Design Guidelines for Aeroponic Plant Growth Systems with Varying Degrees of Complexity, Autonomy, and Performance Capability

by

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Abstract

A continuously increasing world population coupled with a rise in the average global standard of living has resulted in an expanded global economic output that is putting an unsustainable demand on many of the Earth's finite resources. Trees cannot regenerate to meet their rate of harvest. Rivers are being drained from over-pumped aquifers, and soil erosion of cropland exceeds new soil formation while the demand for food continues to rise. Increasing food production while protecting the environment and conserving natural resources exemplifies the challenges associated with sustainable development. Technological advances in recent decades have allowed for industrial-scale pesticide-free food production using techniques that are independent from environmental factors and more efficient than soil-based agriculture. However, until small-scale systems are developed in order to validate crop growth potential and procedures these solutions cannot be integrated into a new sustainable model of agricultural production. As with any maturing field, practices and guidelines need to be developed and tested for efficacy. Aeroponic systems represent a relatively new approach to growing crops; therefore, there is a paucity of published practices and guidelines that may be used to inform their design (Januszkiewicz and Jarmusz, 2018). The value of this thesis is in the guidelines that were developed in order to inform the creation of aeroponic systems with varying degrees of complexity, autonomy, and performance capability.

Acknowledgements

I would like to begin by expressing my heartfelt and profound gratitude to my wife Hope, and my sons Glenn and Teddy. Words are sincerely inadequate to describe my love and thanks to you. I would also like to express my gratitude to my entire family. To my mother, father, stepparents, grandparents, brother, sisters, in-laws, cousins, aunts, uncles, and friends. To my friend Ada I specifically owe gratitude in more than one area. I would also like to specifically thank my grandmother Mary and grandfather Danny. To my Mom for supplying me with Tums and my Dad for helping me push through the end.

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Finally, I would like to thank my God and Creator, without whom nothing past, present or future would matter.

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List of Symbols and Abbreviations

CEA- Controlled Environmental Agriculture

EC- Electrical Conductivity

ESV- Electrical Solenoid Valve

FCS- Food Contact Substances

FDA- Food and Drug Administration

HPA- High Pressure Aeroponics

LPA- Low Pressure Aeroponics

LM- Lumen

LX- Lux

PPM- Parts Per Million

PAR- Photosynthetically Active Radiation

PPF- Photosynthetic Proton Flux

PPFD- Photosynthetic Photon Flux Density

PSI- Pounds Per Square Inch

PSW-Pressure Switch

TDS- Total Dissolved Solids

VMD- Volume Median Diameter

Chapter 1 Introduction

1.1 Problem Statement

By the year 2050, it is predicted that food production must increase by 70% to feed the world's increasing population (Pulsipher, Pulsipher, and Goodwin, 2012). Meeting this demand will require either an increase in the amount of farmable land acres, or an increase in the efficiency of growing methods capable of supporting future world needs. The further practice of contemporary agricultural techniques would require a proportional increase in practices that cause documented environmental damage and potentially devastating adverse health consequences for numerous biological life forms (O'Connor, 2013).

More than one-third of the land in the United States is presently devoted to agriculture (Shahbandeh, 2019). It is fair to assume then that the most fertile farming land is currently being utilized. Increasing the number of farmable acres to meet the growing need for food would require the further consumption of finite resources. In 1977, the councils of the Royal Society of London and the U.S. National Academy of Sciences jointly stated,

Consumption is the human transformation of materials and energy. Consumption is of concern to the extent that it makes the transformed materials or energy less available for future use, or negatively impacts biophysical systems in such a way as to threaten human health, welfare, or other things people value.

The long-term damages caused by humanity's destruction and pollution of the environment are challenging to predict. Researchers have made observations and established trends that point to the irreversible damaging consequences of humanities footprint on the earth, but it appears that this is not enough to surrender present day economic opportunities.

It is therefore our responsibility to be conscious as to the possible future consequences of our actions. No other animal, or any form of life on this planet is capable of the natural devastation as seen by humanity. Considering these facts when addressing the issues of a growing human population moving forward has significant importance not just because it is our innate responsibility, but because our actions are, and will, have a direct impact on the future natural balance on this planet either for the better, or the worse.

1.2 Need for Study

An exponentially increasing world population necessitates an increase in global food output. Meeting this demand using current agricultural methods will result in the increase in known practices that are damaging to humans and the environment. An even greater risk of continuing such practices is the absence of scientific certainty regarding their safety. The importance of developing methods to mitigate these risk factors is therefore becoming increasingly important.

Aeroponics is an alternative agricultural system that uses a nutrient-rich mist to grow plants in a controlled environment without the use of soil or an aggregate media. Research has demonstrated that aeroponic systems can increase production output without the need for pesticides and a reduction in water and fertilizer input. Furthermore, plants can be grown indoors using aeroponics, mitigating weather related crop failures. Due to the promising implications of aeroponics, more research is needed to determine whether it is available system for solving the alarming problems associated with safely increasing food production.

The paucity of scientific research in soilless growing techniques offers significant opportunity for the discovery of fundamental knowledge that could be used in the future development of commercial and experimental agricultural models that could mitigate environmental damage related to agriculture.

1.3 Objective of Study

The primary objective of this study is to develop guidelines for the design of a soilless food production system in the form of aeroponics. It will also be a goal throughout the study to identify aeroponics as an environmentally friendly and economically competitive alternative to soil-based agriculture. It is intended for these guidelines to function as a tool that can be referenced and expanded upon when designing an aeroponic soilless growth system.

Another main objective of this study is to condense the available information related to the topic of interest into a digestible form in an effort to facilitate a transition towards a sustainable and environmentally friendly global agricultural model. This will be accomplished by displaying how to use the design guidelines developed in this study by using them to create a functioning prototype for both amateur and commercial applications.

1.4 Definition of Terms

Aeroponics- the process of growing plants in an air/mist environment without the use of soil or an aggregate media (Clawson et al, 2000).

Atomization-the method of breaking up liquid molecules into fine droplets

Alternative Agriculture- a systematic approach to reduce agricultural pollution, enhance sustainability, and improve the efficiency and profitably of agricultural models.

Atomization-the method of breaking up liquid molecules into fine droplets

Consumption- the human transformation of materials and energy.

Drawdown- the amount of usable water in a tank

Electrical Conductivity (EC)-an index of salt concentration that defines the total amount of salts in a solution (Tellez and Gomez-Marino, 2012).

Federal Crop Insurance Program- The FCIP is a public-private partnership between the U.S. Department of Agriculture's Risk Management Agency (RMA) and 18 private insurance companies and is currently the primary policy tool used by farmers to manage agricultural risk today. (O'Connor, 2013, p. 5)

Manifold- a pipe or chamber branching into several openings.

Pesticides- any chemical used to kill or control populations of fungi, animals, or plants (Enger and Smith, 2002, p. 319).

pH- parameter that measures the acidity or alkalinity of a solution. This value indicates the relationship between the concentration of free ions H+ and OH- present in a solution and ranges between 0 and 14 (Tellez and Gomez-Marino, 2012).

Indemnity- compensation for a loss

Pesticides- any chemical used to kill or control populations of fungi, animals, or plants (Enger and Smith, 2002, p. 319).

1.5 Assumptions

Information has been used in this study from secondary sources including books, journals, and internet sources. It is assumed that the information collected was factually presented and objective in nature. This study has also collected information from primary sources including product manufacturers and government entities. It is assumed that this information was presented accurately and without bias.

1.6 Scope and Limits

The outcome of this study is based solely on a suggested approach to be used in the design of a vertical high pressure aeroponic culture system and will offer a physical output to demonstrate these concepts.

The primary limiting factor in this experiment is time. In short, growing plants takes time, and there is limited control of this variable. Another limiting factor is the possibility of an unforeseen system failure resulting in the entire loss of a crop. This kind of failure is unlikely, but has potential to post- pone the completion of the experiment.

1.7 Procedures and Methods

The primary objective of this study is the formulation of guidelines for the design development of soilless food production systems in the form of aeroponics. The following list identifies the procedures and methods used within this approach.

-Research:

-Define Controlled Environmental Agriculture and Identify benefits, equipment, and scope of its use.

-Development:

-Concepts- Work to develop a concept using the equipment

-Fabrication- Construct and document fabrication methods taken in the development of the system.

-Communication:

-Analyze- Demonstrate whether or not the steps used in the process were successful.

1.8 Anticipated Outcome

The conclusion of this study has several anticipated outcomes: 1. An understanding and development of guidelines to the design of a vertical and scalable high-pressure aeroponic culture system. 2. A fully functional prototype will be produced and tested in order to verify the approach in this study. 3. Another designer should be able to use and evaluate these guidelines and apply the information to their own design.

Chapter 2 Literature Review

2.1 Population Growth and Resource Scarcity

A projection published in 2005 by the United Nations estimates that the world population will reach 9.7 billion by 2050 (Gerland et. al., 2014). This level of growth would require a 70% increase in global food output (Pulsipher, Pulsipher and Goodwin, 2012, p. 24). In 2002 the U.S. National Academy of Sciences published a study conducted by a team of scientists led by Mathis Wackernagel. Their study concluded that humanity's collective demand upon Earth's resource base first exceeded the planets regenerative capacity around the year 1980.

Wackernagel and his team further estimated that by 1999 this capacity was exceeded by 20% (Brown, 2003). Nearly half of a century earlier, President John F. Kennedy addressed the National Academy of Sciences. In his speech he proposed "A worldwide program to protect land and water, forests and wildlife, to combat exhaustion and erosion, to stop the contamination of water and air by industrial as well as nuclear pollution, and to provide for the steady renewal and expansion of the natural bases of life." He later solicited the help of the academy in "Meeting a problem of universal concern: the supply of food to the multiplying mouths of our multiplying world." Figure 1 illustrates the current exponential increase in global population growth.

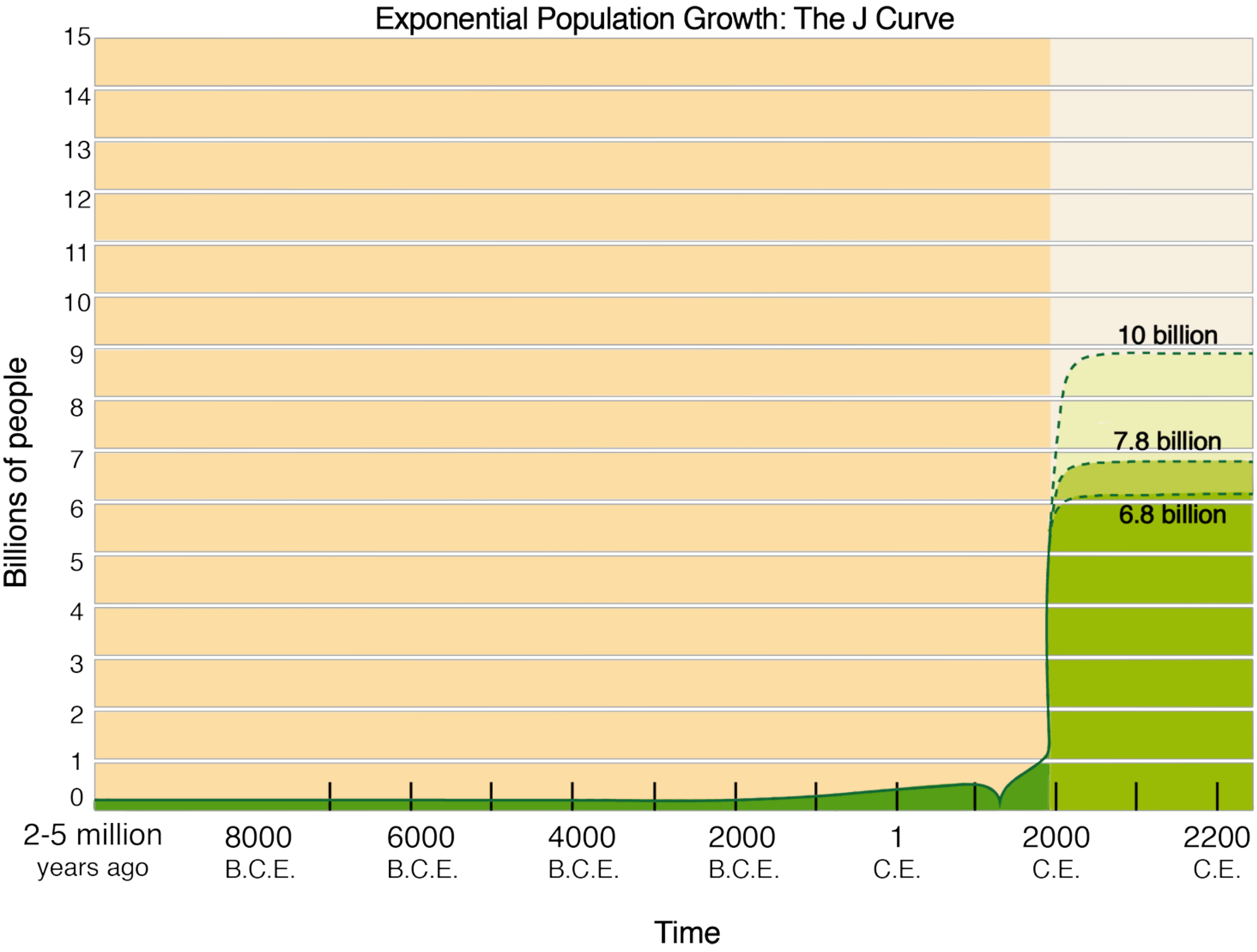

Figure 1: Projected World Population Growth (Pulsipher, Pulsipher, and Goodwin, 2012).

