produce more than three times the yield compared to greenhouses (Vatistas *et al.,* 2022). This data significantly encourages the use of VF as scientists approach the global food crisis. Regarding the environmental impacts of VF, commercial and residential VF users must be very conscious of their VF systems if they wish to reduce related greenhouse gas (GHG) emissions. One study investigating emissions due to transportation of lettuce between local production and the consumer found that when applied in urban areas, VF has been proven to reduce the CO_2 footprint per kilogram of lettuce by a factor of 4.3 (Plawecki *et al.,* 2013). Note that this reduction factor is explicitly referring to GHG emissions caused by transportation of produce. Transportation emissions only make up 11% of the total GHG emissions tied to food systems (Weber and Matthews, 2008). In contrast, the production of food makes up 83% of GHG emissions related to food systems. This percentage is primarily tied to the energy used to grow plants. Specifically, in indoor farming systems such as a VF, this energy usage will be tied to water and artificial sun lighting requirements. One study concluded that 58% of UK horticulture energy input was used for indoor gardens whereas only 9% was used for field crops (Warwick HRI, 2007). The energy usage differential between indoor and outdoor farming appears to be extreme, but massive GHG emissions reductions can be made when renewable energy is incorporated in indoor farming systems. Renewable energy resources such as solar panels, wind energy, and heat pumps have the ability to reduce CO2 emissions by 56-79% (Avgoustaki and Xydis, 2020).

VF is commonly discussed on a large, industrial scale, but its application is also relevant on a small, residential scale. Previous studies have shown the integration of numerous devices from the Internet of Things (IoT) into a VF in a residential setting (Abhay *et al.,* 2021; Ismail and Thamrin, 2017). IoT can frequently be useful in a VF system because it offers automation of lighting and irrigation. Sensors can also be implemented to collect data on the health of the plants within the VF.

1.2 DC Nanogrid House Introduction

This study has taken place through Purdue University's DC Nanogrid House project. The DC Nanogrid House is a house that was constructed during the 1900s. In 2017, it was purchased by Purdue University and taken on as a project within Purdue's Center for High Performance Buildings (CHPB). CHPB is a program within Purdue University's Herrick Laboratories. Its focus is to bring collaboration between industry and Purdue University to support new technologies that are applicable to high performance buildings. Within the DC Nanogrid House, the inefficiency of converting from alternating current (AC) to direct current (DC) is avoided by powering the house from its own DC-powered nano-grid. The placement of the VF within a house that uses its own DC power adds an additional element of unique residential environmental sustainability by decreasing the energy and water usage of the house.

This paper will proceed by presenting the method by with the VF was constructed in Purdue University's DC House. Thorough details regarding the controls and electronics controlling the VF's automatic irrigation system are provided. The automatic irrigation system in this VF was tested to provide a demonstration of its function and ability to self-regulate. A technoeconomic analysis details the costs associated with the system described in this paper. Conclusions are drawn from the testing and expenses associated with this VF. Future work to be completed on this VF system are discussed to provide examples as to how one would bring this system closer to the idealized VF for which researchers have expressed enthusiasm.

2. METHOD

2.1 Description of Mechanical Test Setup

The mechanical components of the VF consisted of timed lighting, PVC, solenoid valves, adjustable valves, plastic tubing, and a water source.

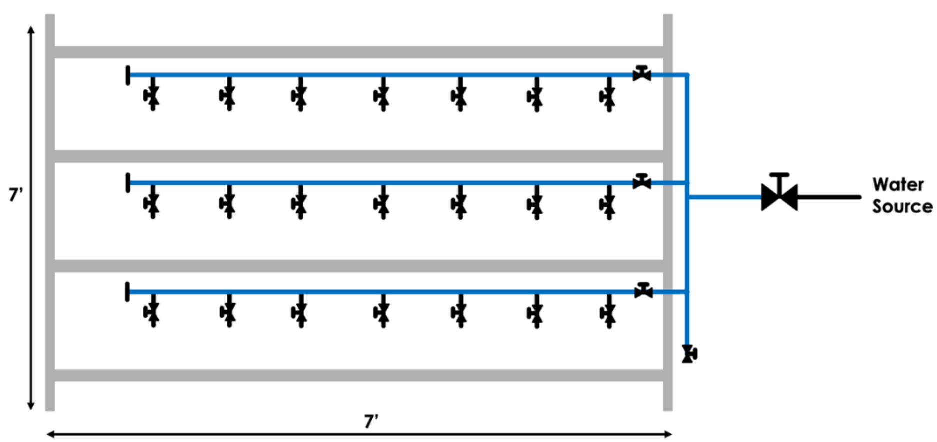

Figure 3: Sketch of the VF that includes three shelves, PVC pipes, one solenoid valve per shelf, seven adjustable valves per shelf, and a water source.

