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Water and Nutrient Reuse within Closed Hydroponic Systems

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ABSTRACT

Currently, little research exists on the maintenance of individual nutrient balance within the nutrient solutions of closed hydroponic systems and how this maintenance may result in reductions in water and nutrient consumption. In this study, a nutrient solution management procedure was developed to maintain outputs while minimizing inputs. *Lactuca sativa* (lettuce) crops were grown in six closed hydroponic systems utilizing the nutrient film technique. Electrical conductivity was used as the primary indicator of nutrient solution quality and determined if the nutrient solution was discarded and replaced (control systems) or restored (test systems). Restorations in test systems were made individually to nitrogen, phosphorus, and potassium through the addition of KH$_2$PO$_4$, KNO$_3$, and Ca(NO$_3$)$_2$ stock solutions. Test and control systems both showed similar fresh mass and foliar nutrient concentrations across two successive growth runs. Test systems consumed approximately 42% less water, 23% less KH$_2$PO$_4$, 57% less KNO$_3$, and 58% less MgSO$_4$ and trace elements than control systems across two runs. This study provides evidence that, for lettuce, similar crop yield with fewer inputs can be achieved under this nutrient solution management plan than under more traditional plans. This research suggests that in many current applications, nutrient solutions are being discarded prematurely and nutrient solution lifespan can be increased through simple procedural changes, decreasing environmental impacts and production costs.

KEY WORDS: Nutrient Solution, Nutrient Film Technique (NFT), Electrical Conductivity (EC), Lettuce (*Lactuca sativa*), Recirculating Systems
WATER AND NUTRIENT REUSE WITHIN CLOSED HYDROPONIC SYSTEMS

by

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DEDICATION

For Humankind, we can work it out.
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CHAPTER 1
INTRODUCTION

1.1 Summary of Rationale

One of the largest challenges of this century will be maintaining supplies of freshwater fit for human use (Simonovic 2002). This perceived challenge is largely associated with projected global population growth estimates and subsequent increase in food demand. Currently, 70% of freshwater usage is attributable to agricultural practices (Wallace 2000; Despommier 2010). Considering that the agricultural industry is the world’s leader in freshwater consumption, it would follow that decreasing the water used by this industry will have the greatest impact (Wallace 2000). Therefore, to prepare for the challenges associated with water scarcity, it is imperative that we develop and implement technologies and processes that maximize agricultural outputs while minimizing inputs.

Hydroponics is a method of agriculture that grows plants without soil using a mixture of water and nutrient salts, commonly called a nutrient solution. The nutrient solution is fully controllable and can be delivered to plants on an as needed basis. This makes hydroponics capable of high yields while minimizing water and nutrient consumption. Although there are many hydroponic techniques, most use approximately 70 – 95% less water than open field agriculture (Bradley 2001; Despommier 2010). Hydroponic systems can generally be delineated into open and closed systems. In open systems, which employ no reuse measures, the nutrient solution flows through the system once and is discarded (Jensen 1997; Nederhoff and Stanghellini 2010). In closed systems, the nutrient solution is reused, by adding more water and nutrients instead of replacing the entire solution (Jensen 1997; Nederhoff and Stanghellini 2010;). Due to this procedural...
change closed systems use 20 – 40% less water and nutrients than open systems, but require more monitoring and maintenance (Nederhoff and Stanghellini 2010).

Researching water and nutrient reuse in closed hydroponic systems will be critical in determining their maximum efficiency and productivity. Little research exists academically on processes that improve water and nutrient reuse in closed hydroponic systems while simultaneously assessing the quality of the crop. This research contributes to the field of closed system hydroponics by demonstrating reuse capabilities with nutrient solution management changes only. These are important developments as they show industrial changes that can be made immediately with no additional technological advancements, further helping the hydroponic industry to become more competitive and push for a more sustainable agricultural future.

1.2 Objectives

This research investigated a procedure for reusing water and nutrients in closed hydroponic systems and the efficiency of that process. It was hypothesized that a closed hydroponic test system, where the nutrient solution was monitored and adjusted, would require less water and nutrients than a closed hydroponic control system, that discarded the nutrient solution after a period of use, while providing a similar crop yield and quality. It is expected that the test systems will consume less water and nutrients than the control systems without impacting crop quality and quantity.

Specific research objectives were to:

- Determine a simple management procedure to reuse the nutrient solution in a closed hydroponic system.
• Maintain nutrient solution quality.

• Quantify and compare water consumption, nutrient consumption, and plant growth between test and control systems.

1.3 Summary of Method

Lettuce (*Lactuca sativa*) was grown in six hydroponic systems utilizing the nutrient film technique (NFT), which grows plants in a sloped channel by exposing plant roots to a shallow continuously flowing nutrient solution. The hydroponic systems were placed in an on campus greenhouse to allow for greater control of environmental factors that could affect the condition of the nutrient solution as well as the growth and yield of the lettuce plants. All systems were identical closed hydroponic systems and differed only in nutrient solution management. Three of the systems were randomly designated as test systems, where the nutrient solution was reused, and three as control systems, where the nutrient solution was discarded after a period of time consistent with timeframes used by industry.

The nutrient solution was monitored daily for several parameters including pH, electrical conductivity (EC), and water consumption. EC and pH served as nutrient solution quality indicators through the entire growth cycle and established range limits for determining when the solution would be adjusted (test systems) or discarded (control systems). Upon completion of the growth cycle, the plants were harvested, mass was determined, and samples of tissue were analyzed for foliar nutrient concentrations. Total water consumption, nutrient consumption, fresh aboveground mass, dry aboveground mass, and foliar nutrient concentrations were compared between test and control systems using analysis of variance (ANOVA).
CHAPTER 2
LITERATURE REVIEW

2.1 Water and Agriculture

2.1.1 Water

The necessity for water is endured by all living creatures and is considered to be one of the fundamental requirements for life. For humans it is not only required in great quantities physiologically but also societally (WWAP 2012). For example, we rely on water to maintain hygiene for ourselves and in our cities, to produce food, and to support many industrial activities. Fresh water is a finite natural resource that serves as the foundation for many of society’s needs and as those needs increase, so will the demand for this resource (Khan and Hanjra 2008).

Although the Earth is seemingly rich with water at approximately 1.4 billion km$^3$, only 2.5% of it is freshwater (Shiklomanov 1998). Further, most of that freshwater is not actually moving through the hydrologic cycle but is instead contained within icecaps, glaciers, and permanent snow (Shiklomanov 1998). This leaves only 0.26% of freshwater in the form of surface water (Shiklomanov 1998). Although humans have discovered ways to utilize groundwater, this surface water remains the primary source of freshwater for a majority of the world’s population (WWAP 2012). The maintenance of these surface water sources, complicated through many years of uncontrolled waste dumping and a growing population, has become both increasingly important and difficult (Horrigan et al. 2002). These problems have given rise to freshwater concerns many would have not predicted 100 years ago.
Most environmental scientists believe that one of the largest challenges in the 21st century will be maintaining a safe supply of freshwater for human use (Simonovic 2002). The lack of available water in a region to satiate demand (i.e. water scarcity) occurs on every continent and is currently affecting approximately 2.8 billion people (WWAP 2012). Water scarcity is considered extreme when the annual amount of available water is less than 1000 m$^3$ per person (Shiklomanov 2004) and is derived from one of two reasons: 1) physical water scarcity, in which the land area itself does not have the water supply to meet the demand and 2) economic water scarcity, which is related to inadequate infrastructure or water management issues (WWAP 2012). While little can be done with regard to physical water scarcity, many adjustments can be made to address these economic water scarcity issues (Hanjra and Qureshi 2010), which are of particular concern within poorer and developing nations (WWAP 2012).

Developing countries throughout the world experience drinking and sanitation water shortages for billions of people (Simonovic 2001; WWAP 2012). Continued population growth will likely increase these water shortages (Wallace 2000; Khan and Hanjra 2008). This impending water crisis is believed to be happening for a variety of reasons, both in and out of human control. Commonly attributed factors include an increasing global population and a variety of industrial demands (Wallace 2000). These factors are difficult to address due to their extreme complexity. Controlling population growth has generated mixed responses from various populations as it involves human rights issues (Warwick 1990). Industrial demands are generally related to population size and can be isolated into separate components and optimized for efficient use. However, industry is a broad category that relates to the production of goods or services within an economy. To this end most water uses not related to human sanitation, direct consumption, or
ecological purposes can often be considered industrial use. Usually this broad categorization is separated into three sectors: agriculture, energy, and industry (WWAP 2012). With the latter being comprised of all other industries not related to energy production or agriculture, this presumably allows for better classification of water consumption.

2.1.2 Agriculture

The agricultural industry, which includes both crop and livestock production, is the largest global consumer of freshwater (Wallace 2000; Bradley 2001; Khan and Hanjra 2008; WWAP 2012) and should be the primary area of focus when it comes to freshwater conservation and management (Wallace 2000; Khan et al. 2008). It is currently estimated that 70% of freshwater usage is attributable to agriculture (Despommier 2010; WWAP 2012). Despite its dominance of global freshwater consumption, it is often overlooked by the scientific community as an area where efficiency can be increased (Wallace 2000).