The modernized form of soil-based agriculture exhibited in countries like the United States is currently reliant on chemical fertilizer, pesticides, and machines. Upon implementation, these systems result in soaring production and massive profit for those that can afford the investment. However, modern soil- based agriculture is reliant on finite resources and will be unable to reliably support the growing population in a in a safe or sustainable way. (Brown, 2003) addresses these issues stating, “Eroding soils, deteriorating rangelands, collapsing fisheries, falling water tables, and rising temperatures are converging to make it more difficult to expand food production fast enough to keep up with demand.”

2.2 Modern Food Security

Today, farmers are becoming increasingly reliant on the Federal Crop Insurance Program (FCIP) in the United States for subsidies meant to manage weather related risks. Unfortunately, federal crop insurance does not incentivize risk-mitigating practices, and rewards risky production methods that result in crop loss and negative environmental consequences (O’Connor, 2013).

Congress created the FCIP in 1938 in response to the enormous losses faced by farmers during the dust bowl. The FCIP is a public-private partnership between the U.S. Department of Agriculture’s Risk Management Agency (RMA) and 18 private insurance companies and is currently the primary policy tool used by farmers to manage agricultural risk today. In fact, by 2012 the FCIP covered roughly 70 percent of the total cropland in the United States (O’Connor, 2013, p. 5).

Insurance premium rates are non-competitively set by the RMA, resulting in very few market signals that private insurance companies can utilize for incentivizing farmers to make risk-reducing choices. This stands in contrast to private home insurance companies for example, that may offer discounts to policyholders with homes equipped with alarm systems. In fact, the FCIP encourages farmers to make riskier choices, such as planting crops in places that are not well suited for their production, by offering them disproportionately low premium rates. Growing crops in these areas also results in increased chemical inputs in the form of pesticides and fertilizers to compensate for the poor soil quality and can increase in erosion, leading to other negative environmental impacts (O’Connor, 2013, p. 7).

2.3 Weather Dependency

In 2012, more than 80% of agricultural lands in the United States experienced drought, accounting for nearly $13 billion in losses and total indemnities paid out by the FCIP for the year reaching a record breaking $17.3 billion (O’Connor, 2013). Irrigation supply failures during this period was also a large contributor to this record-breaking year, accounting for $14.7 million in indemnity payments (O’Connor, 2013, p. 11).

The unpredictable and uncontrollable biotic and abiotic factors associated with soil based food security are damaging on both a micro and macro scale. For example, pest and weather related damages has the Florida Citrus industry on the brink of collapse. The University of Florida estimates that an invasive insect that carries the bacterium that causes greening has resulted in industry wide losses of 7.8 billion dollars and more than 7,800 jobs between 2006 and 2014 (Tribune Wire Reports, 2015). There is no known cure for this disease and volatile weather has only exacerbated the problem. In 2017, Hurricane Irma swept through Florida. The Florida Department of Agriculture estimates that this storm caused approximately 1 billion dollars in agricultural damages in a year that saw the smallest citrus crop recorded since 1941 (Layden, 2018).

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2.4 Pesticides

Pesticides are defined as any chemical used to kill or control populations of fungi, animals, or plants (Enger and Smith, 2002, p. 319). It is estimated that approximately 35% of crops in the United States are lost to pests annually, correlating to a yearly loss of $18.2 billion dollars (Enger and Smith, 2002, p. 329). Although pesticides keep this loss at a minimum, they also cause great collateral damage, much of which is still poorly understood. For example Figure 2 illustrates the "dead zones" in the Gulf of Mexico discovered by scientists in the 1970s that appeared near the mouths of major river systems. These dead zones are so polluted by chemicals washing down from farms that they support almost no life whatsoever (Pulsipher, Pulsipher and Goodwin, 2012, p. 68). An even more direct source of damage is the result of most pesticides being what is called un-specific, meaning that they kill many organisms that they are not directly targeting (Enger and Smith, 2002, p. 319).

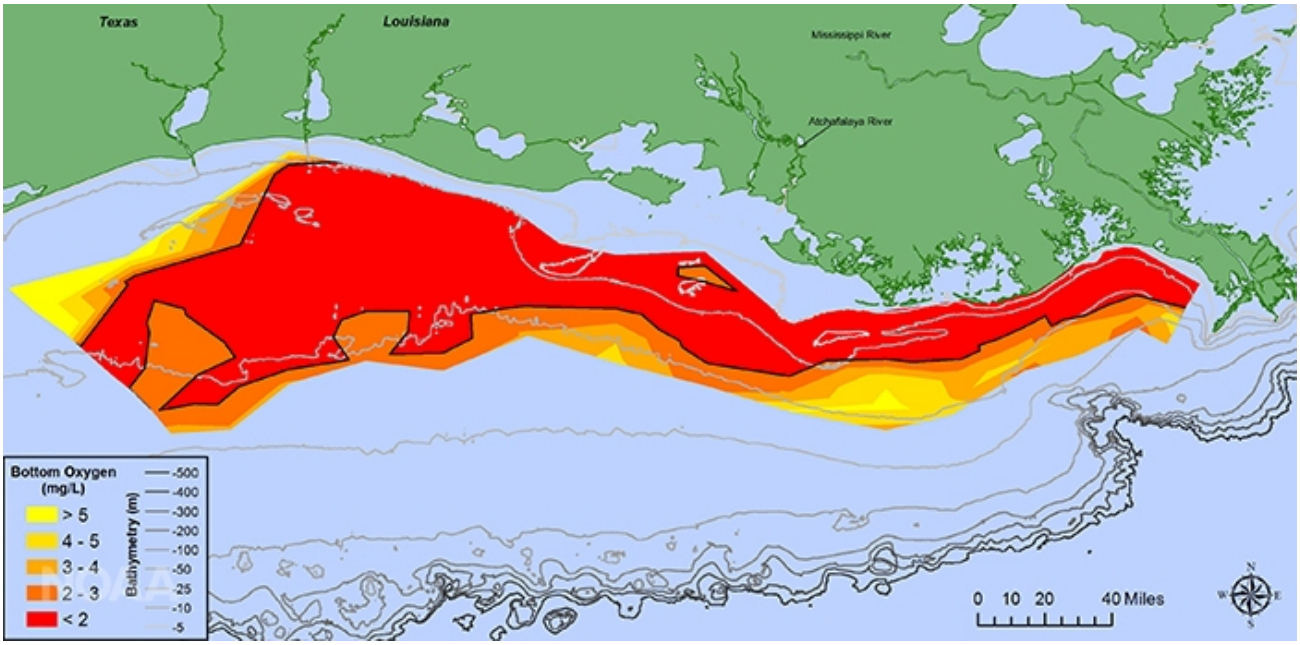


Figure 2: Dead Zone Growth in Gulf of Mexico (National Oceanic and Atmospheric Administration 2017).

2.5 Alternative Agriculture

Because of both present and future issues posed by traditional agricultural growing practices, more attention is being paid to alternative food production methods (Shrouf, 2017). Alternative agriculture is a broad term encompassing all nontraditional agricultural methods including sustainable agriculture, organic agriculture, and alternative methods for raising crops. Both present and future issues posed by current agricultural practices has resulted in the development of alternative practices that are both safe and economically viable.

2.6 Controlled Environmental Agriculture (CEA)

Controlled Environmental Agriculture (CEA) is a form of alternative agriculture that requires sealed conditions where it is possible to fully control such cardinal aspects of cultivation including exposure levels and time, temperature, humidity, nutrient levels, growing medium and air composition. Technological advances in recent decades have enabled the full automation of CEA, allowing for truly industrial scale horticultural production that is more efficient and independent from environmental factors than traditional farming. Figure 3 displays a potential setup for an automated environmental system. The rising number of commercial successes demonstrates that CEA implementation is a key component in soilless horticultural production on an industrial scale (Januszkiewicz and Jarmuesz, 2018).

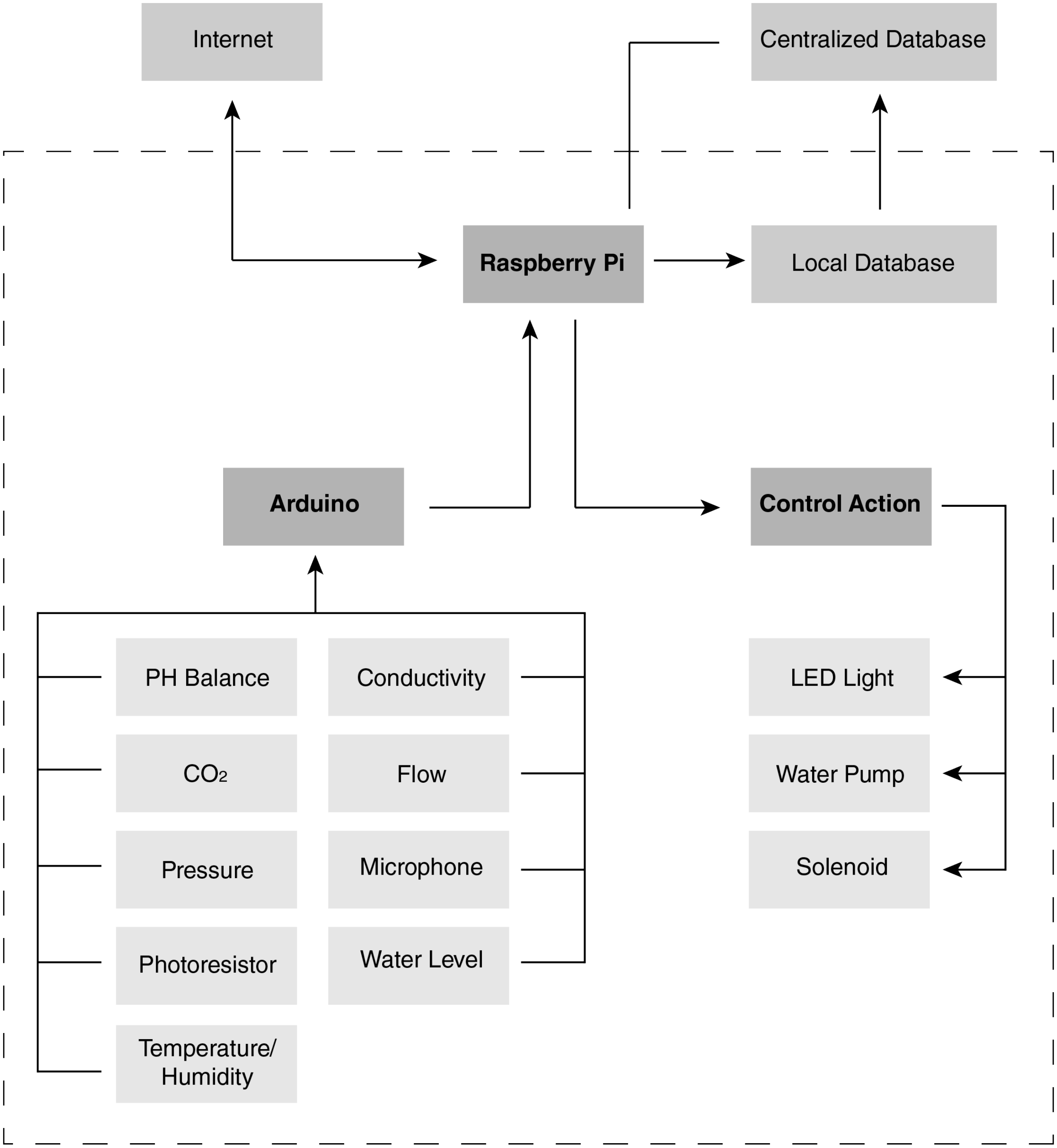


Figure 3: CEA Environmental Monitoring Structure Example.

2.7 Water Quality

Even the best water supplies contain elements and substances that can affect plant growth either positively or negatively. Depending on what may be in the water supply, there may be a need for some form of water treatment.

Treatment may be as easy and inexpensive as acidifying the water to remove bicarbonates (HCO3) and carbonates (CO3). It can be as expensive and complex as requiring reverse osmosis (Jones, 2005). It is advised to submit water samples to an analytical lab for testing before use.

The pH scale is a means of measuring how acidic or alkaline a solution is, and it is measured on a scale of 1-14. A solution with a pH of 0-7 is acidic, and a solution with a pH of 7-14 is alkaline, or basic. When mixing a nutrient solution for agricultural use, it may be necessary to adjust the pH by adding a basic or acidic substance. It is also important to monitor the pH of the nutrient solution over time as changes may occur. This is especially important in a system where the nutrient solution is recycled after root exposure. Among the most common methods of measuring the level of dissolved nutrients in a solution is measuring a solution’s electrical conductivity (EC). Optimal EC varies by crop, and is an important factor to monitor in a nutrient solution for agricultural purposes (Jones, 2005).