Incorporating light-emitting diodes (LED) is a classic method for fostering successful indoor plant growth as one can have more control over plant quality (Dou *et al.,* 2017). Depending on the wavelength of light used in a VF, the quality of vegetables and herbs coming from the garden can significantly increase. Literature has concluded that LED wavelengths such as blue (~425 to 490 nm), green (~490 to 560 nm), red (~640 to 720 nm), and far-red (~720 to 750 nm) produce the best results as they are within the photosynthetically active radiation (PAR) spectrum, allowing for increased plant growth (Rahman *et al.,* 2021). Unfortunately, there is no prescribed lighting procedure that suits all plants. For example, vegetables will grow differently from herbs if placed in the same lighting conditions. White LED lights with a range of approximately 365 to 425 nm were installed in the test setup, allowing each shelf to be equipped with adequate lighting. Although on the lower end of the PAR spectrum, studies have proven that white LED lights are acceptable for the growth of most plants (Nguyen *et al.,* 2021). The same study supports a plant photoperiod of twelve hours per day, so the VF system's LED lights were on a twelve-hour timer.

Figure 4: Each shelf in the VF is equipped with white LED lights that are lit for twelve hours each day.

As shown in Figure 3, manually adjustable flow valves and solenoid valves were used for controlling the volume of water distributed to plants in the VF. On a single shelf, water would enter a PVC pipe through an open solenoid valve and flow through the seven adjustable flow valves. Instead of watering the potted plants individually, water was distributed into each of the seven trays on the shelves of the VF. This way, the roots of the plants would absorb water from the bottom of the pot.

2.2 Controls Logic and Other Automation Details

The automatic irrigation system was controlled by an ESP32 Micro Controller because of its integrated 2.4 GHz Wi-Fi and Bluetooth capabilities. The ESP32 features a 12-bit analog-digital converter (ADC), and a 2 core CPU at 240 MHz. During regular day-to-day function, the EPS32 collected data from system sensors every ten minutes. Sensor data was uploaded to the local computer within the DC House to allow for analysis during testing.

If the soil sensors detected low moisture levels on a specific shelf, the ESP32 would open the solenoid valves to deliver water to that shelf. A flowchart detailing the controls logic governing the automated irrigation can be seen in Figure 5. A single code file was used to irrigate the entire VF, and a soil moisture threshold was programmed for each shelf to prevent plants from receiving too little or too much water from the irrigation system. Figure 6 provides a wiring schematic for the sensor and actuation system. Each sensor is connected to the ADC I/O pins, and the control pins are sent to a relay which drives the solenoid valves to be open or closed.

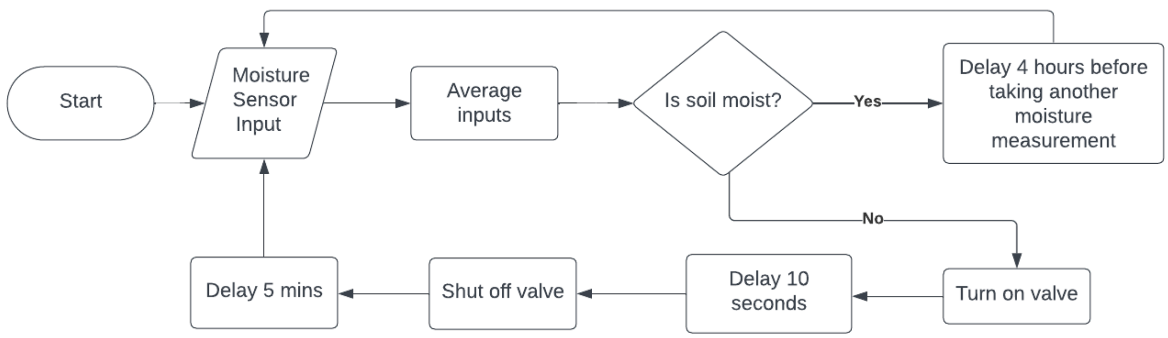

Figure 5: Flowchart indicating the logic for the automated irrigation system.