The United Nations states that, “Water is the key to food security” which is clearly corroborated by the agricultural industry’s current water use. However, this current use is a direct result of current demands. Further, this particular demand is related to global population size, which is currently estimated to increase by approximately 50% by the year 2050 to over 9 billion people (Khan et al. 2008; WWAP 2012). Aside from the direct increase on water consumption, one of the primary concerns when considering this type of population growth is the increased food demand. Anticipated to be a 70% increase in global agriculture production by 2050, with anticipated changes in global diet and affluence (Bruinsma 2009). Creating an indirect increase on water consumption brought on by the agricultural industry to help meet this demand.
Aside from being the greatest direct consumer of freshwater, current agricultural practices also consume great quantities of nutrients in the form of fertilizer. These fertilizers, used to keep maximize productivity, also comprise one of the world’s largest sources of non-point source pollution, agricultural run-off (Tilman et al. 2001; Horrigan et al. 2002; WWAP 2012). It has been estimated that as much as 44% of irrigation water is lost as run-off (Wallace 2000). Carrying with it large quantities of these fertilizers. Though they are unable to be attributed to any specific geographic location, they are likely to come from agriculture due to their high concentrations of nitrogen and phosphorus (Tilman et al. 2001). Eventually this nutrient loaded run-off leads to the eutrophication of many ecological systems including our freshwater and marine systems, resulting in instability and habitat loss (Tilman 1999; Tilman et al. 2001; Horrigan et al. 2002).

2.1.3 Possible Solutions

The solutions to the stated problems above are numerous and could be achieved in many different ways including innovations in irrigation, crop breeding, or genetically modified organisms (GMO) (Hanjra and Qureshi 2010). Much of the current focus is on the modification of traditional open field methods and not in re-evaluating these methods altogether. Traditional open field methods, while effective, require a tremendous amount of resources and create an equally large environmental footprint that will become increasingly unsustainable as we progress into the future (Tilman 1999; Green et al. 2005). In an effort to preserve the current water supply and more importantly ensure future water and food demand, significant changes will have to be implemented in agriculture (Tilman 1999; Wallace 2000). The development, refinement, and/or implementation of technologies, systems, and processes that will allow for decreased water and
nutrient consumption during crop production will be an important step toward the goal of a new agricultural industry.

2.2 Hydroponics

2.2.1 Overview

Hydroponics is a method of agriculture developed to grow plants without soil (Gericke 1940; Gericke 1945; Hoagland and Arnon 1950). This is done by using a nutrient solution and growing plants in either an inert non-soil substrate, sometimes called soilless culture, or with no substrate at all, true hydroponics (Jensen 1997, Jones Jr. 2005). Soil acts as a medium to store the various nutrients required for growth. When water saturates the soil, it picks up these nutrients as salts where they can more readily interact with the plant roots (Campbell and Reece 2002). In hydroponics the need for soil is eliminated through the use of the nutrient solution. This nutrient solution is a combination of water and nutrient salts mixed to specific concentrations to meet plant requirements (Hoagland and Arnon 1950; Graves 1983; Jones Jr. 2005; Resh 2013).

Despite many believing it to be a revolutionary technology, hydroponics has yet to overtake open field agriculture as the primary production method for many crops within the agricultural industry, although there exists room for optimism (Jenner 1980; Jensen 1997). Currently, the method is used primarily to grow tomatoes, cucumbers, peppers, lettuce, and a variety of specialty crops (Spensley 1978; Jenner 1980; Brentlinger 1997; Jensen 1999). Within industry an emphasis has been placed on the growth of tomatoes, cucumbers, and lettuce as these crops have demonstrated the revenues required to make a hydroponic operation profitable (Jensen 1999).
2.2.2 Open and Closed System Types

Presently, within the field of hydroponics there are many different techniques one can utilize when constructing a system. This will depend primarily on the type of plant as well as any limitations of the grower and/or growing space (Jensen 1997). Generally these techniques can be divided into two system types: open and closed (Abd-Elmoniem et al. 2006; Jensen 1997; Nederhoff and Stanghellini 2010). While these system types may share many features, including design, they fundamentally differ in how they manage the nutrient solution.

Open Systems

Open systems, otherwise known as run to waste systems, are those where the nutrient solution flows through the system only once (Jensen 1997; Nederhoff and Stanghellini 2010). This type of nutrient solution management provides two primary advantages: 1) it eliminates the need for nutrient solution maintenance and 2) reduces the risk of infection (Jones Jr. 2005). Aside from these advantages open systems have one primary disadvantage, they waste a large amount of water and nutrients (Nederhoff and Stanghellini 2010).

Closed Systems

Closed systems reuse the nutrient solution via recirculation for an unspecified length of time (Lykas et al. 2006). In this system type, the nutrient solution is regularly monitored and adjusted to maintain proper nutrient ratios. Common adjustments are to maintain nutrient solution volume, through water additions, and nutrient concentration levels, through stock nutrient solution additions. In contrast with open systems, closed systems conserve water and nutrients, which dramatically reduces waste (Abd-Elmoniem et al. 2006). In general closed systems can
use 20-40% less water and nutrients than open systems, but are more difficult to monitor and maintain (Nederhoff and Stanghellini 2010). This difficulty arises from ion accumulation as the nutrient solution recirculates (Lykas et al. 2006). Also, recirculation requires an infrastructure of reservoirs and pumping systems that have to be monitored and maintained in order to perform optimally.

It is important to note that nutrient solutions within closed systems are also discarded, just not before they have been reused at least once (Lykas et al. 2006). In some literature these may also be further classified as semi-closed systems (Nederhoff and Stanghellini 2010). Common times for discarding a nutrient solution are usually after one week (Donnan 1994; Bugbee 2004), two weeks (Spensley et al. 1978; David et. al. 1996; Samarakoon et al. 2006), or through analysis of the nutrient solution usually via electrical conductivity (EC) measurements (Mackowiak 1989; Donnan 1994). Extending the lifespan of the nutrient solution is advantageous from both an economic and environmental perspective. The completely closed system, wherein the nutrient solution is never discarded but instead constantly monitored, adjusted, and controlled, resulting in no waste, is the ultimate desired state for hydroponics.

2.2.3 Disadvantages and Advantages

The primary disadvantages associated with hydroponics are costs. Capital and operating costs of hydroponic systems are considered to be greater than traditional open field crop production (Jensen 1999). As such it is difficult to make hydroponically produced crops as or more profitable than soil produced crops (Jensen 1999). Many hydroponic systems are quite sophisticated in both design and mode of operation; therefore they have high construction costs and need very knowledgeable staff to ensure that crops stay healthy (Graves 1983). Further, as
most hydroponic systems are deployed in controlled agriculture environments (e.g. greenhouses) energy becomes a considerable cost, because of the need for nutrient solution movement and environmental control (Jensen 1999).

When not observed from a strictly financial perspective, hydroponics provides a wide array of advantages, most stemming from soil independence. Growing independently from soil reduces many of the deleterious effects brought about by open field crop production. Plants in carefully controlled hydroponic systems may be grown year round, placed closer together physically, or even stacked vertically, leading to higher production yields. (Graves 1983; Jensen 1999; Jones Jr. 2005; Resh 2013). As hydroponics uses a nutrient solution instead of open field watering, it consumes approximately 70-95% less water that traditional open field crop production does (Bradley 2001, Despommier 2010). The nutrient solution can also be controlled and maintained, effectively preventing it from becoming run-off. Further, hydroponic systems can be built in areas that would normally not support soil crop production (e.g. arid, urban environments) (Jensen 1999; Abd-elmoniem et al. 2004; Sheikh 2006; Nelkin and Caplow 2008). Shifting towards growing food hydroponically in urban settings could limit the loss of natural habitats, retaining more natural ecosystems and creating a natural progression towards habitat restoration.

2.3 Experimental Focus
Currently, the field of hydroponic research is stagnant. The Hydroponic Society of America has been inactive for years and few institutions remain active in hydroponic research (Jones Jr. 2005). Presently, there has been a lack of interest from scientists and most hydroponic work is occurring in industry with an emphasis on applying existing techniques (Jones Jr. 2005). Due to this lack of research, little work is being shared on improving the efficiency of hydroponic
techniques. This research focuses on process management in an effort to extend nutrient solution lifespan to improve hydroponic efficiency.

2.3.1 Nutrient Film Technique

Nutrient Film Technique (NFT) is a broadly used hydroponic technique (Jones Jr. 2005; Resh 2013). Allen Cooper and his colleagues first developed this revolutionary technique in 1966, and continued to develop it over the next decade (Cooper 1975; Graves 1983; Jones Jr. 2005). It was the greatest change in hydroponic growing since the 1930’s and shortly afterwards was believed to be the technique of the future (Spensley 1978; Jenner 1980; Jones Jr. 2005). It consists of a slightly sloping channel that allows for a shallow flow, or film, of nutrient solution to pass over the plant roots that are suspended within the channel (Cooper 1975; Graves 1983, Jones Jr. 2005; Resh 2013). Ideally this shallow flow would be no more than a few centimeters in depth, but any range from a few centimeters to one or two inches is often considered acceptable (Jones Jr. 2005; Resh 2013).

Generally, these systems consist of channels, resting on supports, being supplied with nutrient solution from a reservoir (Cooper 1975; Graves 1983). The channels are molded from various types of plastics that are opaque and allow for UV protection (Graves 1983). The supports provide the means of creating the gentle slope on the channel. This slope will depend on the overall length of the channel and vary with the particular crop. Usually, the desired slope is one that results in an effluent flow rate between 1 and 2 liters per minute (Graves 1983, Jones Jr. 2005). By design NFT systems are usually closed systems. The nutrient solution can easily be recovered at the end of the channel, returned back to the reservoir, and reapplied to the plant roots. Under a closed system approach the nutrient solution will require regular monitoring in
order to maintain its nutrient composition (Graves 1983; Lykas et al. 2006; Nederhoff and Stanghellini 2010).

NFT systems provide a few advantages when compared to other hydroponic systems. This mostly relates to a greater degree of control of the root environment (Graves 1983). Primarily, watering is greatly simplified in this system type as it is essentially replaced with a passive watering system (Cooper 1975; Graves 1983). The nutrient solution can be controlled with ease as the same solution waters all plants, leading to a system that is more efficient than most, conserving both water and nutrients (Cooper 1975; Graves 1983).