2.8 Nutrient Solution

The mismanagement or flawed formulation of the nutrient solution can be the direct cause of poor yields, scraggly plants, and high reagent costs (Gerber, 1985; Jacoby, 1995). The proper management and formulation of the nutrient solution is critical in order to establish a successful growing operation. Although an important consideration, these criteria will not be discussed in detail.

As there is no perfectly prescribed recipe that can be given to growers, it is up to the grower to develop their own scheme of management based on experimentation and observations made that best fit their own system environment and plant growing conditions and needs (Jones, 2005, p. 90). As it relates to the designer, the dispensing method of the nutrient solution must be integrated into the operational plan of the system

2.9 Supplemental Lighting

A lumen (lm) is a unit that measures the amount of light that is visible to the human eye emitted by a source per second. Lux (lx) is a unit measuring the number of lumens per square meter. 100 lumens spread over 1m2 has an illuminance of 100 lx. The same 100 lumens spread over 10m2 has an illuminance of 10 lx. A value measured in foot-candles is a conversion from lumens per square meter into lumens per square feet. These measurements are only relevant for how humans perceive light and should therefore not be used when selecting supplemental lighting for plant growth (Nielsen, 2017).

Photosynthetically Active Radiation (PAR) includes the wavelengths of light within the visible range of 400 to 700nm. Photons within this range are critical for photosynthesis (Szewczyk, 2018). Photosynthetic Proton Flux (PPF) measures the amount of PAR produced by a source per second and is expressed in micromoles per second (Nielson 2017). PPF is an important metric for calculating the efficiency that a lighting system can create PAR but does not represent how much light actually reaches the plants below (Szewczyk, 2018). Photosynthetic Photon Flux Density (PPFD) is a spot number of PAR that actually arrives to the plant. PPFD is measured in micromoles per second per meter squared (μmol/s/m2). This value is perhaps the most important variable to be aware of when selecting lights. Nielson (2017) explains,

> If you want to find out the true light intensity of a lamp over a designated growing area (eg. 4’ x 4’), it is important that the average of several PPFD measurements at a defined height are taken. Lighting companies that only publish the PPFD at the center-point of a coverage area grossly overestimate the true light intensity of a fixture.

This is because most lights are brightest directly below the source with a decreasing intensity moving away from the center as illustrated in Figure 4. Figure 5 goes on to show how multiple grids can be used to determine the necessary number of lights needed.

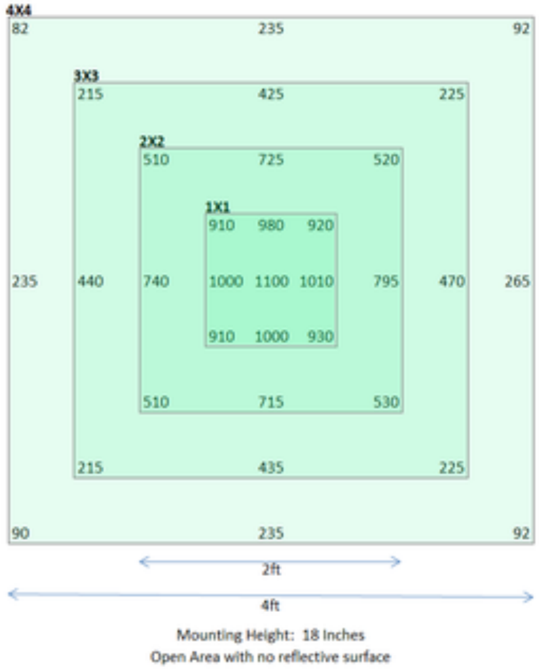


Figure 4: Example PPFD Chart 1 (Horticulture Lighting Group, 2019)

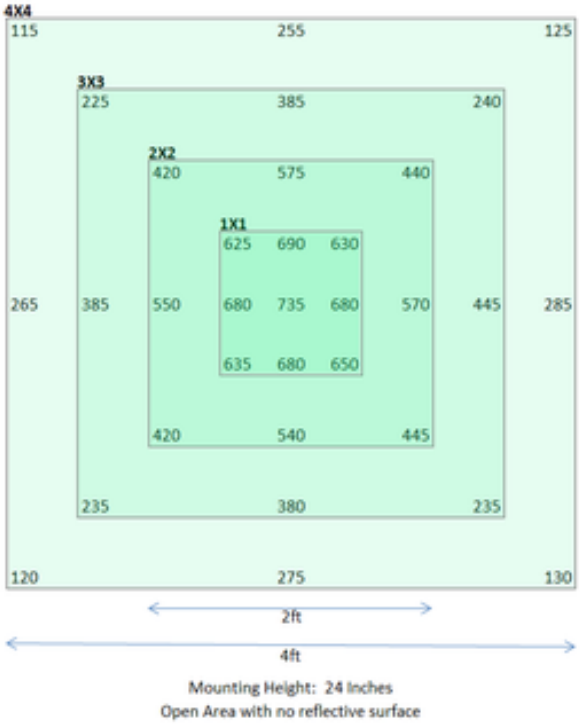


Figure 5: Example PPFD Chart 2 (Horticulture Lighting Group, 2019)

2.10 Ventilation

When designing a controlled growing environment, proper ventilation is very important. Most inline fans are rated in cubic feet per minute (CFM) in North America and cubic meters per hour (m3hr) (Just For Growers, 2019). An exhaust fan selected for a given grow area should ideally be able to exchange the air in the room once every three minutes (Hyland, 2019). Determining the power of ventilation fan capable of this level of exchange is done by calculating the volume of the grow space and dividing this value by three. This formula is given in Figure 6.

$$\boxed{(\underset{\substack{\text{Room Length}\\ \text{(in feet)}}}{L} \times \underset{\substack{\text{Room Width}\\ \text{(in feet)}}}{W} \times \underset{\substack{\text{Room Height}\\ \text{(in feet)}}}{H}) / \underset{\substack{\text{Time in Minutes}\\ \text{Needed to}\\ \text{Replace Air}}}{3} = \underset{\substack{\text{Minimum CFM}\\ \text{Requirement}}}{X}}$$

Figure 6: Formula for Determining Necessary Fan CFM.

2.11 Vertical Farming

In 1964 Australian engineer and inventor Othmar Ruthner unveiled his concept of a 41-meter-high greenhouse tower at the Vienna International Garden Show. Just three years later, his greenhouse tower gained the interest from the United Nations Food and Agriculture Organization for its potential utilization in hunger vulnerable regions. Ruthner’s high-rise greenhouse is arguably the first example of the contemporary meaning of vertical farming (Januszkiewicz and Jarmusz, 2018). Vertical farms come in shapes and sizes varying from simple two level or wall mounted systems to complete warehouses several stories tall. All vertical farms use one of three techniques to provide the plant with nutrients without the use of soil- hydroponics, aquaponics, and aeroponics.

2.12 Vertical Farming Methods

Hydroponics is the current dominating technique in vertical farming. The roots of plants being grown with this technique are completely submerged in a water based nutrient solution. The solution is constantly circulating and closely monitored to ensure plants get proper nutrient supplementation.

Aquaponics is an expanded version of hydroponics. This technique adds fish to the ecosystem with the plants. Fish are raised in an indoor pond, and their nutrient-rich waste water is diverted to the plant bed. Once the plants filter the water, it is then pumped back in to the pond purified of the original waste. Aquaponics is most commonly found in small scale operations, because it is not enough of an economic benefit for large scale farms to add an aquaponics component to a hydroponic system.

2.13 Aeroponics

NASA has paid special attention to a growing technique called “aeroponics.” As defined by NASA, “Aeroponics is the process of growing plants in an air/mist environment without the use of soil or an aggregate media (Clawson et al, 2000, p. 88). Compared with traditional terrestrial farming, this growing system uses 90% less water, a 60% reduction in nutrient use, and can produce a year-round continual harvest. Aeroponics has also shown increases in crop yields by up to 75% while eliminating the use of pesticides (Gopinath, Vethamoni, and Gomathi, 2017, p.89). These benefits result largely from the greater control of growth parameters provided by this system that can be accomplished in an entirely indoor climatized environment. This allows for protection from environmental elements such as weather and pests that can cause unpredictable crop losses seen in traditional growing practices (Clawson et al, 2000, p. 88).

Disease transmission is further limited because of minimal plant to plant contact. Moreover, if one plant were to get infected it can quickly be removed from the system without infecting other plants or disrupting the system. Other disease mitigating factors are a result of being able to provide sterile incoming spray for every cycle, and the ease of cleaning the growing chamber without disrupting the grow cycle (Clawson et al, 2000)

Aeroponics occurred only in nature until 1922, when B.T. Barker succeeded in growing apple trees with a spray. F.W. Went then went on to coin the term aeroponics in 1957 after successfully growing coffee and tomato plants with their roots suspended in the air using a nutrient enhanced mist (Clawson,et al, 2000). Since its development, aeroponics has contributed to the advances in many areas of study and shows great promise as an alternative to current agricultural models.

In 1989, Colorado Power Partners performed a study on the number of tomato crop harvests that could be achieved in an aeroponic growing system as compared to traditional terrestrial models. They determined that when starting their tomato crop from seeds, the first fruit matures on day 68 and the plant further produces harvestable fruits until day 105. Researchers went on to discover that cuttings taken from mature tomato plants of 68 days of age or older could be used as a starter crop in an aeroponic system. These aeroponically grown tomato plants had comparable yields and biomass production compared to the terrestrially grown tomatoes, but allowed for 7.7 crop turn-arounds per year compared to 3.5 turn-arounds in a terrestrial system (Clawson et al, 2000).

One reason for the accelerated growth of plants in an aeroponic system is a result of the exposure of the entire root system of the plant to ambient air (Gopinath, Vethamoni, and Gomathi, 2017, p. 840). In fact, oxygen uptake is increased in aeroponic systems resulting from forced convection caused by open spaces in and around the root systems (Clawson et al, 2000). This not only accelerates root growth, but provides another avenue for growth optimization unavailable in other growing methods. For example, Yurgaleuvitch and James determined that root zone CO2 concentrations between 0.5-5% significantly stimulated seedling growth, while those of 25-50% significantly inhibited growth (Clawson et al, 2000). Information of this nature can be used in the future development of commercially viable aeroponic systems for the optimization of plant growth.

There are however several concerns regarding aeroponics that if ignored can result in decreased productivity or even the loss of entire harvests. For example, Tibbits used a vaporizer in his aeroponic experiments to deliver a constant mist to the stems and roots of his plants. He went on to conclude that even a brief system failure of his aeroponic system would result in the total loss of plant life. This is because plants in a continuous misting system become dependent on the constant flow and become highly sensitive to interruption.

Continuous flow models can also contribute to fungal and bacterial growth on or near the plants (Clawson et al, 2000). However, this issue can be greatly mitigated by using what is known as interval/duration techniques. These techniques produce healthier roots compared to continuous misting techniques that thrive longer on lower moisture levels and are more resistant to an interruption of the misting cycle (Clawson et al, 2000).

Recent technological and scientific advances in controlled environmental agriculture have made growing crops in a sustainable and environmentally friendly way economically competitive with soil-grown crops. However, information on designing CEA systems using techniques like aeroponics is complicated and disjointed. The lack in adequate guidelines for the design of these systems could be prolonging the migration away from unstainable and environmentally damaging agricultural practices.

Chapter 3 Design Guideline Development

3.1 Purpose of the Formation of Design Guidelines

The growth of controlled environment agriculture that utilizes soilless growing techniques such as aeroponics is dependent on the development of production systems that are competitive with open field agriculture in terms of costs and returns (Clawson et al, 2000). The flood of information regarding the above-mentioned techniques is often lacking in a scientific basis that leads to confusion and poor decision making on the part of users. As a result, farmers are more likely to engage in unsustainable and damaging growth methods (Jones, 2005). Clear instruction in the necessary elements of the design and workings of soilless culture systems is absolutely essential. The goal of this thesis specifically is to generate guidelines for an aeroponic culture system for the use of farmers, researchers and hobbyists alike that are clear and user friendly.