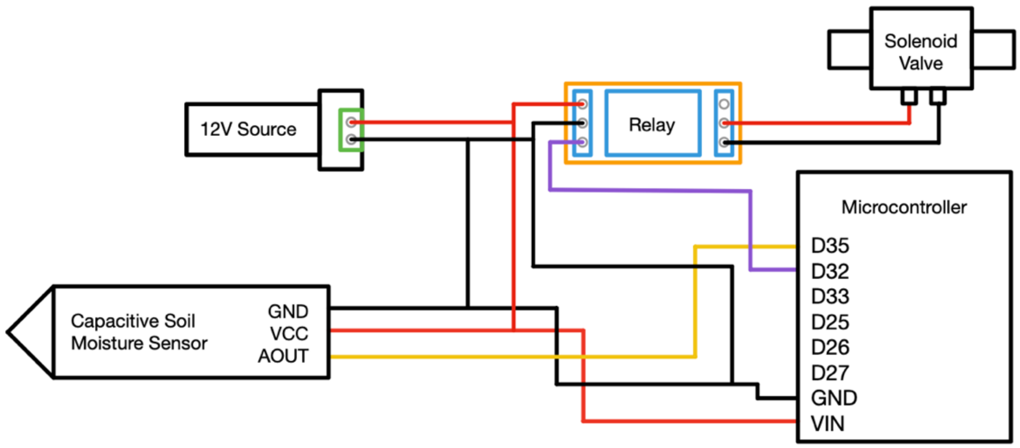

Figure 6: The soil moisture sensors embedded in the plants communicate with a microcontroller to open the solenoid valves in the VF.

2.3 Sensor Performance

Previous studies were used to calibrate the soil moisture sensors before use within the VF (Kizito *et al.,* 2008; Hrisko, 2020). The calibration procedure started with a known mass of soil in a beaker. Water was added to the beaker in increments, and the soil moisture data was recorded with the capacitive soil moisture sensors. Shown in Figure 7, this procedure allowed for the creation of a positive linear relationship between the volumetric water content in the soil and the inverse voltage collected from the soil moisture sensor. The results of this calibration were applied to data analysis to allow users to quickly see how the moisture percentage in soil changed with time.

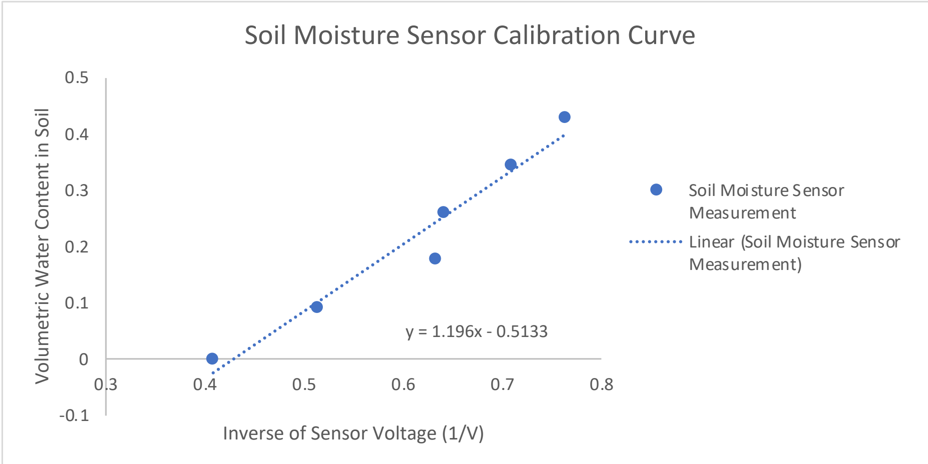

Figure 7: The soil moisture sensor calibration curve allowed for soil moisture voltage to be correlated with a general soil moisture percentage.

3. RESULTS AND DISCUSSION

Cucumber plants and potted grass seeds were hand-watered to determine minimum and maximum soil moisture sensor thresholds. The threshold results from hand-watering were applied to the automatic irrigation system. Then, the automatic irrigation system was tested to ensure the plants were watered to the appropriate moisture levels.