NFT systems also have disadvantages and complications. As with most hydroponic systems the capital costs of NFT are initially high, due primarily to materials and installation costs (Graves 1983; Jensen 1999). NFT hydroponic systems also require a high level of technical skill from the grower to operate properly, especially on a commercial level (Graves 1983). Also, as with most recirculating system types, NFT has a higher risk of disease because all plants share the nutrient solution (Spensley 1978; Graves 1983). More specific disadvantages arise from system design itself and the dynamics of the nutrient solution as it flows through the channel. The first complication arises when the nutrient solution is depleted of dissolved oxygen and nutrients by plants earlier in the system. This can then result in a nutrient gradient that will manifest as deficiencies in the plants at the farther end of the system (Graves 1983, Jones Jr. 2005). The second complication arises from the physical barrier created by the plant roots as they grow into the channel. This slows the flow rate, which again can cause a nutrient gradient (Graves 1983, Jones Jr. 2005). In order to eliminate this disadvantage the only option is to make the channels
shorter in length, no longer than 30 or 50ft, and/or wider; both of which can affect costs (Jones Jr. 2005; Resh 2013). Overall, these disadvantages can be minimized or eliminated through proper system management and design. Under the control of an experienced grower NFT has remained an extremely common and productive hydroponic technique both in research and industry.

2.3.2 Lettuce

*Lactuca sativa*, commonly known as lettuce, is a flowering plant from the family Asteraceae (Ryder 1999). Since its domestication, the plants popularity has continued to rise and today it is one of the world’s most popular vegetables and is the most used salad crop (Ryder 1999). Hydroponic growth of lettuce is considered to be quite easy, requiring less skill from the grower (Jones Jr. 2005). This makes it a widely grown commercial hydroponic crop (Ryder 1999) with many varieties performing well under a multitude of conditions (Jenner 1999; Jones Jr. 2005; Resh 2013. The cultivation of lettuce in a hydroponic system requires a nutrient solution within specific target ranges for a multitude of water quality parameters. For this reason lettuce is typically grown using NFT (Ryder 1999).

2.3.3 Nutrient Solution

Nutrient solutions used to grow lettuce hydroponically have widely reported EC and pH ranges, generally between 800 – 2,500 $\mu S \text{ cm}^{-1}$ and 5 – 7, respectively (Economakis 1990; Huett 1994; Gent 2003; Karimaei et al. 2004; Seo et al. 2009). Many early nutrient solution formulations are still in use today both experimentally and commercially (Resh 2013). Of the many available formulations few are as well documented in use as Hoagland’s nutrient solution (Hoagland and Arnon 1950; Karimaei et al. 2004). It has been shown that Hoagland’s nutrient solution falls
within the proper range of EC and pH and provides adequate nutrient concentrations for lettuce
growth (Karimaei et al. 2004). Although as indicated by Jones Jr. (2005), Hoagland solution has
use limits and any derivation of it, the so-called “modified Hoagland solution”, is itself a novel
nutrient solution. However, the replication of any particular nutrient solution is not as important
as maintaining it, in closed systems.

Water is the primary ingredient in a nutrient solution and therefore the single most important
factor to growth (Graves 1983). Today most municipal water contains a variety of ions (Spensley
et al. 1978) and/or is chemically treated resulting in unusually high amounts of chlorine residuals
(Graves 1983). While this may not be immediately detrimental to plant growth, in combination
with continuous nutrient solution use it could contribute to toxic ion buildup over time (Lykas et
al. 2006) or interference while analyzing certain parameters within the nutrient solution (Resh
2013). Municipal water usually has a pH near or above 7, which can in turn adversely effect
plant nutrient uptake. Utilization of some type of filtration system, such as a reverse osmosis
unit, is commonly advised as it removes most impurities from whatever water source is used
(Resh 2013).

Nutrient solution maintenance is critical to ensuring optimum plant nutrition. Nutrient solutions
must be mixed with a variety of nutrient salts to ensure healthy plants. These nutrients are added
based on the idea of essentiality, where a nutrient is determined to be essential if its absence will:
1) make it impossible for the plant to grow or reproduce, 2) is specific to the element in question,
and 3) is specifically required by the plant and does not create favorable environmental
conditions for the plant (Arnon and Stout 1939). Many, if not all, of the essential nutrients
required for plant growth have been identified and are well documented. They are traditionally split into two groups, macronutrients, each comprising >1000 mg/kg dry mass and micronutrients, each comprising <100 mg/kg dry mass (Epstein 1965). The three primary macronutrients nitrogen (N), phosphorus (P), and potassium (K) are emphasized in this work. Their high level of requirement and physiological importance make N, P, and K the most common nutrient deficiencies and the greatest limiters of plant growth (Campbell and Reece 2002). Maintaining the concentration of these nutrients in solution at levels tolerable and available for the plant is vital to the success of recirculating systems. Continuous monitoring of specific nutrient ion concentrations is ideal, but costly for most ions and not currently possible for others, as the technology does not yet exist to reliably monitor their concentrations in solution. However, an indirect approach based on the EC of the solution can be used to approximately monitor nutrient status.

Nutrient solution EC is a common parameter used by commercial and research growers alike as the main indicator of nutrient concentration within a nutrient solution (Mackowiak 1989; Donnan 1994). The EC of a solution is proportional to the total ions present making it an effective measure of nutrient solution strength (Graves 1983). EC has also been used in estimating nutrient requirements in a recirculating nutrient solution (Savvas and Manos 1998). It is important to note that the EC measurement is only for total ion concentration and cannot be directly used to determine individual ion concentrations that would quantify specific nutrient levels (Graves 1983).
Nutrient solution pH is another common parameter used in hydroponic growing. The pH of the root zone effectively determines what nutrients are available to the plant, as plants can only uptake certain ions within a specific pH range (Clark 1982). With an optimum pH range identified between 5 and 7, as this is the range total maximum ion uptake occurs (Clark 1982; Graves 1983). Soil composition determines the pH of the root zone under normal growing conditions and acts as a pH buffer to maintain an adequate range (Campbell and Reece 2002). However, in hydroponics, maintaining this pH range is critical because there is no soil to act as a pH buffer. Therefore, any pH change will result in a response by the plants, as they will not be able to easily control the pH around them (Graves 1983; Jones Jr. 2005; Resh 2013).

The only definitive way of determining the concentration of individual ions is through direct measurement. As stated previously, ion specific electrodes are available, however, they are expensive and not yet available for every ion of interest within a nutrient solution. Spectrophotometry can provide a fast and cheap way of determining specific nutrient concentrations within the nutrient solution at any given time. It works through measuring a concentration based on the absorbance of light. An accurate measure of ion concentration can be used to calculate how much stock nutrient solution must be added to maintain a healthy nutrient solution concentration. In the absence of ion specific electrodes, spectrophotometry is the best alternative to determine nutrient concentration.
CHAPTER 3
MATERIALS AND METHODS

3.1 Experimental Design

The hydroponic systems (Figure 3-1), assembly details contained within the Appendix A, were placed in a greenhouse located at Georgia Southern University in Statesboro, GA. The greenhouse was used to provide a growing space that was sufficiently out of the elements (e.g. wind/rain) with limited pest intrusion while still allowing for natural sunlight to be used. This particular greenhouse was an approximately 12 x 15ft glass and aluminum structure containing no environmental controls other than roof vents, a circulation fan, and a 30% shade cloth.

![Diagram of a hydroponic system with labels for positions 1 to 12, influent, effluent, pump, and reservoir.](image)

Figure 3-1. General system diagram displaying plant positions as well as influent and effluent locations.

Two nutrient solution management plans designated as: 1) test systems, where the nutrient solution was restored and reused, and 2) control systems, where the nutrient solution was discarded and replaced, were compared. Specific procedures surrounding nutrient solution restoration and nutrient solution replacement are outlined in Section 3.8.5.
The greenhouse was separated into three blocks (Figure 3-2) for three primary reasons: 1) to provide a minimum number of replicates for statistical analyses; 2) it was the most logical manner to evenly and consistently divide the study within the greenhouse; and 3) it took into consideration sun exposure for different areas within the greenhouse. Systems 1 – 6 were randomly assigned a number using Microsoft® Office Excel™ 2011 (Microsoft, Redmond, WA, USA). The lowest randomly assigned number in each block was designated as the test system.

Figure 3-2. Greenhouse layout displaying system numbering scheme, system type, and block segmentation.

The hydroponic systems had continuous environmental monitoring via data logger for air and nutrient solution temperature at each system. Although there was no mechanism in place to control the internal temperature or humidity of the greenhouse or the temperature of the
reservoirs, data were collected for monitoring purposes in the event that plant performance suffered for unknown reasons. The data logger was programmed to record air temperature and reservoir temperature every minute and averaged the temperatures on fifteen minute intervals. An unknown error was recognized at the end of the study, that the data logger memory was erased upon battery changes. This resulted in only partial monitoring data to be collected. This did not impact the study.

3.2 Selection of Lettuce Crop

*Lactuca sativa* (lettuce) is one of the world’s most popular vegetables and has been cultivated into many varieties (Ryder 1999). It is considered easy to grow hydroponically with most varieties maturing in six to twelve weeks (Ryder 1999). Of the many varieties available, oak leaf was used in this research for two key reasons: 1) Oak leaf has considerable tolerance for temperature fluctuations and high temperatures. This is absolutely critical as the lettuce, due to research constraints, was grown primarily in the off-season within a greenhouse that has no environmental controls in southeast Georgia. 2) Oak leaf also exhibits a rapid seed to harvest time of approximately six weeks, which allows for multiple runs in a shorter timeframe.