3.2 Aeroponic Design Guideline Flowchart

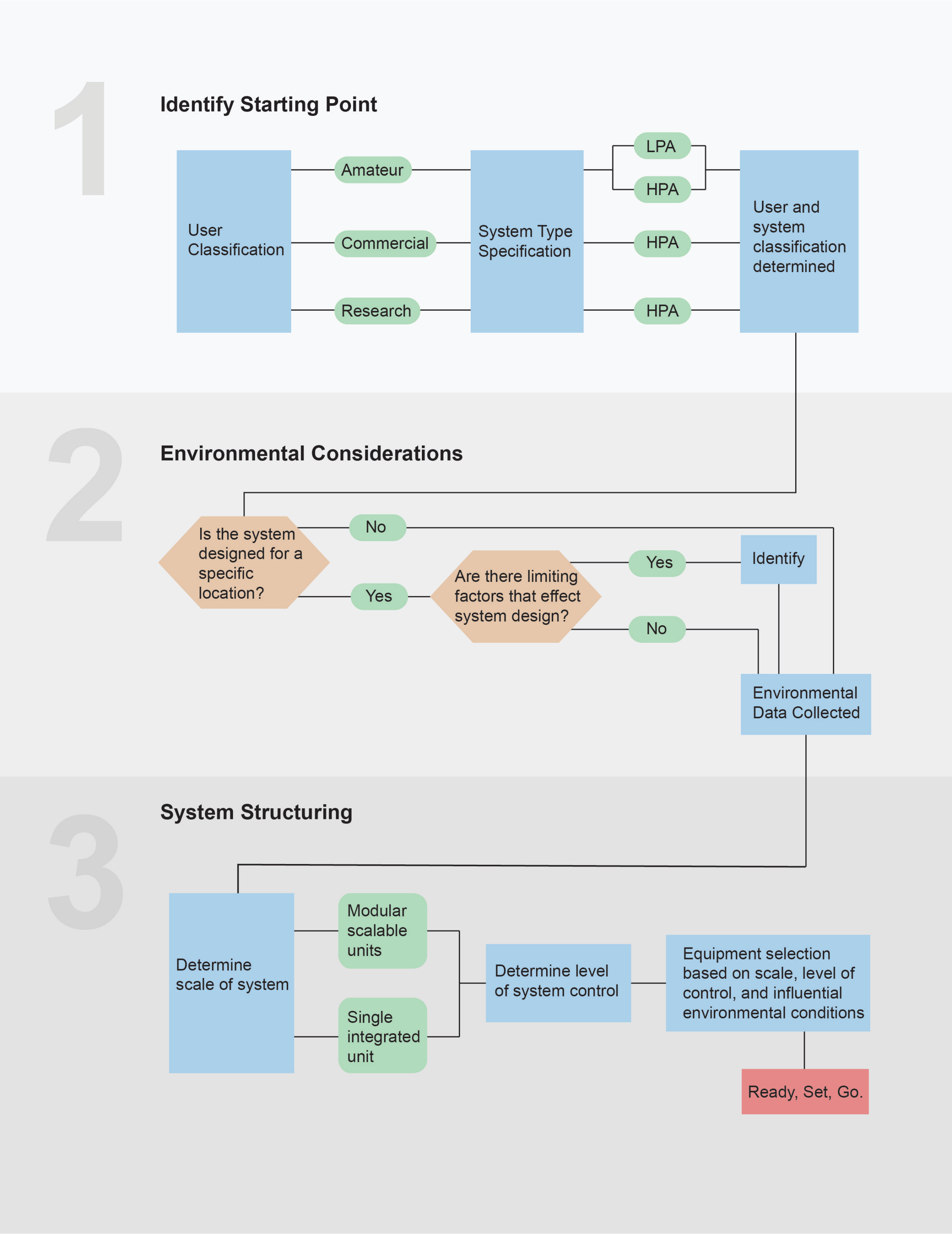


Figure 7: Three Phase Design Guideline Flowchart.

3.2.1 Phase 1: Identify Starting Point

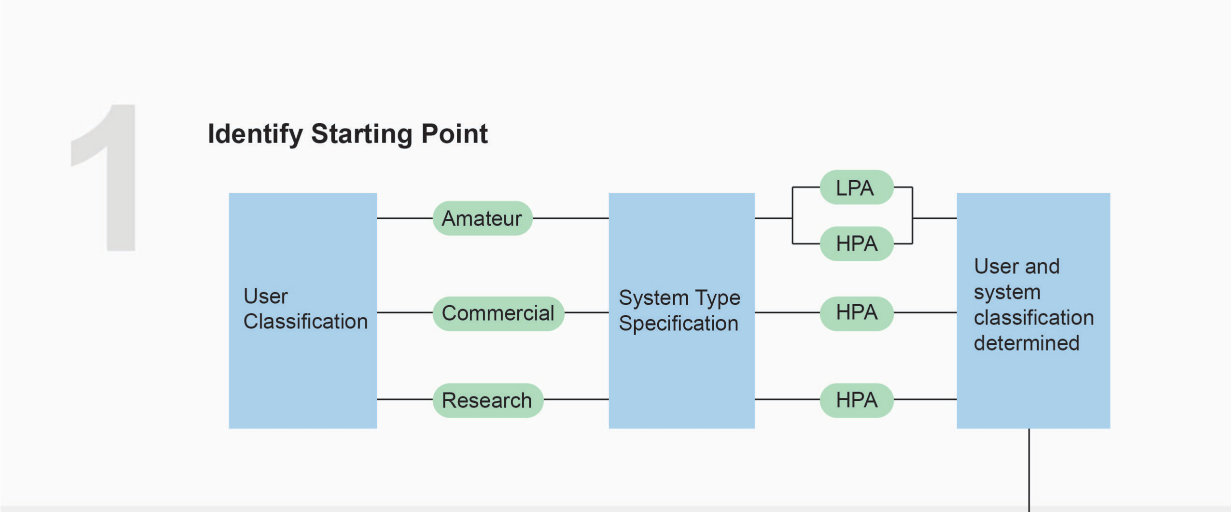


Figure 8: Phase 1 of Design Guidelines.

The first step of these guidelines requires the designer to identify for what purpose the system is intended to be used. Identifying this purpose will determine whether the system design should be high or low pressure.

An aeroponics system used in a commercial or research setting requires a combination of control and efficiency that only an HPA system can offer. If a system is intended for an amateur grower, the system classification choice is up to the designer based on intended market.

3.2.2 Phase Two: Environmental Considerations

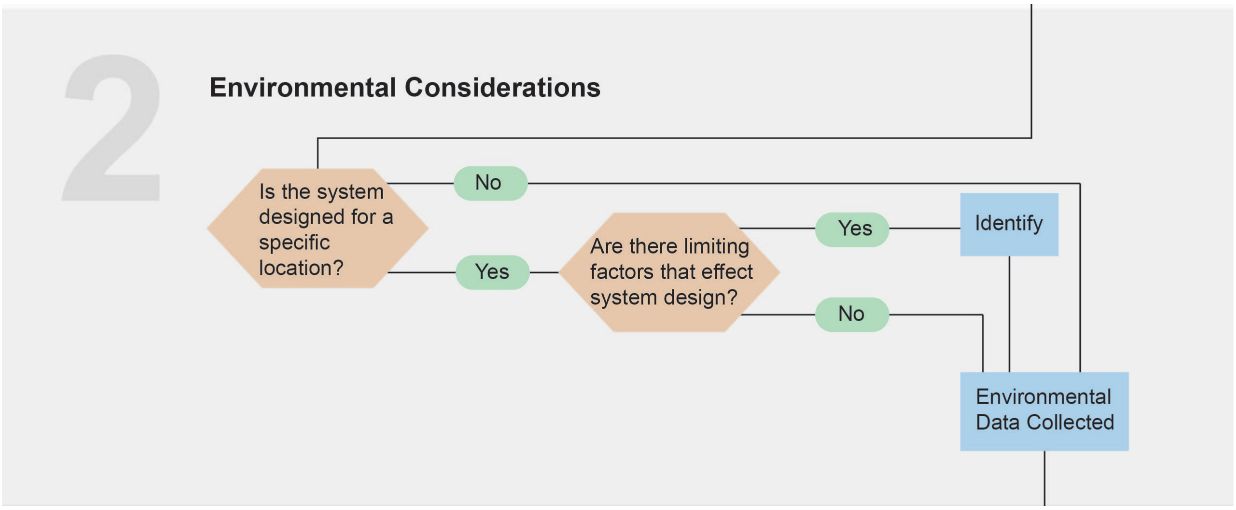


Figure 9: Phase 2 of Design Guidelines.

After the user and system classification has been determined, it is important to consider the intended environment in which the system will operate. This is because there are certain aspects of the system design that should be considered based on the level of environmental control in which the system resides. For example, a system that is designed to operate indoors may or may not require supplemental lighting. If supplemental lighting is required, it could then be integrated into the system design itself or be independent of the system completely.

3.2.3 Phase 3: System Structuring

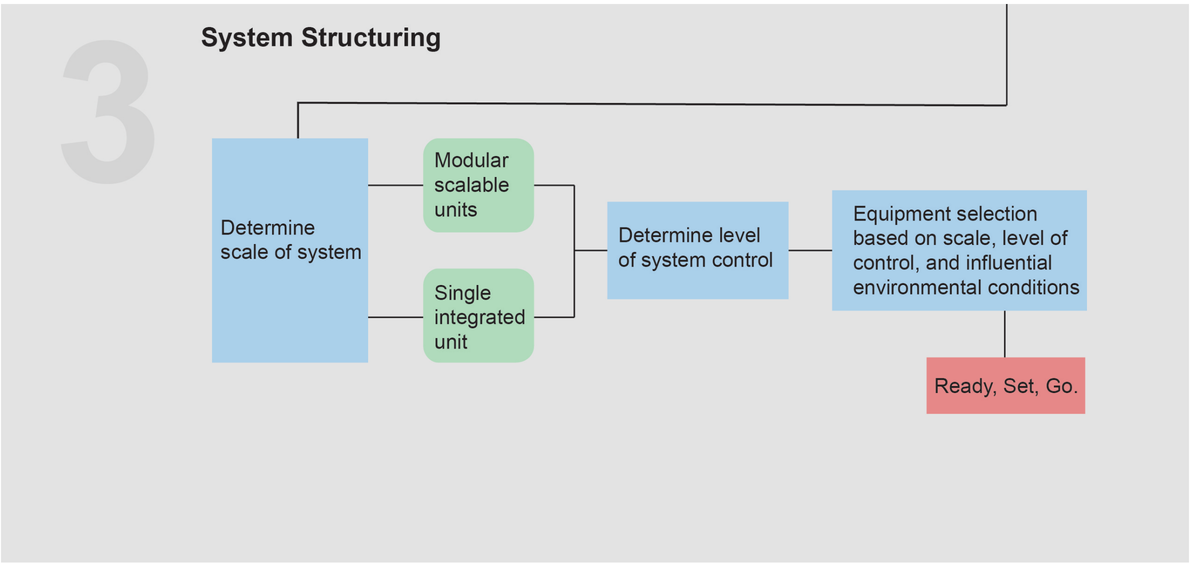


Figure 10: Phase 3 of Design Guidelines.

Upon reaching phase three of the flow chart, the designer will have identified the intended user, system classification and influencing environmental factors that will impact the system design. Step three begins with determining the scale of the system design. This may or may not be influenced by the information gathered in the first and second phases of the flow chart. The design decision of reaching the desired system scale through a modular or fixed system design is then made. At this point the designer must determine the desired level of system control for the system. This choice may or may not also be influenced by the information gathered in the first two phases of the flow chart. After finishing step three of the flow chart, the designer should have the information needed to begin equipment selection.

3.3 Equipment Selection Guidelines Introduction

Navigating through the flowchart in section 3.2 will result in the identification of three key data points that will serve as the primary guidelines for equipment selection that are as follows:

Phase 1: System Type Identification- HPA/LPA

Phase 2: Environmental Considerations and Restrictions

Phase 3: System Structure/Control

The following equipment identification and selection guidelines are divided into fundamental and supplemental equipment categories. The fundamental equipment category includes the principal components that are critical for functional system operation. The fundamental equipment necessary for a system varies between high and low pressure aeroponics. It is for this reason that the next section contains fundamental equipment identification and selection guidelines for both a high and low-pressure system. The supplemental equipment category primarily includes the equipment that may or may not be incorporated into a system design based on the information gathered from the flow chart. The equipment and technology identified in this category could be applied to either system type and therefore do not have independent supplemental equipment identification sections.

3.4 LPA Overview

A low-pressure aeroponics system uses low-pressure pumps to deliver nutrient solution via sprayer nozzles or ultrasonic transducers. In most LPA systems the plant roots are suspended above a reservoir of nutrient solution or inside of a channel connected to a reservoir. Although LPA systems are less expensive to build and easier to maintain than High-Pressure systems, they are not suitable for commercial applications. The nozzles used in LPA systems produce larger droplets that reduce the amount of available oxygen to the plant root systems. Low-Pressure Aeroponics is suitable for amateur growers or demonstrating the principles of aeroponics.