3.1 Irrigation Testing

Cucumber plants were watered by hand when the soil appeared to be dry, and the moisture of the soil was recorded as shown in Figure 8. Throughout testing, soil moisture was not checked to ensure plants were only watered based on the user's perception of plant soil moisture. Completion of this test provided a lower soil moisture threshold of about 39% and upper soil moisture threshold of about 49%.

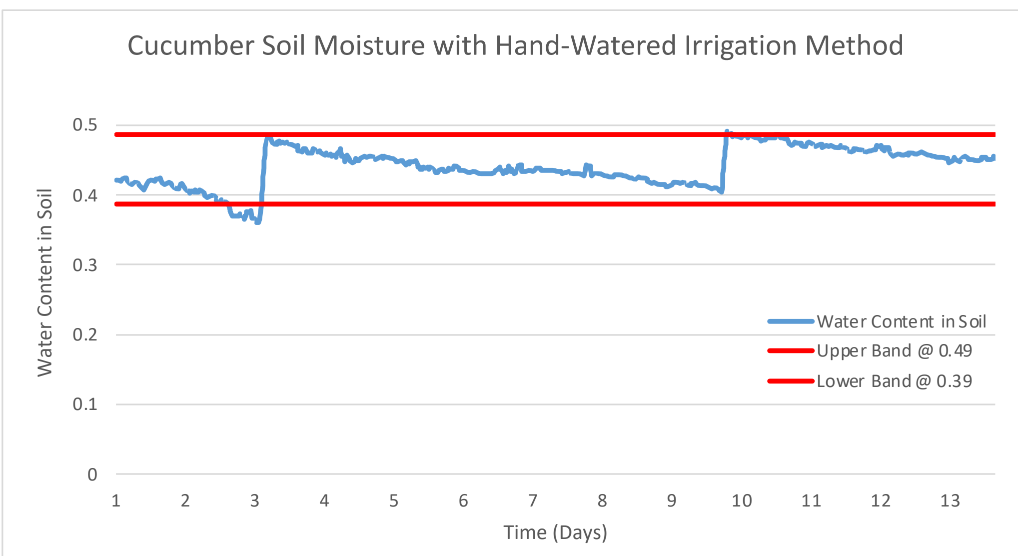

Figure 8: The blue curve shows how the soil moisture percentage in cucumber plants changed over a period of 13 days. Water was added to the system on days 3 and 10. Horizontal minimum and maximum threshold lines are shown in red at moistures of approximately 39 and 49%.

A second hand-watering procedure was conducted using grass seeds. Throughout the 32-day experimental period, small amounts of water were added to the system, and the user did not check the soil moisture throughout the period. The resulting soil moisture thresholds were about 41 and 50% as shown in Figure 9.