3.3 Reverse Osmosis

A reverse osmosis (R.O.) unit or similar filtration device must be used in order to purify the water used in the systems. An R.O. unit filters out chlorine and other particulates by forcing the water through a variety of filters including at least one membrane filter. For this project a Hydrologic® Stealth 100 R.O. unit (Hydrologic, Santa Cruz, CA, USA) was used to achieve an approximate 98% particle removal rate and create nutrient solution water with acceptable parameters to ensure consistent and reliable electrical conductivity (EC) and pH readings throughout the process.
3.4 Nutrient Solution

The nutrient solution is a mixture of R.O. water and dry nutrient salts. Nutrient solutions used to grow lettuce hydroponically have widely reported electrical conductivity (EC) and pH ranges. Generally these ranges fall within an EC of 800 – 2,500 µS cm\(^{-1}\) and a pH between 5 – 7 (Economakis 1990; Huett 1994; Gent 2003; Karimaei et al. 2004; Seo et al. 2009). Therefore these ranges were used as the study target ranges. Further, when the EC fell out of this range the nutrient solution was replaced or restored for test and control systems, respectively. Although Hoagland solution has been reported to provide proper conditions for lettuce growth (Karimaei et al. 2004), a nutrient solution mixed to ratios consistent with that of a full strength Hoagland solution was determined to be on the high end of EC (2,340 µS cm\(^{-1}\)) and low end of pH (5.4) ranges for lettuce. As R.O. water is a low conductor and near neutral pH, it was assumed and verified through direct measurement that a nutrient solution mixed to ratios half that of full strength Hoagland solution would provide a nutrient solution with an EC on the low end and pH in the middle of the target ranges for lettuce. This allowed for a minimum use of nutrients while remaining within the target ranges and provided more room to adjust the nutrient solution through nutrient or pH buffer additions.

Concentrated stock solutions of the nutrient salts were prepared from dry nutrient salts and R.O. water. Potassium nitrate (KNO\(_3\)), potassium phosphate (KH\(_2\)PO\(_4\)), and magnesium sulfate heptahydrate (MgSO\(_4\) + 7 H\(_2\)O) solutions were prepared at a 1 molar concentration. Calcium nitrate (Ca(NO\(_3\))\(_2\)) was initially prepared as a 1 molar solution of calcium nitrate tetra-hydrate (Ca(NO\(_3\))\(_2\) + 4 H\(_2\)O). However, it was discovered that the Ca(NO\(_3\))\(_2\) used was not a pure calcium nitrate tetra-hydrate but rather a double salt blend (5 Ca(NO\(_3\))\(_2\), NH\(_4\)NO\(_3\) + 10 H\(_2\)O). This Ca(NO\(_3\))\(_2\) double salt resulted in a solution with a concentration of 236 g/L containing
approximately 63% NO₃⁻, 10% higher than the approximate 53% NO₃⁻ that comprises calcium nitrate tetra-hydrate. This was determined to have very little impact, as the slight increase of NO₃⁻ in the nutrient solution was not enough to harm the plants or push the nutrient solution out of the target EC or pH range. A commercially available trace element blend, Earth Juice® Microblast™, was used to provide adequate concentrations of these trace elements to the nutrient solution.

The nutrient solution was prepared by filling each reservoir, 5-gallon bucket, with 16L of R.O. water. This level was marked on the reservoir and used as the fill level for the duration of the growth cycles. The reservoir pumps were then switched on and the channels of the hydroponic systems were allowed to fill until providing a continuous flow. As each hydroponic channel contained approximately 8L of R.O. water within it at all times, an additional 8L of R.O. water was added to the reservoir to compensate for the amount now contained within the channels. Concentrated stock solutions were added to the reservoirs according to Table 3-1. A total of 24L of nutrient solution was mixed per system.

Table 3-1. Nutrient solution mixing ratios.

<table>
<thead>
<tr>
<th>Stock Solution</th>
<th>Stock Solution (mL) per Water (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KH₂PO₄</td>
<td>0.5</td>
</tr>
<tr>
<td>KNO₃</td>
<td>2.5</td>
</tr>
<tr>
<td>CaNO₃ Double Salt</td>
<td>2.5</td>
</tr>
<tr>
<td>MgSO₄</td>
<td>1</td>
</tr>
<tr>
<td>Trace Elements</td>
<td>0.5</td>
</tr>
</tbody>
</table>
3.5 Calibration of Electrical Conductivity and pH Meters

Two handheld meters were used for daily monitoring operations of the hydroponic systems, Oakton Cond 6+ and pH 6+ (Oakton Instruments, Vernon Hills, IL, USA). Due to the nature of the greenhouse and the tendency for reservoir temperatures to fluctuate considerably, each device was calibrated weekly per manufacturer recommendations for use in extreme temperatures. The EC meter was calibrated using a standard solution of HACH 5,000µS. The pH meter was set-up with a two-point calibration using pH 7.00 and pH 4.01 standard solutions and was re-calibrated weekly using the pH 7.00 solution.

3.6 Preparation of Rockwool

During the manufacturing process rockwool is rinsed in a basic solution resulting in a final product that creates a high pH environment. This could in turn inhibit or prevent the growth of young plants, as they will be unable to absorb the necessary nutrients since nutrient availability is pH dependent (Clark 1982). In order to prevent this the rockwool was prepared for use, per manufacturer instruction, by soaking it in an acidic solution for 15 to 60 minutes. The solution was made with approximately 16 L of R.O. water and General Hydroponics pH down buffer solution (phosphoric acid). The pH down was added slowly to the water until the pH was lowered to approximately 5.0.

3.7 Growth Cycles

Two separate growth cycles, Cycle 1 (C1) and Cycle 2 (C2), were performed; each growth cycle consisted of two runs, Run 1 (R1) and Run 2 (R2). Runs consisted of all 3 test and all 3 control systems growing lettuce plants in tandem from seed to harvest, with test systems reusing the nutrient solution from R1 to R2 (Figure 3-3).
Figure 3-3. Diagram of Cycles and Runs

3.8 Procedure: Cycle 1

Cycle 1 (C1) was completed to provide preliminary data on C1 methodology. Primarily, C1 was used to determine any required methodology changes and consisted of two runs: run 1 (R1), March through April 2013, and run 2 (R2), April through June 2013. Each run consisted of germinating approximately 100 oak leaf lettuce plants in rockwool cubes, placing them into hydroponic systems, growing them to maturity, and harvesting them.

3.8.1 Germination of Lettuce Seeds

After preparing the rockwool, per manufacturer instructions, it was placed into small aluminum trays in an area of moderate sunlight and lettuce seeds were placed in each cube. The trays were filled, approximately 1 inch, with a 50% strength nutrient solution and left undisturbed with the exception of adding more nutrient solution as needed. Germination was generally visible after 24 hours and cotyledons emerged after 3 days (Figure 3-4).
3.8.2 Lettuce Transfer

After 10 – 14 days the lettuce plants were ready for transfer into the hydroponic systems. Plants were separated and placed into 2” net pots that were inserted into the systems (Figure 3-5).
3.8.3 Nutrient Solution Monitoring

Prior to April 15\textsuperscript{th} 2013 the methodology was to make no adjustments to the reservoir until the EC indicated an adjustment was required. This procedure was changed for three primary reasons: 1) to ensure that the pumps were always submerged in the nutrient solution to prevent damage; 2) to better monitor the quantity of water and nutrients the plants were up-taking overtime; and 3) to reflect industry practices. Beginning April 15\textsuperscript{th} 2013 through the end of R1 and the remainder of the study the nutrient solution levels were monitored and adjusted daily. Adjustments were made by filling the reservoir with R.O. water and documenting the volume added to the nearest 0.05 L. This allowed for the EC of the nutrient solution to serve as an indicator of nutrient strength.

Using handheld meters, EC and pH measurements were taken daily from the reservoir of each system after adjusting reservoir water. Both meters provide automatic temperature compensation features; these features were used during measurements as the temperature of the nutrient solution fluctuated throughout the day.

3.8.4 Sampling Procedures

Nutrient solution samples of approximately 10 mL were taken from the reservoir of the test systems when the EC went out of the target range for lettuce, 800 $\mu$S cm$^{-1} – 2500$ $\mu$S cm$^{-1}$. Sampling of the reservoirs and the analysis of the nutrient solution samples were done on the same day. Samples were diluted 1:100 by pipetting 1 mL of sample into 99 mL of R.O. water. This dilution was performed to bring the nutrient solution concentration down to a level that could be measured by the HACH DR5000 Spectrophotometer (HACH, Loveland, CO, USA).
3.8.5 Nutrient Solution Replacement and Restoration

Control and test systems underwent nutrient solution replacement and restoration, respectively, when the EC fell out of the target range of $800 \, \mu S \, cm^{-1} - 2,500 \, \mu S \, cm^{-1}$. It is important to note that, despite the monitoring instruments having onboard temperature compensation capabilities, temperature fluctuations seemed to affect the EC and pH. Short-term trend changes in both EC and pH occurred and it was unknown if this was due to instrumentation error or the plants reacting to the temperature changes. In the event a trend change was determined to impact nutrient solution restoration or replacement, the trend change was ignored and nutrient solution restoration or replacement proceeded. This was done to minimize study impact and ensure that plants in both system types would not develop sudden nutrient deficiencies.

Control systems underwent nutrient solution replacement, meaning that the system was drained, the nutrient solution discarded, and a fresh nutrient solution added (Figure 3-6). Test systems underwent nutrient solution restoration (Figure 3-6), which consisted of sampling per Section 3.8.4 and the addition of stock solutions outlined below. The nutrients of primary interest for plant growth are nitrogen (N), phosphorus (P), and potassium (K) as they are consumed by plants in great quantities and similarly comprise the bulk of nutrients within the nutrient solution. In nutrient solutions these elements are available to the plants in the form of nitrate ($NO_3^-$), phosphate ($PO_4^{3-}$), and $K^+$ ions. Concentrations of $NO_3^-$, $PO_4^{3-}$, and $K^+$ were measured by spectrophotometry using their respective methods (HACH 2012a, HACH 2012b, HACH 2012c). Due to the cost of testing reagents, nutrient concentrations were measured only once. In the case that samples were below the measuring range of the spectrophotometer, due to nutrient
depletion, the highest concentration that would go undetected by the particular HACH method was assumed.