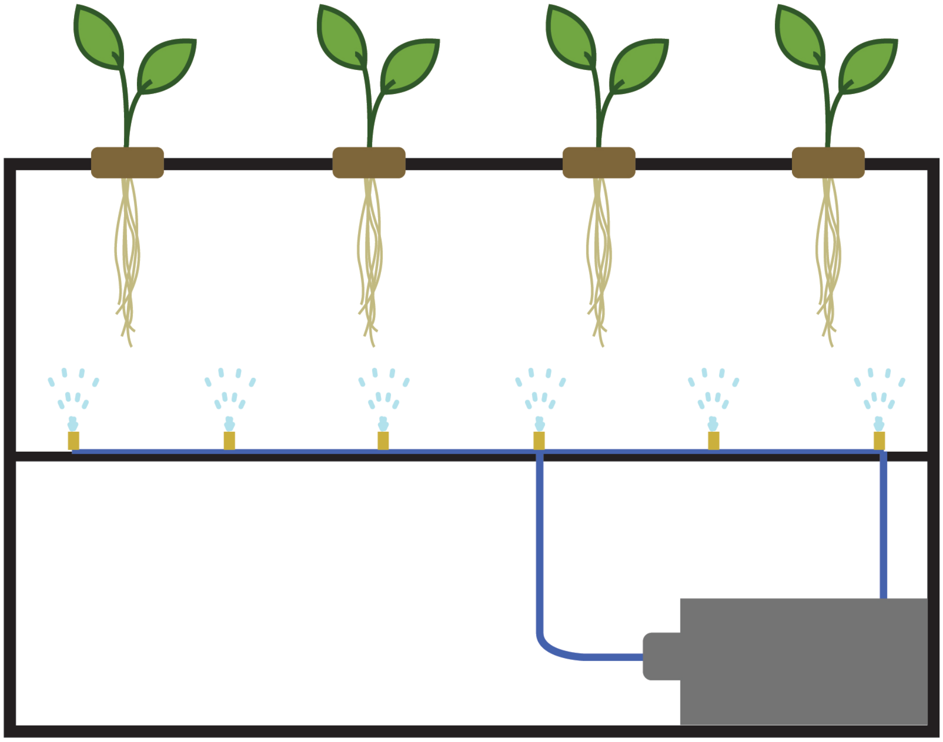


Figure 11: LPA Basic System Illustration

3.5 LPA Fundamental Equipment Identification

3.5.1 Nutrient Reservoir

In most LPA systems the reservoir both contains the nutrient solution and functions as the grow chamber. A LPA system designed in this way has the advantage of being self-contained and highly portable. The size of the reservoir must be large enough to contain enough nutrient solution for the submersible pump to function properly with enough left-over space to allow for root growth. A disadvantage that should be considered for such a self-contained system is that the roots of maturing plants will eventually reach and become submerged in the nutrient solution below. If a separate growth chamber and nutrient reservoir is desired, it is important that the pump chosen for the system has enough power to supply the mister heads with adequate pressure to function.

3.5.2 Submersible Fountain/Pond Pump

In LPA systems, costly specialized pumps are not required. Submersible fountain or pond pumps will appropriately serve the technical function of these systems. Unlike pumps used in high-pressure systems, these pumps are not rated by pressure. Instead, they are measured by Max Flow Rate in gallons per hour (GPH) or Liters per hour (LPH) with a maximum lift height as seen in Figure 12.

Figure 12: Low Pressure Aquarium Pump Label.

The type and number of desired misting heads in a LPA design is the primary influencing factor that should be considered when determining the pump strength needed as each additional mister results in a decrease in system pressure.

3.5.3 Mister/Sprinkler Heads

The misting heads for LPA systems are cheaper and easier to maintain than those used in HPA systems. There are multiple mister head options that can be used in LPA system designs. The number and placement of mister heads will vary depending on the design of the growth chamber. The mister head location in any growth chamber should result in an overlapping spray directed towards what will be the root zone of the growth chamber.

3.5.4 Growth Chamber

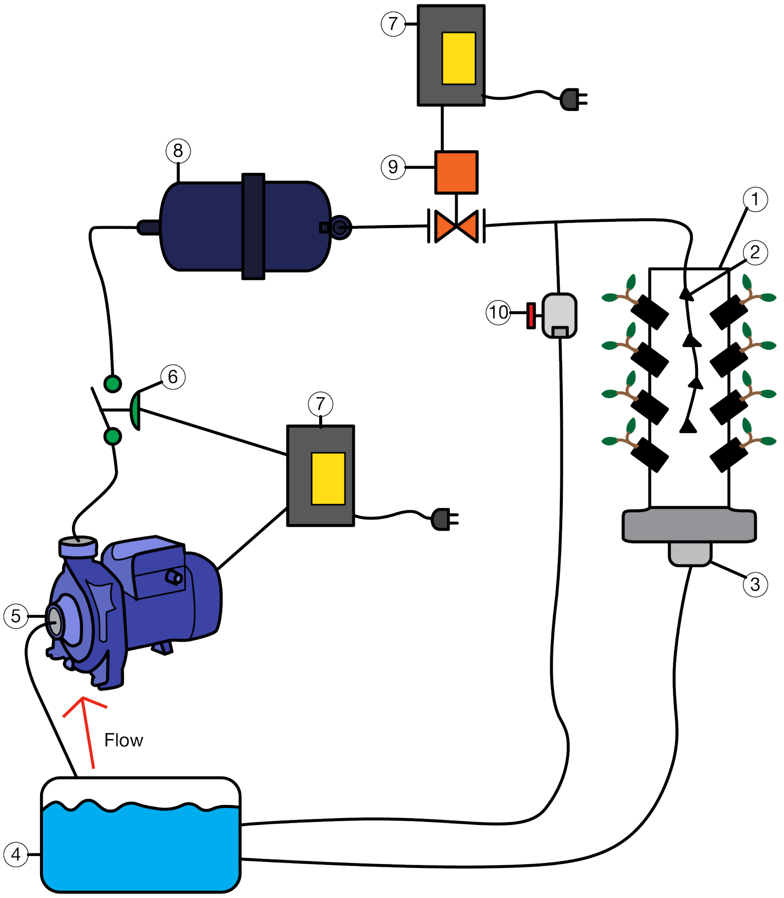
There are certain guidelines that should be followed if designing a LPA system with a growth chamber separate from the nutrient reservoir. Firstly, the placement of the growth chamber in relation to the nutrient reservoir should allow for the excess nutrient solution not absorbed by the plant roots to drain back into the reservoir. Transferring the nutrient solution from the reservoir to the growth chamber will require some design consideration.

3.5.5 Nutrient Solution Delivery

The method of transferring the nutrient solution from the reservoir to the mister heads can widely vary in LPA systems and can be either modular or fully integrated into the system. Some mister heads can be inserted directly into tubing leaving the pump. Another option is designing a manifold using a material like PVC. The pump will run directly into the manifold and pressurize it. The misting heads are then installed directly onto the manifold. The guideline that should be followed in the design of the transfer system is to avoid choosing any tubing or pipe that is more than one-half inch in diameter. Anything larger will result in a pressure loss that will cause poor coverage from the misting heads.

3.6 HPA Overview

High-pressure aeroponics differs primarily from LPA in the method of nutrient delivery. HPA requires a pump that is capable of generating enough pressure to produce an extremely fine mist. There are specific components required in any HPA design in order to operate on an accurate misting cycle that creates the proper sized mist.



1	Housing
2	Misters
3	Runoff drain
4	Nutrient solution
5	Booster pump
6	Pressure Switch
7	Transformer
8	Prepressurized accumulator tank
9	Soleniod valve
10	Relief Valve
11	Speaker
12	SIgnal Generator
13	12 volt battery

Figure 13: HPA Basic System Illustration.

3.7 HPA Fundamental Equipment Identification

3.7.1 Nutrient Reservoir

These guidelines suggest housing the nutrient solution in a container made with an FDA approved food-safe plastic resign. These approved plastics are known as food contact substances (FCS) (Commissioner, 2017). The chosen material should not allow light to filter through to the nutrient solution, as this will cause undesired algae growth inside of the reservoir. The nutrient reservoir functions as the beginning of the closed portion of the system and the end of the open portion. The size, shape and design of the reservoir can also vary to best integrate into total system design.

Figure 14: Nutrient Reservoir Example, (Growershouse, 2019).

3.7.2 High-Pressure Water Pump

High Pressure Aeroponics requires a pump that is capable of generating enough pressure to produce an extremely fine mist. Both diaphragm and reverse osmosis booster pumps have been used in HPE with success. The primary technical function that the pump must meet is the steady generation of a minimum 80 PSI. However, a pump capable of generating 100 PSI or more is desirable (Massie, 2018).

Figure 15: Aquatec 6800 Booster Pump and Pressure Switch (Aquatec, 2019).

3.7.3 Pressure Switch

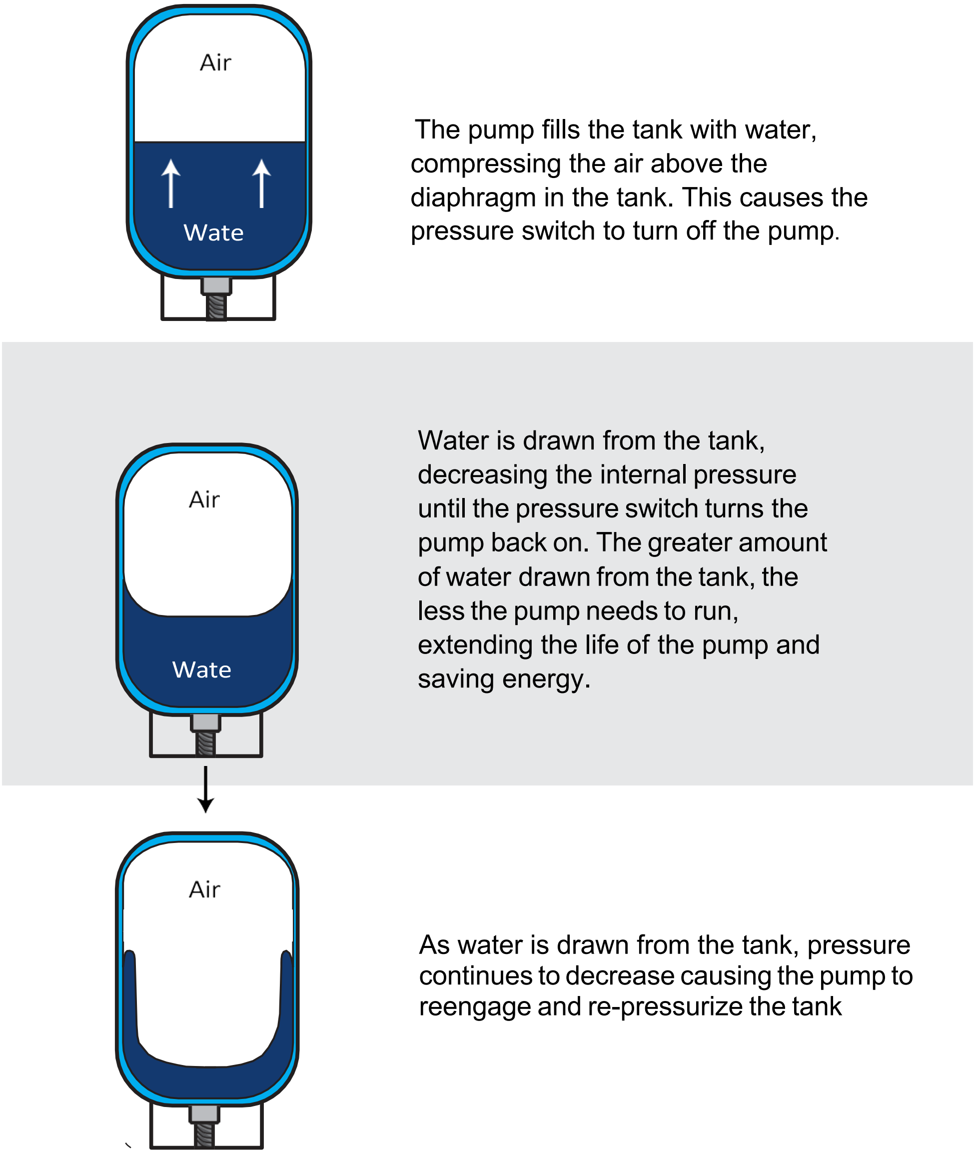
The pressure sensor maintains the pressure of the entire system by activating the booster pump in response to a drop in system pressure. Upon activation, the booster pump fills up the accumulator tank with nutrient solution that is pumped out from the nutrient reservoir until the desired pre-determined system pressure is reached. The pressure sensor then deactivates the pump until the next drop in system pressure. The switch wires directly into the pump and should be placed in between the pump and the accumulator tank.

Although not required for system operation, installing a fine mesh filter in between the nutrient reservoir and the booster pump can prevent particle buildup in the system that can eventually cause the pump to malfunction or more critically block the mister heads at the far end of the system (Massie, 2018).

3.7.4 Pre-Pressurized Accumulator Tank

Accumulator tanks are used in many homes that use well water and in travel trailers to help maintain water pressure in the pipes and prevent the pump from overworking every time water is called to the faucet. In a HPA system these tanks prevent the pump from having to run in between every misting cycle which both extends the life of the pump and reduces the energy use of the system. They also allow the spray nozzles to operate with the precise pressure needed for the desired droplet size by manually adjusting the internal tank pressure. Without the tank, each misting cycle would begin with a pressure buildup that would create droplet sizes that would negatively affect plant growth by impeding root impingement.

Before choosing an accumulator tank for an HPA system, it is important to ensure that the tank can tolerate the desired system operating pressure. Furthermore, proper installation of the tank can vary dependent on the manufacturer. It is therefore advised to carefully follow the manufacturer's installation and operational instructions provided with any chosen tank.



The pump fills the tank with water, compressing the air above the diaphragm in the tank. This causes the pressure switch to turn off the pump.

Water is drawn from the tank, decreasing the internal pressure until the pressure switch turns the pump back on. The greater amount of water drawn from the tank, the less the pump needs to run, extending the life of the pump and saving energy.

As water is drawn from the tank, pressure continues to decrease causing the pump to reengage and re-pressurize the tank

Figure 16: Internal Function of Pressurized Accumulator Tank (WaterWorker, 2019).