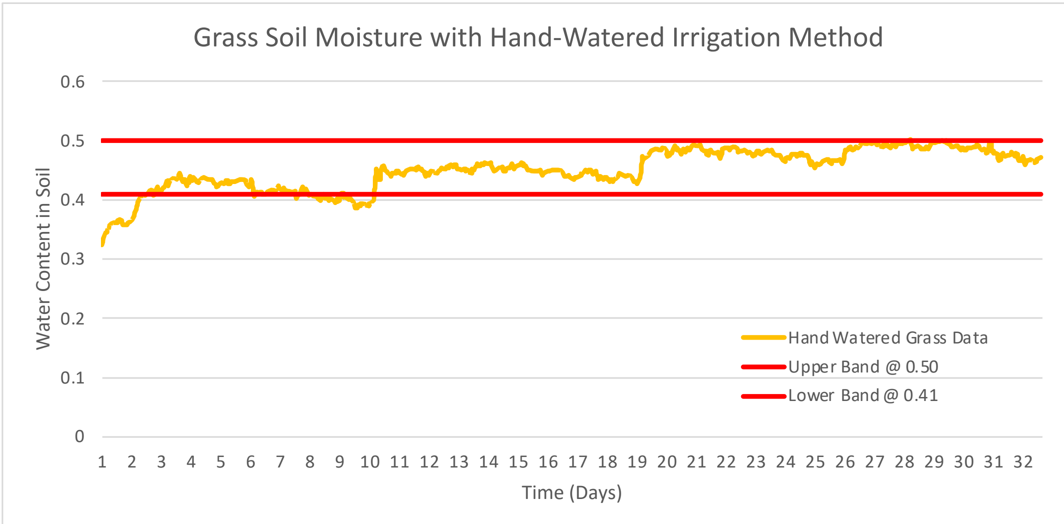

Figure 9: The yellow curve shows how the soil moisture percentage in grass seeds changed due to watering over a period of 32 days. The horizontal minimum and maximum threshold lines are shown in red at moisture levels of approximately 41 and 50%.

Results of both hand-watering experiments were used to determine the minimum soil moisture in the automatic irrigation system. Plants watered by hand reached a minimum moisture of about 39-41%, but the automatic irrigation system allowed plants to reach 39%. A lower soil moisture was chosen as a safety precaution to prevent overwatering or flooding. After completion of hand-watering experiments, the automatic irrigation system was tested for performance with cucumber and grass plants. The current data available for these two experiments are shown in Figures 10 and 11.

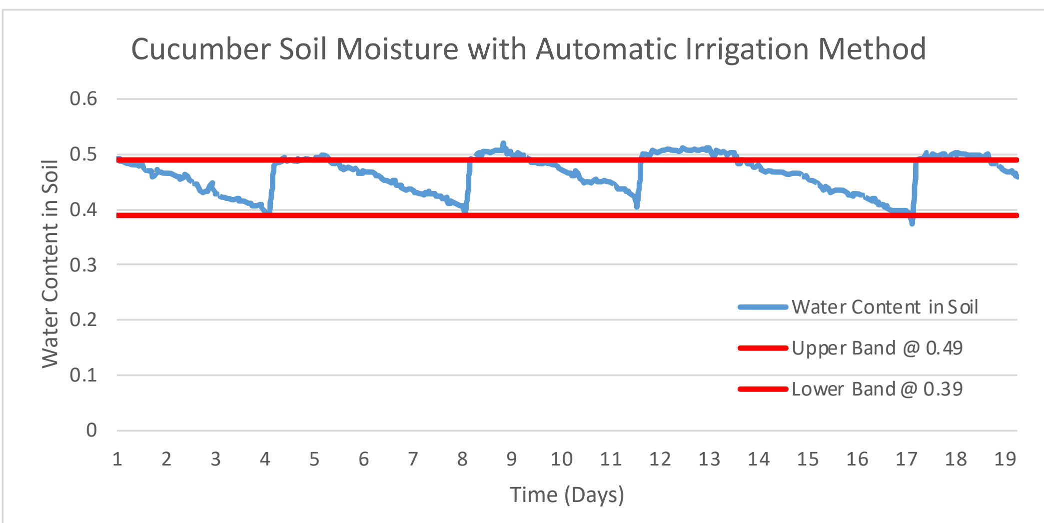

Figure 10: The blue curve shows how the soil moisture percentage in cucumber plants changed over a period of 19 days. The horizontal minimum and maximum threshold lines are shown in red at moisture levels of approximately 39 and 49%.

Figure 10 shows cucumber plant moisture steadily decreasing until reaching a moisture level of about 39%, in which the automatic irrigation system released water to increase moisture percentages. Figure 11 shows the same automatic irrigation system being tested with grass seeds.