These measured values were used to calculate the amount of stock solution to be added to the test systems to bring NO$_3^-$, PO$_4^{3-}$, and K$^+$ concentrations back up to theoretical concentrations. Calculations were performed using the dilution equation:

$$C_1 \cdot V_1 = C_2 \cdot V_2$$

Stock solution additions were made by first calculating the amount of PO$_4^{3-}$ required to be added in the form of KH$_2$PO$_4$. Next, the amount of K to be added, in the form of KNO$_3$, was calculated after considering the amount already in the nutrient solution and the amount added by the KH$_2$PO$_4$. Finally, the amount of NO$_3^-$ to be added, in the form of Ca(NO$_3$)$_2$, was calculated based on the remaining NO$_3^-$ needs of the system. See Appendix A for sample calculations. To ensure MgSO$_4$ and micronutrient availability to all plants, 8mL of the trace element stock solution and 16mL of the MgSO$_4$ stock solution were added to the test systems at the start of R2.
3.8.6 Harvest

After approximately 4 weeks within the systems, 29 days for R1 and 27 days for R2, the plants were harvested. Harvest consisted of removing the aboveground portion of the plant, where the plant stem emerged from the Rockwool cube, from the below ground portion and placing them in separate labeled paper bags. The fresh aboveground mass was recorded immediately following harvest, as this was the marketable portion of the plant. The plants were then dried in a 60°C oven until a constant mass was achieved, approximately one week. Once the plants were dried their dry mass was recorded.

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Figure 3-6. Diagram of nutrient solution management process for test and control systems.
Figure 3-7. Mature lettuce plants prior to harvest.

3.9 Procedure: Cycle 2

Cycle 2 (C2) was completed to provide data on the final methodology. This final methodology was developed based off of preliminary data and experiences collected during C1. Procedures for C2 were identical to those used in C1 unless otherwise noted. C2 consisted of two runs: run 1 (R1), from August through September 2013, and run 2 (R2), from September through November 2013.

3.9.1 Sampling Procedures

During C2-R2 the established range of 800 µS cm\(^{-1}\) – 2,500 µS cm\(^{-1}\) no longer was an acceptable range for determining nutrient solution balance within test systems. This was because R2 test systems nutrient solution EC was scaled up due to carry over nutrients from the previous run. Therefore a new lower range limit was determined. First the C2-R1 starting EC was rounded, which gave a starting average of 1,200 µS cm\(^{-1}\). This was 400 µS cm\(^{-1}\) from the previous lower range limit of 800 µS cm\(^{-1}\). It was assumed that all systems would decrease nutrient solution EC
at a similar rate: Based on this assumption, 400 µS cm\(^{-1}\) was subtracted from the starting EC’s for C2-R2 test systems to yield the new lower range limit. Example: System 1 C2-R2 starting EC = 1,440 µS cm\(^{-1}\), therefore system 1 lower range limit = 1,440 µS cm\(^{-1}\) – 400 µS cm\(^{-1}\) = 1,040 µS cm\(^{-1}\). At this EC nutrient solution restoration was initiated.

3.9.2 Nutrient Solution Replacement and Restoration

During C2 adjustments were also performed to maintain a pH range of 5.0 – 7.0. The nutrient solution was allowed to be outside of this range for two consecutive measurements. This was determined using monitoring data from C1, which showed that two consecutive daily pH measurements out of range was the minimum before the pH returned to range limits. These adjustments were completed using General Hydroponics pH Up (potassium hydroxide and potassium carbonate) or pH Down (phosphoric acid) buffer solution, adding 0.25 mL at a time until the pH returned to range limits (Appendix B: Table B-3). Also, at the start of C2-R2 test systems underwent nutrient solution restoration prior to plants being transferred into the systems. These procedures were added after C1-R2 test system plants failed to grow.

3.9.3 Harvest

A metric for plant viability was established based off of C1-R2 fresh aboveground mass. Plants from systems 1 and 4 were considered to be non-viable as they stopped growing shortly after entering the systems. All plants from these two systems were below 15g of fresh aboveground mass. Therefore this fresh mass became the study minimum to be considered viable. Non-viable plants were not included in biomass analyses. This decision was made in order to address incidences of plant damage and to reduce the impact of outliers, as the masses from non-viable plants were much lower than any system type mean.
Plants in C2 were harvested after 30 days for R1 and 32 days for R2. During R2, on 10/13/13, damage to lettuce plants from an unknown pest occurred: control system 2 plant positions 5, 6, 8, 9, 10 and control system 3 plant positions 5 and 6 were damaged. System 2 position 8 and system 3 position 6 were non-viable at the end of R2. The remaining plants were viable per procedure but had less fresh aboveground mass than the control system means. The impact on the study cannot be fully determined.

3.9.4 Foliar Tissue Analysis

Foliar tissue analyses were performed on harvested tissue from both runs of C2. After the final dry mass was taken, a leaf sample from each plant within a system was collected and ground together to form a homogenized leaf sample, this was repeated for each individual system. These homogenized samples were sent to the University of Georgia Agricultural and Environmental Services Laboratories for a foliar tissue analysis to determine the nutrient concentration within the lettuce tissue.

3.10 Lettuce Production Cost Analysis

Consumption data for test and control systems along with data volunteered from Georgia hydroponic lettuce farmers was used to complete a comparative analysis on cost to produce lettuce for test and control systems. Farmers were queried via email to provide general information regarding water consumption, nutrient consumption, and production quantities (Appendix A). No two hydroponic systems are identical and many subtle changes between them in both construction and set-up potentially impact their function and efficiency. To maintain simplicity the cost analysis within this study was strictly a comparison of the water and nutrient
costs to produce lettuce from the research systems under test constraints, control constraints, and industry constraints common or reported. All costs were based on the actual cost of nutrients used during this research, the current (2013) water rates for Bulloch County, GA, and the current (2013) power rates from Georgia Power (FS-8).

3.11 Data Analysis

Data for C1 were analyzed for differences in water consumption, nutrient consumption, and aboveground mass between system types by analysis of variance (ANOVA) with a significance level ($\alpha = 0.05$) using JMP® 10 (SAS Inc., Cary, NC, USA). Data for C2 were analyzed using mixed effects repeat measures analysis of variance (rmANOVA) with $\alpha = 0.05$ through JMP® 10 (SAS Inc., Cary, NC, USA) for differences in water consumption, nutrient consumption, aboveground mass, and foliar nutrient concentrations between system types, runs, and the interaction. This type of analysis takes into consideration that the experimental units have been measured multiple times and individual data points may therefore be correlated.

Test statistics in ANOVAs are similar to those in other statistical analyses. A $p$ value lower than $\alpha$ indicates a statistically significant result. The F-statistic ($F$) is the ratio of variance among treatment means to variance within treatment means. The closer the value is to 1, the more identical the means are and therefore they are less likely show statistical significance. There are two separate degrees of freedom (DF) associated with an ANOVA. In this study design DF$_1$ was 1 because the means come from one of two treatments, test or control. Only one treatment mean may be selected before the other is implied. DF$_2$ is representative of the total number of possible observations with respect to treatment means. In this study design the total number of possible observations was six, the number of systems, and the number of treatment means remained two.
Using the same logic from above it was said to have a DF of 4. Note that the data used were of the same size and therefore all analyses have the same degrees of freedom, DF (1, 4), unless otherwise reported.
CHAPTER 4
RESULTS AND DISCUSSION

4.1 Cycle 1

As discussed in Section 3.8 Cycle 1 (C1) was completed for preliminary data and to determine any methodology changes. Water and nutrient consumption data between test and control systems for Run 1 (R1) were analyzed without Run 2 (R2) data, due to the test system plants failing to grow (Section 4.1.3). Interpretation of C1 data was restricted to methodological implications only.

4.1.1 Water Consumption

Total water consumption for test systems was approximately 33% less than the total water consumption for control systems during C1-R1; $F=75.91, p = 0.001$. This was to be expected given that the experimental design called for replacing the nutrient solution, which added 24 L of water, within the control systems compared to reusing the nutrient solution within the test systems, reflected in Figure 4-1.
4.1.2 Nutrient Consumption

Total nutrient consumption varied between test and control systems for C1-R1 amongst the KH$_2$PO$_4$, KNO$_3$, Ca(NO$_3$)$_2$, MgSO$_4$, and trace element stock solutions (Figure 4-2). Test systems consumed 20% less KH$_2$PO$_4$ ($F=800.33$, $p < 0.0001$), 40% less KNO$_3$ ($F=87.47$, $p = 0.0007$), and 11% more Ca(NO$_3$)$_2$ ($F=30.99$, $p=0.0051$) stock solutions compared to the control systems. MgSO$_4$, and trace element stock solutions were not part of the restoration procedure and are therefore reported at their exact values, which were also both consumed 50% less in test systems. These results in total nutrient consumption were expected, with the exception of Ca(NO$_3$)$_2$, because the experimental design called for the replacement of nutrient solution within control systems causing them to consume more stock solution. The increase in Ca(NO$_3$)$_2$ consumption was attributed to the nutrient solution restoration that occurs within the test systems (Section 3.8.5). During the restoration process nitrate needed to be added to achieve the desired concentration and could be added in the form of KNO$_3$ or Ca(NO$_3$)$_2$ stock solutions. However,
because potassium was maintained at a desired concentration, only a limited volume of KNO₃ could be added. This resulted in the Ca(NO₃)₂ stock solution being the primary source of nitrate during the restoration process and was therefore consumed in greater quantities by the test systems.

Figure 4-2. C1-R1 total nutrient consumption means ± SE for test and control systems.