The two main considerations that should be made when selecting an accumulator tank for a HPA system are the tank type and the size needed to support the drawdown needed for a given system design. Figure X illustrates the three leading types of available accumulator tanks. The accumulator tank type selection should be made based on which type best fits the overall system design. Type selection could however be limited by the amount of fluid storage that a given system design requires because the availability of tank sizes varies by tank type. It should also be considered that the available drawdown of a tank varies by manufacturer. The chart found in Appendix A compares the tank cost and drawdown for the three main tank types at the pressure needed for a HPA system for two of the main suppliers.

Figure 17: Well Tank Types (WaterWorker, 2019).

The accumulator tank will need to be fit with a relief valve to protect against extreme pressure buildup within the system. Relief valves come with different pressure sensitivities. It is therefore critical to ensure that the selected relief valve is rated at the pressure with which the system will be running.

Figure 18: Relief Valve.

A pressure gauge is needed to ensure that proper pressure is being maintained within the system. The best placement is in between the accumulator tank and the electronic solenoid valve.

Figure 19: Pressure Gauge with 1/4” Quick Connect Fittings.

Figure 20: Relief Valve Setup for HPA System.

Figure 21: Reduction Fittings and Teflon Tape Used on 26 Gallon Accumulator Tank.

3.7.5 Electrical Solenoid Valve (ESV)

The ESV blocks the flow of water from the booster pump from reaching the open section of the system, allowing for the pressure buildup necessary to create proper mist size upon scheduled release into the open portion of the system via communication with the cycle timer. It functions as the gateway to the open portion of the system.

Figure 22: DIGITEN 1/4" Quick Connect Solenoid Valve (Dogiten, 2019).

3.7.6 Timer

The timer in an HPA system releases the pressurized nutrient solution through the solenoid valve and towards the mister heads. As long as the timing mechanism is capable of delivering the nutrient solution every few minutes for only a few seconds there are few restrictions in this area.

Figure 23: Repeat Cycle Timer (Century Products, 2019).

3.7.7 Nozzles

In a misting system, nozzles break a liquid into droplets that form unique spray patterns that vary based on nozzle type. The size of a droplet is measured in microns and is primarily influenced by nozzle type and application pressure (Grisso et al, 2013). The droplet sizes that a given nozzle produces is known as Droplet Size Spectrum (DSS) or Spray Quality (Peters, 2017). Droplet size and velocity in an aeroponic system plays a critical role in both mist collection efficiency and the depth of spray penetration. The collection efficiency of a root depends on its filament size, droplet size, and velocity.

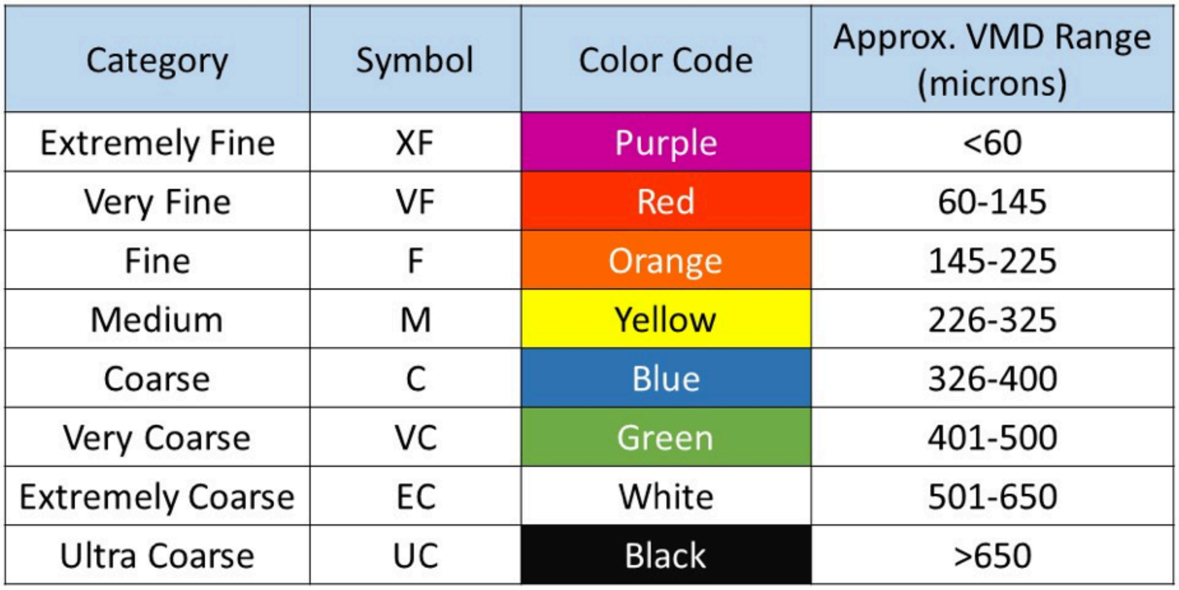
The Volume Median Diameter (VMD) is a value assigned to a nozzle representing the median droplet size that the nozzle produces. For a given spray volume, half of the droplets produced are smaller than the VMD and half of the droplets are larger than the VMD.

Even a small change in droplet diameter can dramatically alter root impingement (Clawson et al, 2000). As stated in NASA's Review of Aeroponics,

> The proper mist size for effective impingement occurs with drop sizes in the 30 micrometer range. Here, the droplets do not fall rapidly out of the air stream and will follow the gradual curvature of pipes and internal surfaces, but will impinge on root-sized filaments. (Clawson et al, 2000).

Nozzle discharge depends on liquid flow, size, and pump pressure. Jet spray nozzles with a 0.025 millimeter orifice will deliver a drop size of 5-50 microns under an operating pressure of 80-100 PSI (Imran, 2018).

The American Society of Agricultural and Biological Engineers (ASABE) developed the ASABE S572.1 standard shown in Table 1 that is commonly used for nozzle selection.



Category	Symbol	Color Code	Approx. VMD Range (microns)
Extremely Fine	XF	Purple	<60
Very Fine	VF	Red	60-145
Fine	F	Orange	145-225
Medium	M	Yellow	226-325
Coarse	C	Blue	326-400
Very Coarse	VC	Green	401-500
Extremely Coarse	EC	White	501-650
Ultra Coarse	UC	Black	>650

Table 1: ASABE S572.1 standard for spray nozzle selection. (Klein, Jhala, Knezevic, and Kruger, 2017).

Chapter 4 Implementation of Design Guidelines

4.1 Overview

Both a high and low-pressure aeroponic system are designed in this chapter with the use of the previously discussed guidelines. The documentation for each prototype begins by mapping the navigation through the development flowchart and is followed with the identification of the fundamental equipment selected for each prototype design. Further information regarding how select fundamental components are integrated into the overall system is also given in an effort to communicate a better overall understanding of the system design. This includes the detailed documentation of the design and fabrication of the growth chamber and nutrient delivery system. The documentation for each design concludes with photos taken during the field testing of each prototype.

4.2 LPA System Design Using Design Guidelines

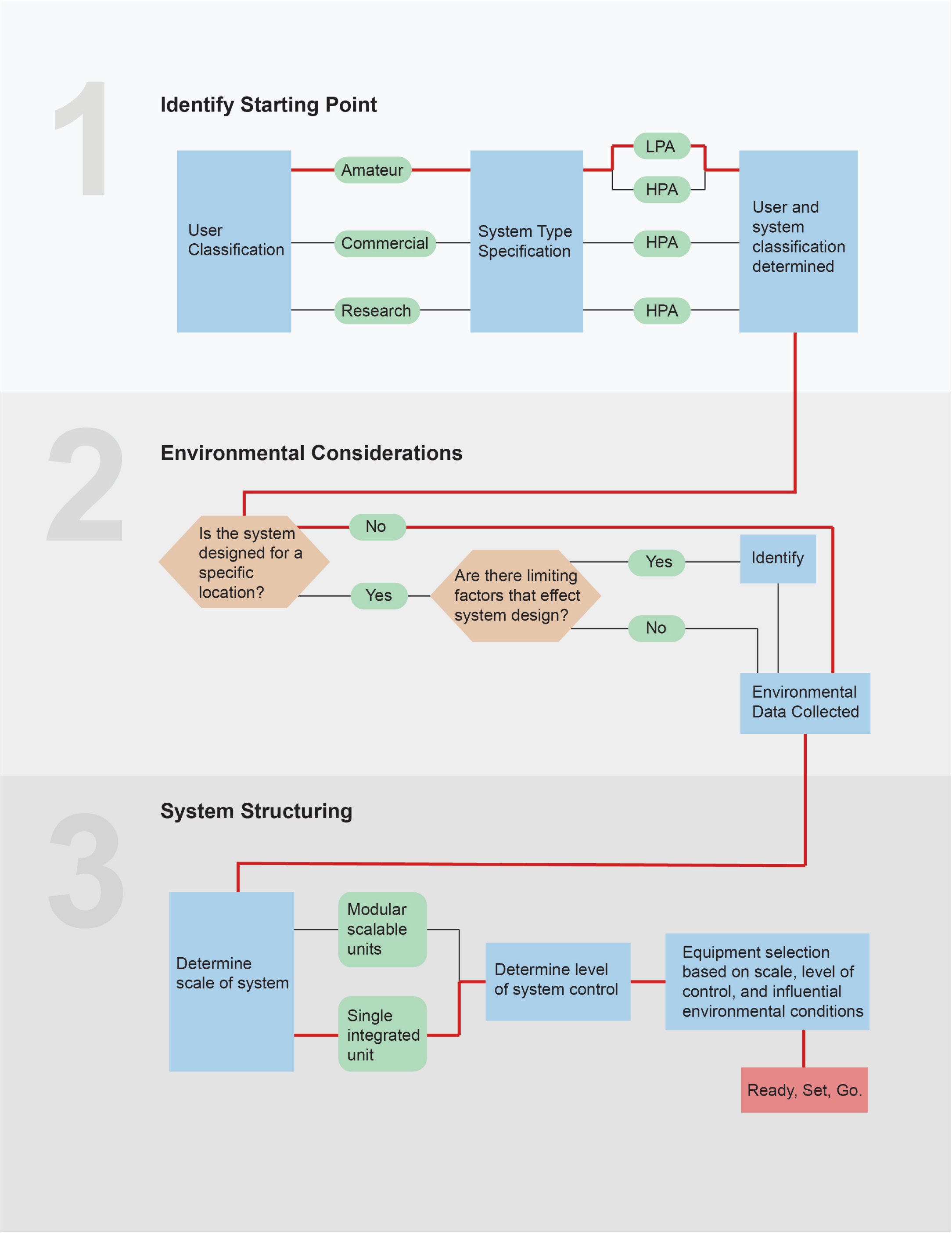


Figure 24: Flowchart Route for First Prototype.

4.3 LPA Fundamental Equipment Selection

4.3.1 Nutrient Reservoir and Growth Chamber

Figure 25: Construction of Growth Chamber and Nutrient Reservoir.

4.3.2 Pump

Figure 26: 550 GPH Submersible Water Pump used for LPA Prototype (Waterpumpguide 2018).

4.3.3 Sprinkler Heads

Figure 27: Misting Heads Selected for LPA prototype (xGarden 2019).

4.3.4 Timer

Figure 28: Timer Selected for LPA Prototype (Nearpow 2018).

4.3.5 Nutrient Delivery Method

Figure 29: Nutrient Delivery Manifold 3D Rendering.

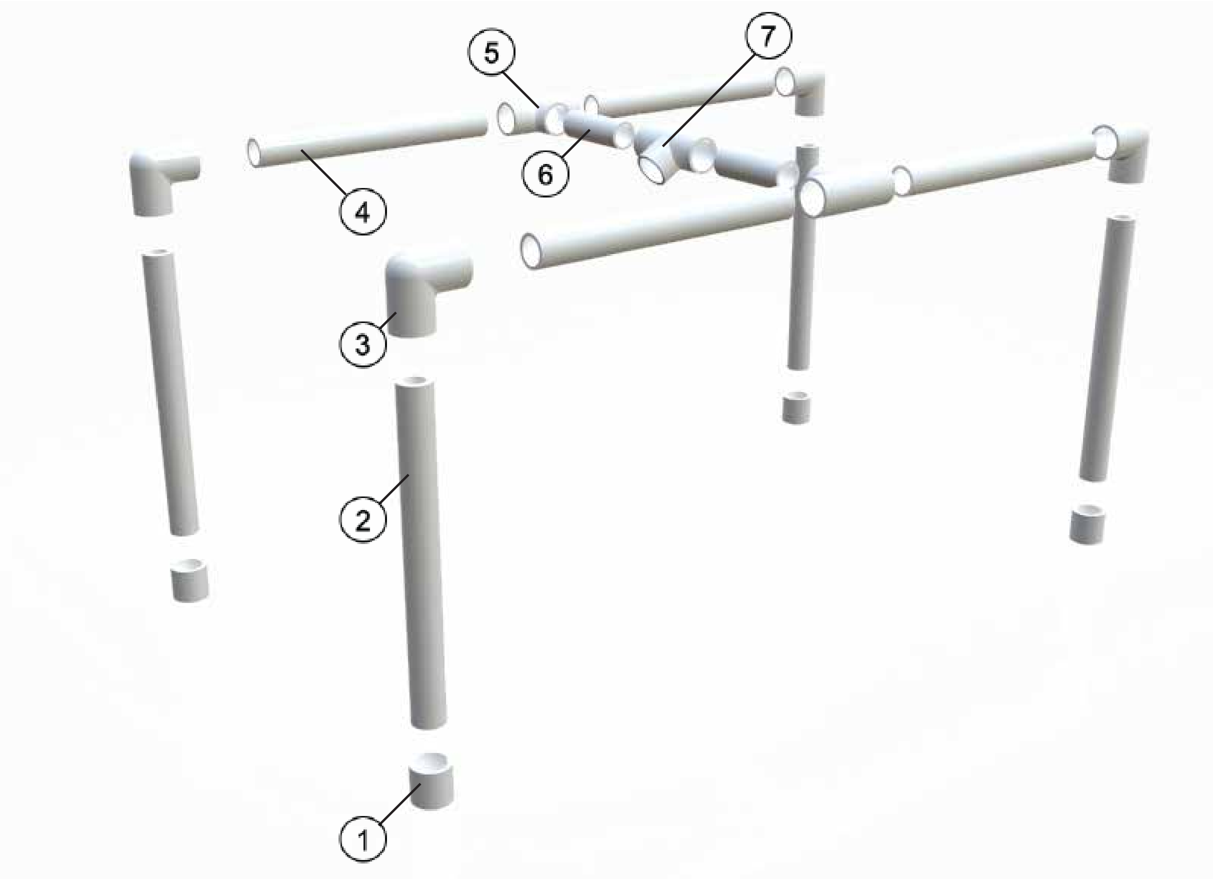


Figure 30: LPA Prototype Manifold Exploded View.