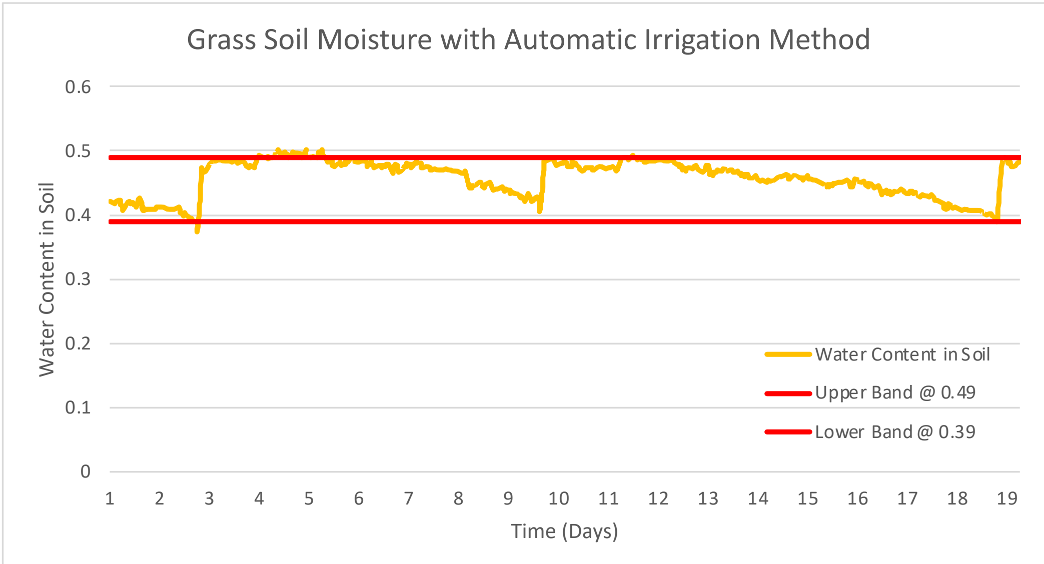

Figure 11: The yellow curve shows how the soil moisture percentage in grass plants changed over a period of 19 days. The horizontal minimum and maximum threshold lines are shown in red at moisture levels of approximately 39 and 49%.

3.2 Techno-Economic Analysis

The VF system discussed in this paper cost approximately 850.00 (US$). Given that cost, is this system realistic for at-home use? Between 2022 and 2023 in the United States, fresh fruits and vegetables have increased in price by 0.7% and 0.9%, respectively (USDA, 2024). Some families may consider sourcing their own produce in response to increasing prices. Depending on factors such as level of education or race, the median household income within the United States can range from 34,850.00 to 118,300.00 (US$) (United States Census Bureau, 2023). Given the disparities in household incomes, an at-home VF may not be realistic for some families. Instead, community VF systems could provide more benefits for a smaller cost per household.

Rather than one family taking on the entire cost of a VF system, the community VF would lower the cost per family and allow access to high-quality, low-cost produce. Furthermore, easily accessible produce is important because less than 50% of children in the United States consume enough fruit and less than 12% consume enough vegetables (Moffat *et al.,* 2021). Implementation of a VF within a community setting removes many financial barriers associated with starting a VF and increases community access to fresh produce.

3.3 Future Work

The work for this VF has numerous directions by which it could expand. The primary topics of interest are grow-lights, reflective environments, sensors, and renewable energy.

Currently, white LED lights are secured above the plants. Plant yield and quality of nutrients would significantly improve with the incorporation of a variation of lighting wavelengths that fall within the PAR spectrum as discussed in Section 2.1. One study has concluded that alternating various wavelengths in LED illumination can increase plant health (Rahman *et al.,* 2021). Furthermore, a VF system containing overhead lighting is susceptible to the loss of energy. The plants in the center of each shelf in the VF shown in Figure 4 will receive significant amounts of light for photosynthesis, but plants receive less light when positioned at the edge of each shelf. Uniform distribution of light, or photosynthetic photon flux (PPF), is desirable for optimized energy usage and plant growth (Rahman *et al.,* 2021). A reflective wall, as shown towards the back of the VF in Figure 4, can aid in PPF regulation. In future applications, the VF should be surrounded by reflective walls on all four sides to achieve even light distribution.

Furthermore, a digital temperature and humidity (DHT) sensor would be beneficial in the VF. Previous studies have strongly supported the use of a DHT sensor within agricultural applications because they support a balanced environment allowing for healthy crops and increased economic benefits (Srivastava *et al.,* 2018).

VF systems consume large amounts of energy compared to greenhouses, therefore renewable energy incorporation is critical to establishing an energy efficient system (Vatistas *et al.,* 2022). The DC Nanogrid House has capacity for solar panels, so future efforts should be devoted to ensuring the VF uses only renewable energy.

4. CONCLUSION

This study contextualized VF as it relates to industry and community applications today. An at-home application of a VF was constructed and described for repeatability. It was discovered that while self-sufficient in watering capabilities, a VF may be best suited for a community application rather than limited to use from one household. Increasing the efficiency of the system is possible in many areas including grow-lights, reflective environments, sensors, and renewable energy.

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