4.1.3 Lettuce Mass

There was no difference in fresh (F=0.19, p=0.69) and dry (F=0.91, p=0.39) aboveground mass between test and control systems during C1-R1 (Figure 4-3). These were the desired results and showed neither methodology could be seen as more advantageous with respect to mass.
Test systems did not produce as much fresh aboveground mass ($F=35.81, p=0.0039$) as control systems during C1-R2 (Figure 4-4). This is a result of the R2 test system plants failing to grow. The fresh aboveground mass means of test systems 1 and 4 were $8.65 \pm 0.84 \, g$ and $3.49 \pm 0.27 \, g$ respectively was attributed to the pH in the test systems being too high for plant growth. Therefore it was determined that the maintenance of EC and nutrient concentrations at theoretical values did not ensure an acceptable pH range. This was further supported by mass data obtained from system 5. Adjustments in pH were made to system 5 and after adjustments were made, in the form of $\text{KH}_2\text{PO}_4$ stock solution, system 5 plants were able to recover resulting in a higher fresh aboveground mass ($35.07 \pm 3.23 \, g$) at harvest compared to the other test systems. These results provided the rationale for the procedural change present in Cycle 2 (Section 3.9.2) and the metric for plant viability (Section 3.9.3).
4.2 Cycle 2

4.2.1 Water Consumption

Total Cycle 2 (C2) water consumption for test systems was 42% less than control systems, decreased from Run 1 (R1) to Run 2 (R2), and the magnitude of the difference increased during R2 (i.e. system type-by-run interaction; F=121.25, p=0.0004). This was expected due to the experimental design. Figure 4-5 shows the total water consumption by system type for R1 and R2. The total R1 water consumption for test systems was approximately 23% less than control systems. This decreased further during R2 where test systems consumed approximately 63% less than control systems. These results were expected as the control systems had an additional 24L of water added through nutrient solution replacement as needed.

Little research exists comparing the efficiency of closed hydroponic systems under different nutrient solution management procedures. However, data comparing closed hydroponic systems
to open systems report a range of savings, with one group reporting a 33% reduction in water consumption for closed systems (Grewal et al. 2010) and another reporting a greater than 50% reduction (Giuffrida and Lipari 2003). This data, in conjunction with research from others, appears to indicate that hydroponic system water use efficiency is extremely diverse and merits additional investigation.

Figure 4-5. C2 total water consumption means ± SE for test and control systems.

4.2.2 Nutrient Consumption

Relationships during C2 in total nutrient consumption between control and test systems, R1 and R2, and the interaction varied amongst the KH$_2$PO$_4$, KNO$_3$, Ca(NO$_3$)$_2$, MgSO$_4$, and trace element stock solutions (Figures 4-6 and 4-7). Some of the observed differences in nutrient consumption were expected; however, other differences were unexpected. MgSO$_4$ and trace element stock solutions were not part of the restoration procedure and were therefore reported at their exact values with test systems consuming approximately 58% less than control systems. Test systems consumed approximately 23% less KH$_2$PO$_4$ stock solution than control systems, consumption decreased from R1 to R2, and the magnitude of the difference increased during R2
This decreased overall consumption and the further decrease from R1 to R2 was expected because the experimental design called for the replacement of the nutrient solution within control systems. Test systems consumed 57% less KNO$_3$ stock solution than control systems (F=237.58, $p=0.0001$). However, there was no difference in consumption between R1 and R2 (F=3.81, $p=0.12$). A difference between system types was expected, but the lack of a run effect was not. This could be due in part to the much larger standard error in R2. There was no difference in the consumption of Ca(NO$_3$)$_2$ stock solution between test and control systems (F=1.77, $p=0.25$) or between R1 and R2 (F=7.48, $p=0.052$). Although not expected, this lack of difference was attributed to the nutrient solution restoration that occurred within the test systems, discussed previously in Section 4.1.2. Which resulted in the Ca(NO$_3$)$_2$ stock solution being the primary source of nitrate during the restoration process and was therefore consumed in greater quantities by the test systems.

Research comparing nutrient consumption rates of closed hydroponic systems under different nutrient solution management processes is minimal. Further complicated as any available research used different nutrient solution compositions. However, the reduction in nutrient consumption findings from this research do align with previous findings that drained nutrient solutions contained high percentages of N, P, and K; which could have been reused (Grewal et al. 2010).
Figure 4-6. C2-R1 total nutrient consumption means ± SE for test and control systems.

Figure 4-7. C2-R2 total nutrient consumption means ± SE for test and control systems.
4.2.3 Lettuce Mass

Fresh aboveground mass was similar between test and control systems (F=1.89, \( p=0.24 \)) (system type-by-run interaction; F=4.63, \( p=0.098 \)) and was lower in R2 (F=25.99, \( p=0.007 \)) for both system types (Figure 4-8). Dry aboveground mass data were similar: No difference in mass was observed between test and control systems (F=0.53, \( p=0.51 \)) (system type-by-run interaction; F=1.29, \( p=0.32 \)), and mass was lower in R2 (F = 38.38, \( p=0.0035 \)) for both system types. From Figure 4-8 it can be seen that R1 test system fresh aboveground mass appeared to be greater than that of control systems, the reasons for this are unknown and were not shown to be significant as the standard error was large and overlapped between system types. The difference in mass between runs could have indicated some seasonal effect based on the timeframe from R1 to R2 (August to November). However, since the test and control systems as well as the interaction between system type and run showed no difference, the results were desirable as they showed test and control systems generated similar crop yield, in terms of mass. Therefore neither methodology could be seen as more advantageous.

As with water and nutrient consumption, comparisons of yield between closed hydroponic systems utilizing different nutrient solution management processes are few. Wheat has been shown to maintain consistent productivity within closed systems that were closely monitored for nutrient content (Mackowiak et al. 1989). Zucchini yields within closed systems have shown seasonal effects with a decrease in total yield of 35% in the summer-fall season compared to the spring-summer season (Rouphael and Colla 2004), therefore it is possible that other crops, like lettuce, may be impacted by seasonality. Lettuce has been demonstrated to grow to a
commercially viable size in hydroponic systems (Huett 1994, Ryder 1999) and these results corroborate that.

Figure 4-8. C2 fresh aboveground mass means ± SE for test and control systems.

4.2.4 Lettuce Foliar Tissue Analysis

Foliar nutrient concentrations during C2 between control and test systems, R1 and R2, and the interaction varied amongst the nutrients. All rmANOVA results for foliar nutrient concentrations can be seen in Table 4-1. Ideally foliar nutrient concentrations between control and test systems across runs would not show differences. However, this was not the case for many of the nutrients. As with prior observed differences, these can most likely be attributed to the experimental design. Iron (Fe), Zinc (Zn), Sulfur (S), Manganese (Mn), and K all showed test system concentrations to be less than control system concentrations. Further, Fe and Zn concentrations decreased and the magnitude of that difference increased from R1 to R2. Since the test systems have nutrient solution restoration, rather than nutrient solution replacement, they are exposed to less of these nutrients than control systems. Calcium (Ca) is the only nutrient that was consumed at a similar amount in both test and control systems, as more of that nutrient was
added to test systems in the form of the Ca(NO₃)₂ stock solution, which was also due to nutrient solution restoration. Aluminum (Al) concentrations decreased from R1 to R2 but no difference was observed between test and control systems. The remaining nutrients; Nitrogen (N), Phosphorus (P), Magnesium (Mg), Boron (B), and Copper (Cu); all showed no difference between control and test systems, which were the desired results, as there were no foliar nutrient concentration differences between the two system types for these nutrients. Providing further evidence that neither system type was more advantageous with respect to foliar nutrient concentrations.

Table 4-1. C2 rmANOVA foliar nutrient concentrations. Values are reported as F, p with *italics* indicating nutrients with *p < 0.05.*

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>System Type</th>
<th>Run</th>
<th>Run*System Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (%)</td>
<td>1.81, 0.25</td>
<td>1.95, 0.23</td>
<td>0.24, 0.65</td>
</tr>
<tr>
<td>P (%)</td>
<td>2.96, 0.16</td>
<td>0.39, 0.57</td>
<td>0.02, 0.88</td>
</tr>
<tr>
<td>K (%)</td>
<td>13.32, 0.0218</td>
<td>0.78, 0.43</td>
<td>0.0002, 0.99</td>
</tr>
<tr>
<td>Ca (%)</td>
<td>45.78, 0.0025</td>
<td>6.66, 0.06</td>
<td>6.45, 0.06</td>
</tr>
<tr>
<td>Mg (%)</td>
<td>1.91, 0.24</td>
<td>1.53, 0.28</td>
<td>0.03, 0.87</td>
</tr>
<tr>
<td>S (%)</td>
<td>14.56, 0.0188</td>
<td>1.28, 0.32</td>
<td>0.14, 0.72</td>
</tr>
<tr>
<td>Mn (ppm)</td>
<td>124.30, 0.0004</td>
<td>0.58, 0.49</td>
<td>0.84, 0.41</td>
</tr>
<tr>
<td>Fe (ppm)</td>
<td>14.75, 0.0185</td>
<td>18.86, 0.0122</td>
<td>13.86, 0.0204</td>
</tr>
<tr>
<td>Al (ppm)</td>
<td>0.0008, 0.98</td>
<td>12.99, 0.0227</td>
<td>0.53, 0.51</td>
</tr>
<tr>
<td>B (ppm)</td>
<td>0.30, 0.61</td>
<td>0.20, 0.68</td>
<td>0.20, 0.68</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>7.16, 0.06</td>
<td>0.10, 0.76</td>
<td>1.41, 0.30</td>
</tr>
<tr>
<td>Zn (ppm)</td>
<td>185.79, 0.0002</td>
<td>532.28, 0.0001</td>
<td>421.29, 0.0001</td>
</tr>
</tbody>
</table>