Low Pressure Aeroponic System			
Item No.	**Description**	**Length**	**QTY**
1	½” PVC Sch. 40 Socket Cap	-	4
2	½” 600-PSI Schedule 40 PVC Plain End Pipe	8 ½”	4
3	½” PVC Sch. 40 90-Degree Elbow	-	4
4	½” 600-PSI Schedule 40 PVC Plain End Pipe	7 ¾”	4
5	½“ PVC Sch. 40 Tee	-	2
6	½” 600-PSI Schedule 40 PVC Plain End Pipe	2 ½”	2
7	½” PVC Sch. 40 Female Pipe Thread Tee	-	1

Table 2: Nutrient Delivery Manifold Exploded View and Parts List.

4.4 LPA Prototype Development and Testing

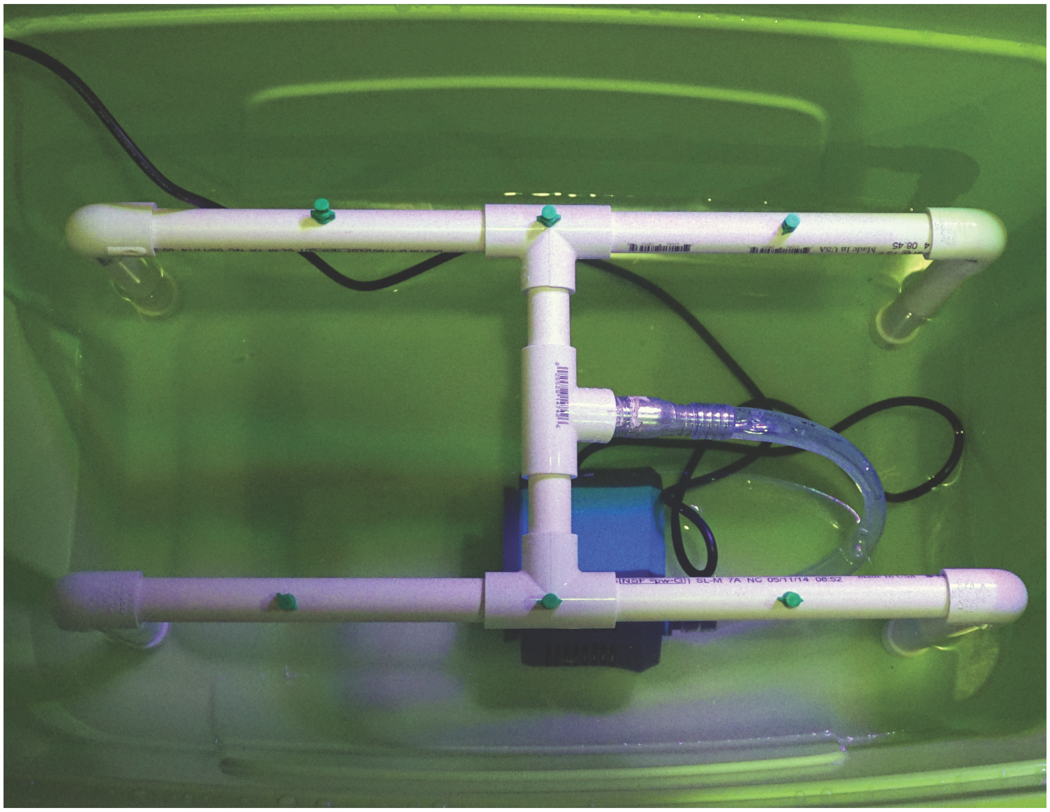


Figure 31: Manifold positioned inside of Nutrient Reservoir Connected to Pump.

4.4.1 Indoor Prototype Testing

Figure 32: Indoor Setup of LPA Prototype with Supplemental Lighting.

4.4.2 Movement of System to Fully Outdoor Environment

Figure 33: Outdoor Transition of LPA System.

4.4.3 Final Results from Prototype Testing

Figure 34: Cucumbers Grown Using Prototype Developed Using Design Guidelines.

4.5 HPA System Design Using Design Guidelines

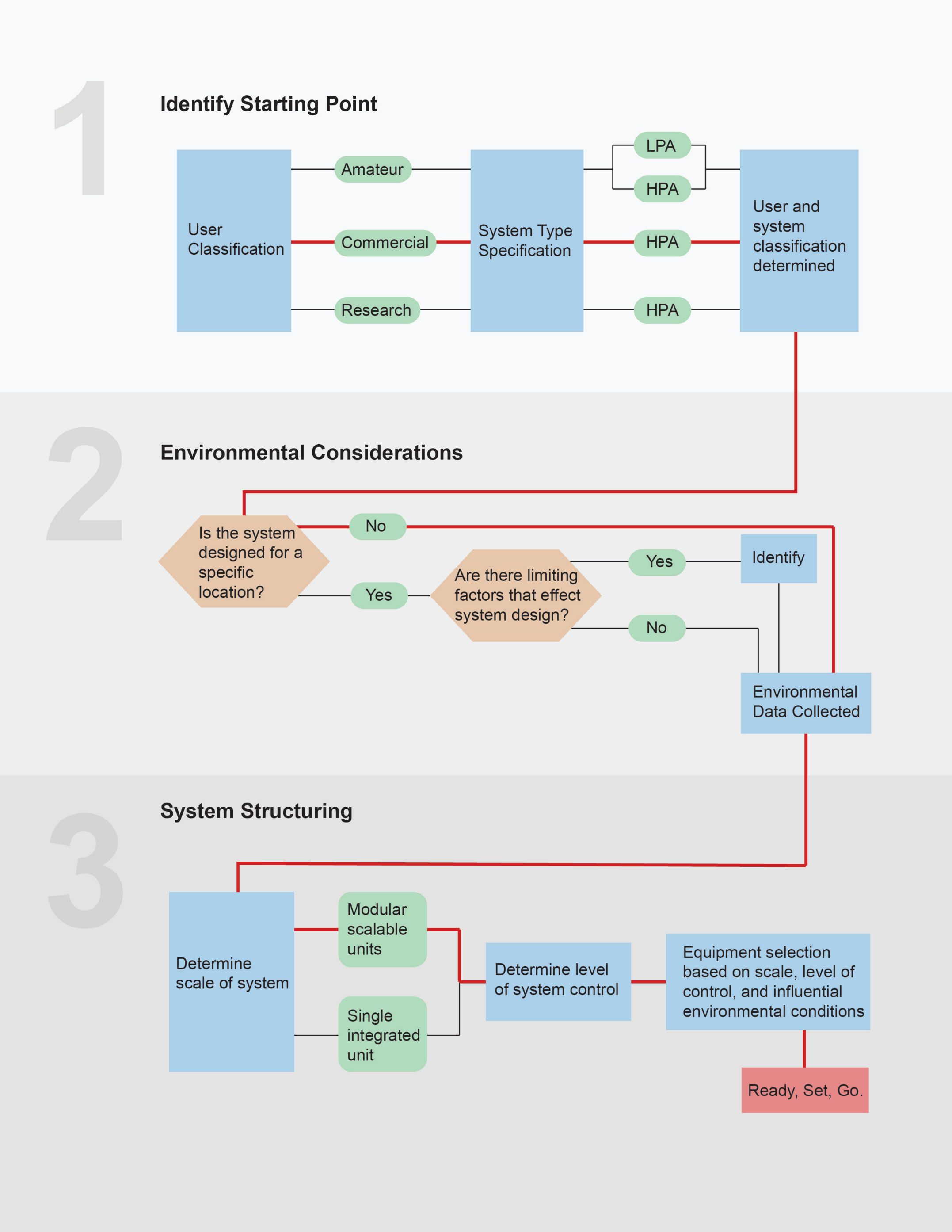


Figure 35: Flowchart Route for Second Prototype.

4.6 HPA Fundamental Equipment Selection

4.6.1 Nutrient Reservoir

Figure 36: Nutrient Reservoir Used in HPA Prototype.

4.6.2 Booster Pump and Pressure Switch

Figure 37: Booster Pump Used in HPA Prototype.

4.6.3 Accumulator Tank

Figure 38: Five Gallon Accumulator Tank Used in HPA Prototype.

4.6.4 Accumulator Tank Setup and System Integration

Step 1: Determine Initial Tank Pressure

Both HPA systems made using the guidelines in this chapter used WaterWorker Pre-Charged Well Tanks. These tanks were chosen because they have a maximum working pressure of 100 PSI, which is well over the previously discussed preferred system operation of 80 PSI. These WaterWorker tanks arrive from the manufacturer charged to 40 PSI.

The standard tire gauge seen in Figure 39 was used to determine the initial tank pressure which measured an expected 40 PSI. However, these gauges typically cannot measure the desired tank pressure for HPA systems. A high pressure gauge as seen in Figure 41 capable of reading these high pressures can be purchased in the automotive section of most Department Stores for less than 10 dollars, and is a critical tool for the next step of the tank set-up.

Figure 39: Measuring of Initial Pressure of 26 Gallon WaterWorker Accumulator Tank.

Step 2: Manually Increase Tank Pressure

The desired internal pressure of the accumulator can be reached by adding air with an air compressor as seen in Figure 40. After ensuring that the selected tank has an appropriate working pressure, air can be added to the tank in short five to ten second intervals. Check the tank pressure in between each interval as seen in Figures 41 and 42 to prevent overcharging the tank.

Figure 40: Pressure Added to Accumulator Tank.

Figure 41: Pressure Reading Displaying Need for AdditionalPressure.

Figure 42: Final Pressure Reading Displaying Desired TankPressure.

Step 3: Reduce Tank Fittings and Install Relief Valve

A relief valve must be installed onto the tank followed by a total reduction down to 1/4” fittings as seen in Figure 16 in order to be incorporated into the HPA system. The necessary fittings needed for this reduction will vary depending on tank size and selection. It is important when performing these reductions to wrap the threaded male ends of fittings with Teflon tape as seen in Figure 44. Completing this step has prepared the tank for system incorporation.

Figure 43: Pressure Relief Valve with 1/4" Total Reduction.

Figure 44: Reduction Fittings and Teflon Tape Used on 26 Gallon Accumulator Tank.

4.2.1 Timer

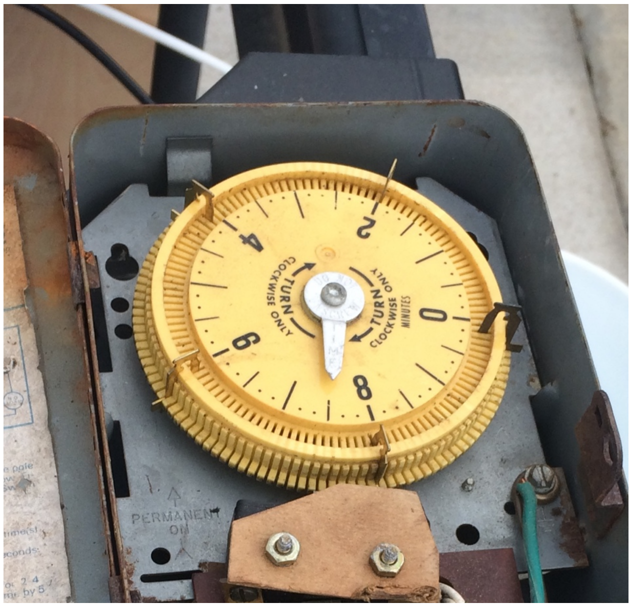


Figure 45: Cycle Timer Used in HPA Prototype.

4.6.5 Nozzle Selection

Jet spray nozzles seen in Figure 46 with a 0.025 millimeter orifice are chosen because they will a drop size of 5-50 microns under an operating pressure of 80- 100 PSI (Imran et al, 2018).

Figure 46: Nozzle Setup in HPA Prototype.

4.7 HPA Prototype Design and Evolution

4.7.1 Initial Growth Chamber Design

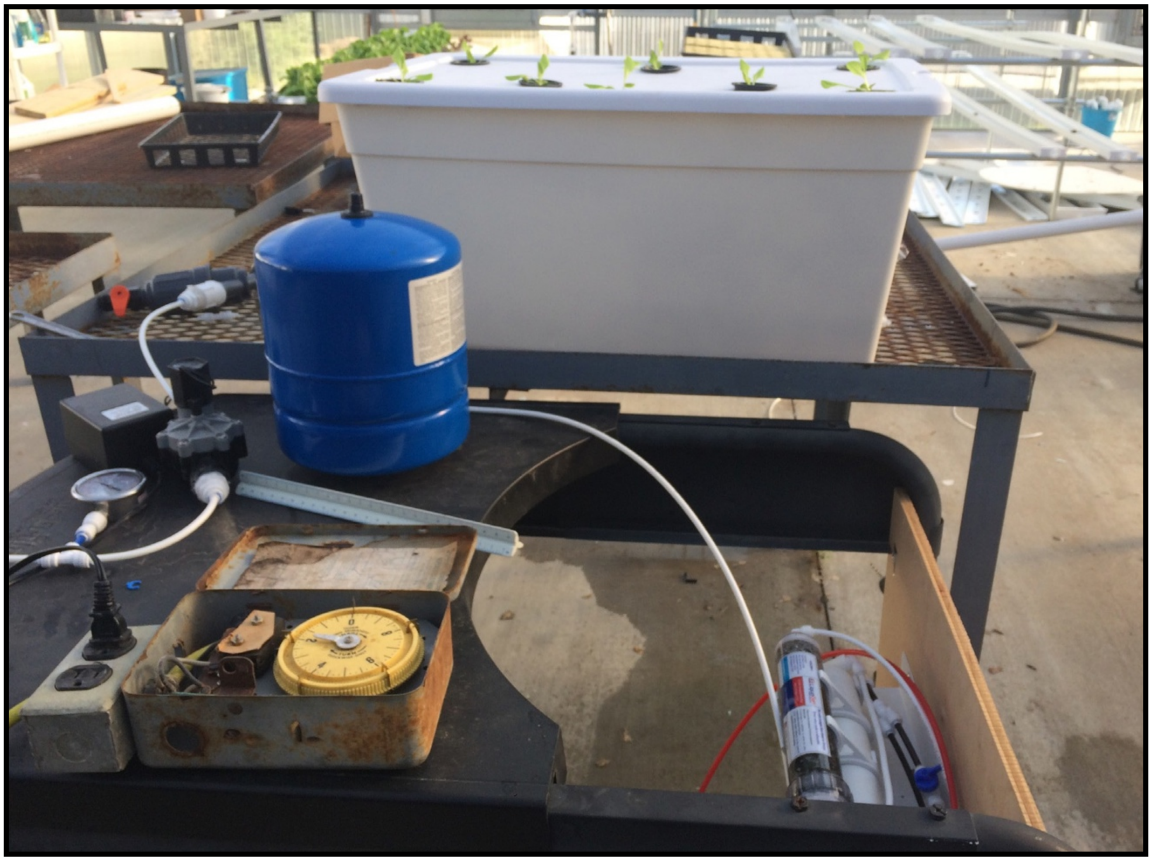


Figure 47: Initial HPA Prototype Growth Chamber.

4.7.2 Vertical Chamber Development

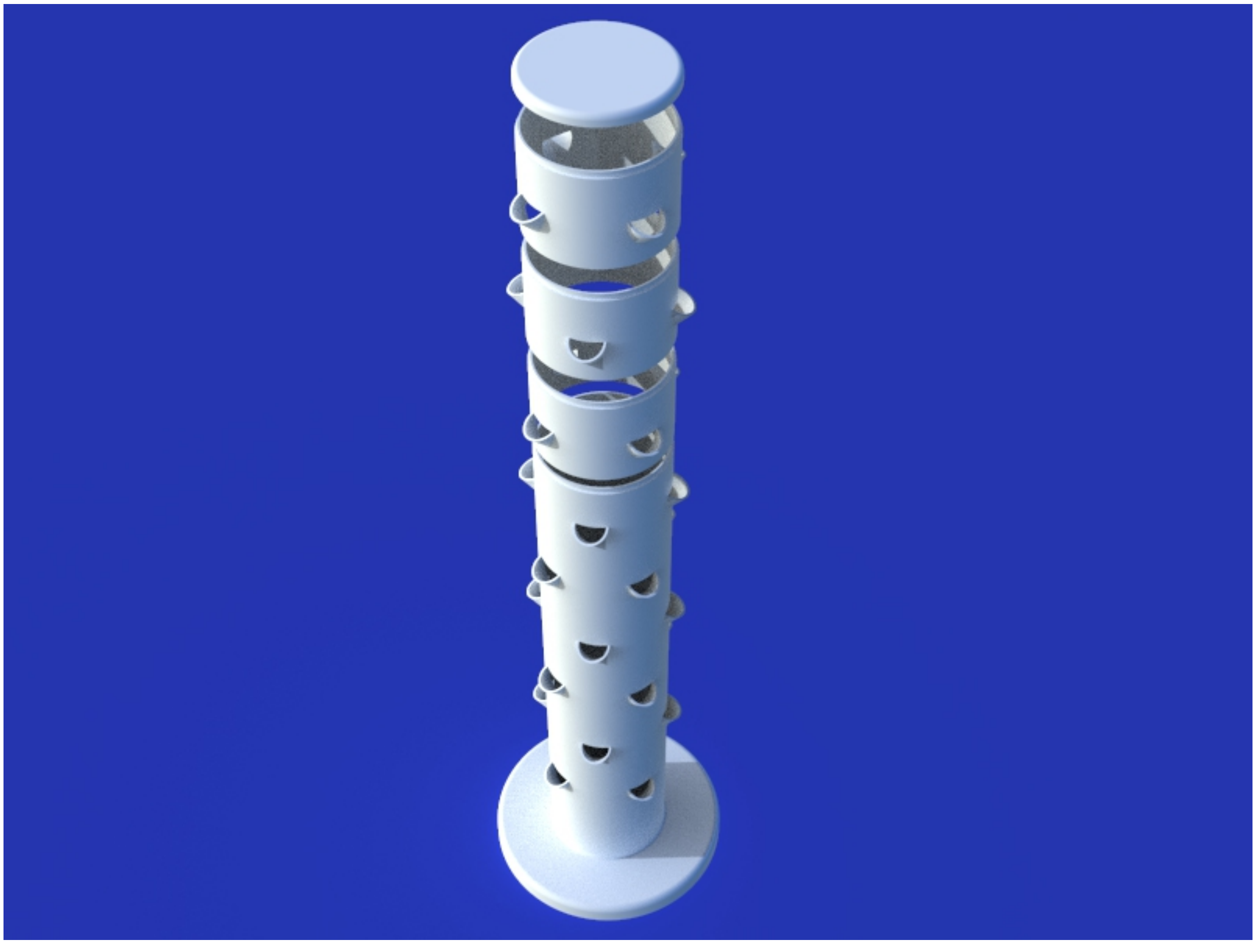


Figure 48: Vertical Growth Chamber 3D Rendering.

4.7.3 Vertical Growth Chamber Prototype Fabrication

Step 1: Choosing the Right Material

The decision to make the grow towers five feet in length derived from the material availability. The standard length of the PVC pipe sold in home improvement stores is 10 feet. Cutting the pipe in half was necessary for transporting the material based on available vehicles, and it maximized material usability when compared to cutting the pipe into thirds. Schedule 40 PVC pipe was used in the first prototype attempt, but the wall thickness was too thick to manipulate during the heating process. In contrast, Drain and Sewer PVC pipe has a wall thickness four times thinner and proved much easier to form into the necessary shapes for cup support.

Figure 49: 4" PVC Pipe Used for HPA Vertical Tower Prototype.

Figure 50: Step 2 of Tower Fabrication.

Step 2:

Measure the circumference of the top opening of the pipe.

Figure 51: Step Three of Tower Fabrication.

Step 3:

Divide the circumference by four and make a mark at each respective interval dividing the pipe into fourths

Figure 52: Step Four of Tower Fabrication.

Step 4:

Use a straight edge to draw a line down length of the tube at each mark. It is recommended to push the tube against another object for stability

Figure 53: Step Five of Tower Fabrication.

Step 5:

On one of the lines previously drawn, make a mark four inches below the top of the pipe. Make six additional marks following the same line at eight inch intervals. Repeat these steps for the line opposite the line. On the two remaining lines, make the first mark 8 inch below the top of the pipe and make five more marks at eight inch intervals.

Figure 54: Step Six of Tower Fabrication.

Step 6:

At each mark made down the lines, mark a centered a two and one half inch horizontal line. These lines will be the final guides for cutting the cup slots, and it is important that their width is correct to avoid gaps that will cause a loss in humidity.

Figure 55: Step Seven of Tower Fabrication.

Step 7: Cutting

For the cleanest and fastest results, use a miter saw to follow the guide lines and cut the 26 holes for cup placement. If a miter saw is not available, this step can be completed using smaller tools such as a rotary tool or hand saw.

Figure 56: Step Eight of Tower Fabrication.

Step 8: Heating

Using a heat gun, slowly heat the area above and below the cut. It is important to heat more of the space above the cut than below. Heat both areas in a triangular shape as this will encourage the correct final form when the cup is inserted. The tube should be heated to the point of malleability, but not until it melts or burns. Over-heating can result in the corners tearing upon cup insertion.

Figure 57: Step Nine of Tower Fabrication.

Step 9: Cup Insertion

Immediately after heating, insert the cup into the hole all the way using a twisting motion. Use caution as the pipe can still be hot to the touch. Momentarily hold the cup in place while the pipe begins to cool. Do not push the cup past the opening, or it will fall into the pipe. If a cup gets stuck inside the pipe, reheat the hole in order to remove it, but avoid this when possible as it adds unnecessary stress on the pipe and can cause warping.

4.7.4 Vertical Growth Chamber Prototype Testing

Figure 58: Empty Tower.

Figure 59: Seedlings Placed in System 17 Days AfterPlanting.

Figure 60: Growth At 30 Days.

Figure 61: Growth At 45 Days.

4.7.5 Scalability and Modular Aspect of Tower Design

One of the most important features of the vertical aspect of these design guidelines is that is allows for a system having only one tower or a system with 100 towers

Figure 62: Single Tower Setup

Figure 65: Multiple Tower Setup

Figure 63: Multiple Tower SetupFigure 64: Single Tower Setup

Chapter 5 Conclusions

5.1 Summary of Study

Chapter One focuses on what exactly this study if about beginning with the problem statement and the need for the study. The chapter then concludes with objectives, assumptions, scope and limits, procedures and methods, and finally the anticipated outcome.

Chapter Two is focused on the literature review on research related to the topic introduced in chapter one and is meant to provide a greater understanding for the design of the final solution by providing structural support.

Chapter Three lays out the necessary components and guidelines for the design of an aeroponics system

Chapter Four demonstrates the implementation of the design guidelines that were given in chapter three. This includes the detailed development of working prototypes for both a high and low-pressure aeroponic system. The way that the prototypes for both systems were developed was done specifically in an effort to communicate a more in depth understanding of how the fundamental components of the system relate to one another and a better overall understanding of the system design.

5.2 Recommendations

Due to a lack of system design instruction in aeroponic culture techniques, it is hoped that others can use this document as a guide. The basic guidelines for designing such a system have been provided, but it will ultimately be up to the designer to incorporate their own methodology in their own approach. The same could also be said regarding the fabrication process used for the functioning prototype.

It is hoped that the guidelines laid out in this document will be expanded to cover more details that are important to the topic, as some topics were only briefly covered that could be valuable to another designer focusing on less critical aspects in relation to this study. Further research should be done in order to test the efficacy of these guidelines considering the ever-changing knowledge and technology development in the field of alternative agriculture.

5.3 Synopsis

The guidelines created in this document were successful in that they can be used as a guide for developing a working vertical high-pressure aeroponic culture system.

It was challenging to narrow down the information presented in this documentation. There was no shortage of information, that although relevant and worthy of investigation, did not apply to the main focus of this topic. The goal was to focus on relevant information without overwhelming the reader.

Appendix A

Water Worker

Vertical Tank	Cost	Drawdown (gallons) at 80 psi
14 gal	$109.99	~3.3
26 gal	$137.51	~4.6
32 gal	$209.99	~7.3
62 gal	$284.74	~14.5
119 gal	$611.09	~27.2
In-Line Tank		
2 gal	$49.08	~0.4
4 gal	$68.93	~1.0
Horizontal Tank		
6 gal	$143.67	~1.12
14 gal	$174.99	~2.9
20 gal	$184.99	~4.6

WELLXTROL

Vertical Tank	Cost	Drawdown (gallons) at 80 psi
14 gal	$225.99	~2.7
26 gal	$262.99	~5.2
32 gal	$360.99	~6.5
62 gal	$699.99	~12.0
119 gal	$1015.99	~26.1
In-Line Tank		
2 gal	$69.99	~0.5
4.4 gal	$99.99	~0.8
Horizontal Tank		
4.4 gal	$148.99	~.8
7.4 gal	$289.99	~1.6
20 gal	$349.99	~3.9

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