Perhaps more important than the foliar nutrient concentrations between test and control systems are how these concentrations relate to expected foliar nutrient concentration ranges for healthy lettuce tissue (Table 4-2). It should be noted that these nutrient concentration ranges for healthy lettuce are for no specific cultivar. Published values for N, P, K, Ca, and Mg of Buttercrunch and
Summer Bibb varieties are shown to fall within these ranges (Wlodzimierz and Weston 1992) and it is assumed that the Oak Leaf variety would also have similar foliar nutrient concentrations. No foliar nutrient concentration was below the lowest acceptable value listed, with most falling within the acceptable ranges. Intermittently, a few foliar nutrient concentrations were above the highest acceptable value listed. In general this was not considered to be of concern, as the plants exhibited no physical symptoms indicating toxicity and the concentrations were not high enough to be of concern to humans. However, it was an indicator that these concentrations could increase to toxic levels should successive runs be introduced. The same trends identified through the statistics were seen in these data as well. Primarily that the test systems in general had lower foliar nutrient concentrations per run than the control systems, with the exception of Ca. It is important to note that control systems had more nutrients with concentrations above the highest acceptable value listed. Therefore these data indicate that test systems, under these conditions, were more advantageous as they resulted in lettuce with leaf tissue at the appropriate nutrient concentration.
Table 4-2. C2 average foliar nutrient concentrations. Values are means ± SE. Acceptable ranges are for lettuce (*Lactuca sativa*) and are adapted from: Resh 2013 and those provided by UGA Agricultural and Environmental Services Laboratories. *Italicized* values are above the highest acceptable range value listed.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Resh</th>
<th>UGA</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Test</td>
<td>Control</td>
<td>Test</td>
</tr>
<tr>
<td>N (%)</td>
<td>3.0 - 6.0</td>
<td>3.30 - 4.50</td>
<td>6.13 ± 0.15</td>
<td>5.97 ± 0.38</td>
</tr>
<tr>
<td>P (%)</td>
<td>0.8 - 1.3</td>
<td>0.40 - 0.60</td>
<td>0.88 ± 0.04</td>
<td>0.79 ± 0.04</td>
</tr>
<tr>
<td>K (%)</td>
<td>5.0 - 10.8</td>
<td>4.50 - 8.00</td>
<td>12.62 ± 1.16</td>
<td>7.17 ± 1.65</td>
</tr>
<tr>
<td>Ca (%)</td>
<td>1.1 - 2.1</td>
<td>1.40 - 2.00</td>
<td>1.83 ± 0.11</td>
<td>2.45 ± 0.06</td>
</tr>
<tr>
<td>Mg (%)</td>
<td>0.3 - 0.9</td>
<td>0.30 - 0.70</td>
<td>0.72 ± 0.07</td>
<td>0.8 ± 0.08</td>
</tr>
<tr>
<td>S (%)</td>
<td>Not Listed</td>
<td>&gt;0.30</td>
<td>0.6 ± 0.06</td>
<td>0.47 ± 0.05</td>
</tr>
<tr>
<td>Mn (ppm)</td>
<td>20 - 150</td>
<td>30 - 200</td>
<td>384.67 ± 5.93</td>
<td>130.33 ± 33.74</td>
</tr>
<tr>
<td>Fe (ppm)</td>
<td>130 - 600</td>
<td>50 - 500</td>
<td>749.33 ± 165.82</td>
<td>101.33 ± 15.17</td>
</tr>
<tr>
<td>Al (ppm)</td>
<td>Not Listed</td>
<td>Unknown</td>
<td>76.33 ± 21.53</td>
<td>83.33 ± 9.28</td>
</tr>
<tr>
<td>B (ppm)</td>
<td>25 - 40</td>
<td>25 - 55</td>
<td>34.33 ± 3.53</td>
<td>34.67 ± 3.48</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>7 - 17</td>
<td>10 - 35</td>
<td>19 ± 2.65</td>
<td>15.33 ± 2.4</td>
</tr>
<tr>
<td>Zn (ppm)</td>
<td>60 - 120</td>
<td>25 - 150</td>
<td>371.67 ± 9.21</td>
<td>154.33 ± 18.78</td>
</tr>
</tbody>
</table>
4.3 Lettuce Production Cost Analysis

Unfortunately, limited data from industry sources were available for comparison of water and nutrient consumption. Of the 6 Georgia hydroponic lettuce farms queried for information regarding their production, only two responded. Of the two respondents, one refused to provide any specific information. The other did not keep specific information but were able to confirm that the nutrient solution in their system was changed weekly. This information is reflected in Table 4-3.

Currently, water costs in the United States are not high enough to have a strong impact on system economics when compared to the costs of nutrients (Table 4-3) or other potential costs not assessed here (e.g. energy). Water savings provided by the test systems translate into an approximate 3% reduction in costs assessed compared to control, 2-wk replacement, and 1-wk replacement systems. Also, the ecological and anthropogenic benefits for reducing water consumption cannot be underemphasized. A reduction in water used for agriculture could allow more water to be allocated toward other uses and also creates a much smaller waste stream, which could result in further decreased costs.

Decreased nutrient consumption amongst test systems provided the largest reduction in costs assessed; approximately 34% compared to control and 2-wk replacement systems, and approximately 60% compared to 1-wk replacement systems (Table 4-3). Additionally, this reduction of nutrient consumption is ecologically beneficial as it decreases the waste stream. While not specifically analyzed in this research, this waste stream reduction could result in further cost savings, thereby making the system more profitable.
Table 4-3. Cost analysis per system under test, control, industry standard two-week replacement, and industry reported one-week replacement. Parameters evaluated are only those considered under experimental design.

<table>
<thead>
<tr>
<th>Item</th>
<th>Test System</th>
<th>Control System</th>
<th>2 wk Replacement</th>
<th>1 wk Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$0.05</td>
<td>$0.09</td>
<td>$0.09</td>
<td>$0.15</td>
</tr>
<tr>
<td>Ca(NO₃)₂ Double Salt</td>
<td>$0.36</td>
<td>$0.37</td>
<td>$0.37</td>
<td>$0.75</td>
</tr>
<tr>
<td>KNO₃</td>
<td>$0.08</td>
<td>$0.18</td>
<td>$0.18</td>
<td>$0.35</td>
</tr>
<tr>
<td>KH₂PO₄</td>
<td>$0.23</td>
<td>$0.29</td>
<td>$0.29</td>
<td>$0.59</td>
</tr>
<tr>
<td>Trace Elements</td>
<td>$0.20</td>
<td>$0.49</td>
<td>$0.49</td>
<td>$0.98</td>
</tr>
<tr>
<td>MgSO₄</td>
<td>$0.03</td>
<td>$0.07</td>
<td>$0.07</td>
<td>$0.13</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$0.95</strong></td>
<td><strong>$1.49</strong></td>
<td><strong>$1.49</strong></td>
<td><strong>$2.95</strong></td>
</tr>
</tbody>
</table>

Reducing energy needs of closed hydroponic systems was not the aim of this study. However, the impacts of energy requirements on hydroponics are both well known and problematic (Jenner 1999). Energy is a cost that can vary substantially depending on the environment the hydroponic system is in. When energy, consumed by the pump, was considered for research systems (Table 4-4), it was seen to represent a considerable portion of the lettuce production cost; approximately 37% for test systems, 27% for control and 2-wk replacement systems, and 16% for 1-wk replacement systems.
Table 4-4. Cost analysis per system under test, control, industry standard two-week replacement, and industry reported one-week replacement. Parameters evaluated are those considered under experimental design, with energy included.

<table>
<thead>
<tr>
<th>Item</th>
<th>Test System</th>
<th>Control System</th>
<th>2 wk Replacement</th>
<th>1 wk Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$0.05</td>
<td>$0.09</td>
<td>$0.09</td>
<td>$0.15</td>
</tr>
<tr>
<td>Energy</td>
<td>$0.55</td>
<td>$0.55</td>
<td>$0.55</td>
<td>$0.55</td>
</tr>
<tr>
<td>CaNO\textsubscript{3} Double Salt</td>
<td>$0.36</td>
<td>$0.37</td>
<td>$0.37</td>
<td>$0.75</td>
</tr>
<tr>
<td>KNO\textsubscript{3}</td>
<td>$0.08</td>
<td>$0.18</td>
<td>$0.18</td>
<td>$0.35</td>
</tr>
<tr>
<td>KH\textsubscript{2}PO\textsubscript{4}</td>
<td>$0.23</td>
<td>$0.29</td>
<td>$0.29</td>
<td>$0.59</td>
</tr>
<tr>
<td>Trace Elements</td>
<td>$0.20</td>
<td>$0.49</td>
<td>$0.49</td>
<td>$0.98</td>
</tr>
<tr>
<td>MgSO\textsubscript{4}</td>
<td>$0.03</td>
<td>$0.07</td>
<td>$0.07</td>
<td>$0.13</td>
</tr>
<tr>
<td>Total</td>
<td>$1.50</td>
<td>$2.04</td>
<td>$2.04</td>
<td>$3.50</td>
</tr>
</tbody>
</table>

4.4 Environmental Data

Greenhouse Temperature

Continuous monitoring of air temperature was recorded via data logger during C1 and C2.

Temperature fluctuations varied daily throughout the growth cycles, approximate maximum of 40°C and minimum of 6°C, and showed subtle seasonal changes. Although the particular variety of lettuce, oak leaf, was selected because of its ability to tolerate higher temperature environments: the large air temperature fluctuations provided an unknown impact upon the study. It can only be stated that the greenhouse air temperatures did not prevent plant growth as plants grew during each cycle. Some of the data, 5/11/13 – 5/27/13 and 8/21/13 – 10/2/13, were automatically deleted from the data logger during battery changes, resulting in partial monitoring data collection. This loss of data had no impact on the study as these data were collected strictly for monitoring purposes. Available data can be viewed in Appendix B (Figures B-13, 15, 17, 19, 21, and 23).
Nutrient Solution Temperature and Condition

Nutrient solution temperature was recorded throughout the study. Temperature fluctuations varied daily throughout the growth cycles but the fluctuations in the nutrient solution reservoir temperatures were less than the ambient air, approximate maximum of 36°C and minimum of 8°C. As with air temperature, the large reservoir temperature fluctuations also provided an unknown impact upon the study and it can only be stated that reservoir temperature did not prevent plant growth as plants grew during each cycle. Between 5/11/13 – 5/27/13 and 8/21/13 – 10/2/13 data were automatically deleted from the data logger during battery changes, resulting in partial monitoring data collection. This loss of data had no impact on the study as these data were collected strictly for monitoring purposes. Available data can be viewed in Appendix B (Figures B-14, 16, 18, 20, 22, and 24).

During R2 of both C1 and C2 algae began to colonize the test systems. There were no control measures in place to prevent this, nor any treatment measures implemented. This incidence seemed to indicate that test system nutrient solution favored algal growth. The cause of this was unclear but could be do in part to test systems having a brief period, between R1 harvest and R2 start, where no plants were in the systems. The impact of this algae growth cannot be fully assessed. However, it can be stated that because no algae were present within the control systems and because test and control systems produced a similar yield of similar quality, that any impact was low.

Over time it is anticipated that most closed hydroponic systems will develop some type of microbial community (Ehret et al. 2001). If these communities are not controlled they can harm
the plants through infection or nutrient competition (Garland 1994; Ehret et al. 2001). Within industry this would normally be controlled for through either discarding or treating (e.g. UV) the nutrient solution.

4.5 Nutrient Solution Characterization

Serial dilution of the nutrient solution with R.O. water showed a linear relationship ($R^2 = 0.999$) between solution strength and EC (Figure 4-9). Also, serial dilution showed a linear relationship ($R^2 = 0.953$) between solution strength and pH (Figure 4-10). Recognition of these relationships are important as they provide another tool for determining the EC or pH at a particular water to nutrient ratio or a general idea of nutrient solution strength given a particular EC or pH. However, they may become limited in their usefulness when the nutrient solution is reused for long durations.

![Figure 4-9. EC of nutrient solution serial dilution with R.O. water, with linear regression fitted.](image)

$R^2 = 0.999$
Figure 4-10. pH of nutrient solution serial dilution with R.O. water, with linear regression fitted.

More beneficial to understanding changes in the nutrient solution over successive runs and being able to predict the behavior in the future, is the documentation of EC and pH changes. The EC and pH measurements of test and control systems during C2 (Figures 4-11 and 4-12) show the actual pattern of change for these systems during successive runs. Throughout C2-R1 test and control system EC behaved similarly and did not begin to deviate until the nutrient solution restoration/replacement procedures were completed for the first time. At this point it was observed that although test system EC appeared to be behaving similar to control system EC it was shifted to a higher baseline EC. This observation became more pronounced at the start of C2-R1 when the test systems were again restored and their EC had an increased starting value than that of both the control system and the R1 starting values. Preliminary, characterization of the nutrient solution in test systems was possible through these data as they provided the corresponding control system data for any given point in time. These data can be used in the
future as a model for test systems, to predict nutrient solution behavior and by extension allow for better nutrient solution control and ultimately plant performance. Comprehensive EC and pH data for all cycles can be found in Appendix B (Figures B-5 through B-12).

The preliminary trend for the EC to have an increased starting value with each successive run corroborates with data from other researchers that unused ions will build up in nutrient solutions over time (Savvas and Gizas 2002; Lykas et al. 2006). The results also corroborate with other sources that pH is not directly related to nutrient solution EC and requires additional consideration (Clark 1982).

Figure 4-11. C2 mean EC ± SE for both system types.
Figure 4-12. C2 mean pH ± SE for both system types.
5.1 Research Findings and Implications

This research intended to provide a nutrient solution management process that could be implemented by industry with minimal technology changes. The findings indicate several new considerations within the hydroponic industry and verify many current practices.

- For at least two continuous runs (approximately 8-10 weeks) lettuce could be produced without discarding water or nutrients. Resulting in approximately 42% less water, 23% less KH$_2$PO$_4$ stock solution, 57% less KNO$_3$ stock solution, 58% less MgSO$_4$ stock solution, and 58% less trace element stock solution consumed by test systems compared to control systems. Moreover the lettuce produced by the test systems was not only viable but was of similar yield and contained minimal differences in foliar nutrient concentrations compared to those of reported healthy lettuce tissue and the more traditionally managed hydroponic control systems.

- The decrease in water and nutrient consumption in test systems also resulted in an anticipated 36% cost savings compared to control systems. Any costs saved will benefit a business and allow the industry as a whole to become more competitive.

- The most important impacts of this reduction in water and nutrient consumption are ecological and anthropogenic. The data above indicate savings that can be made to hydroponic systems both in terms of resources and economics. It is the hope of this research that implementing new management practices will make hydroponic agriculture
more competitive and by extension alleviate the strain put forth by traditional soil agriculture. The 42% decrease in water consumption in test systems will allow for increased food production in a world of growing population.

- Many specifics of nutrient solution management were clarified. Primarily, the change in nutrient solution EC and pH within and across runs. During C1-R2 it became obvious that pH adjustments in conjunction with EC monitoring and nutrient balancing would be required to maintain proper nutrient solution ranges. Further, it was observed during C2-R2 that the EC would no longer be an effective means of inferring nutrient solution concentration or the point of adjustment, as previously unused ions in solution began to build up.

- The preliminary trend for the EC to have an increased starting value with each successive run is an important step to characterizing nutrient solutions over time and making management of them easier in reuse systems. By understanding how various solution parameters change during each run and from one run to the next a set of diagnostic information can be developed and used as a metric for comparing and understanding future growth cycles with successive runs.

5.2 Research Limitations

Although the hydroponic systems were deployed in a greenhouse, the structure had no environmental controls except for a circulation fan and roof vents. This of course meant that the plants and nutrient solution were subject to large and rapid temperature changes as well as fluctuations in humidity. Although the particular variety of lettuce, oak leaf, was selected
because of its ability to tolerate higher temperature environments: the lack of environmental controls surely had an impact on the entire study that cannot be determined. Additionally, on one occasion an unknown pest entered the greenhouse through the open roof vents and did damage to plants from several systems: again resulting in an impact that cannot be fully determined.

Crop growth and viability is also strongly tied with climate, and the impact of the southeastern Georgia climate on crops grown in a greenhouse without environmental controls is another factor to consider when interpreting the results of this research. In addition, the seasonality of the region plays a considerable role as both growth cycles occurred during different seasons.

5.3 Recommendations of Future Research

There exist many recommendations for future research that both expand on the findings of this research and address the limitations as well. The first is to reproduce the results of this research within a fully controlled indoor growth environment using artificial lighting. This would effectively eliminate all the environmental and geographic impacts on the study and, although it would be more costly to perform, the results obtained would be a better indication of the principles surrounding nutrient solution reuse. Also, increasing the number of runs per cycle until either a difference in crop quality or non-viability is seen will contribute to understanding maximum nutrient solution lifespan (i.e. stress test).

Utilizing modern electrodes to monitor specific nutrients within the nutrient solution would also provide an enhanced ability to manage the nutrient solution. Instead of using the EC as an indicator of nutrient solution status, drawing a water sample, and analyzing it for the primary nutrient concentrations. The nutrient concentration itself could be recorded directly and
monitored over time. This would provide far greater precision in managing and maintaining the nutrient solution and could potentially result in increased yields or increased nutrient solution lifespan.

As stated in the research and literature, the energy requirements within hydroponics are much higher compared with soil agriculture and make it much more difficult for the industry to be competitive. Although a great quantity of research exists on alternative energy sources, future hydroponic research should focus on reducing the energy budget of hydroponic production through alternative techniques such as passive filtration and decreasing pumping.

The aforementioned data is for lettuce growth only. Industrial farmers should be advised to introduce reuse practices slowly. Crop type plays a profound role in nutrient consumption rates and directly impacts nutrient restoration and sampling protocol. As every hydroponic system construction and setup is different, farmers should start at a small scale and fully characterize the nutrient solution within their system for their crop. This will help them determine their point of maximum risk and what control measures they need to put in place before they begin transitioning to reuse practices on a larger scale. However, the results of this study indicate that some of the more common hydroponic practices are wasteful and with minimal process changes savings can be acquired immediately.
REFERENCES


Economakis, C.D. 1990. Effect of Solution Conductivity on Growth and Yield of Lettuce in


APPENDIX A: SUPPLEMENTAL MATERIALS AND METHODS

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Nutrient Film Technique Hydroponic System Construction

<table>
<thead>
<tr>
<th>Materials per Hydroponic System</th>
<th>Equipment List</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 3” PVC cap, Qty. 1</td>
<td>- Drill</td>
</tr>
<tr>
<td>- 3” 90º PVC elbow, Qty. 2</td>
<td>- Mandrel</td>
</tr>
<tr>
<td>- 3” to 1 1/2” 90º PVC reducer, Qty. 1</td>
<td>- 2” hole saw</td>
</tr>
<tr>
<td>- 10’ of 3” PVC pipe, Qty. 1</td>
<td>- 1/2” drill bit</td>
</tr>
<tr>
<td>- 1’ of 3” PVC pipe, Qty. 1</td>
<td>- PVC primer</td>
</tr>
<tr>
<td>- 2’ of 1 1/2” PVC pipe, Qty. 1</td>
<td>- PVC glue</td>
</tr>
<tr>
<td>- 100 GPH fountain pump, Qty. 1</td>
<td>- PVC cutter</td>
</tr>
<tr>
<td>- 2 1/2’ of 1/2” black vinyl tubing, Qty. 1</td>
<td>- PVC saw</td>
</tr>
<tr>
<td>- 5 gallon bucket with lid, Qty. 1</td>
<td>- Tape measure</td>
</tr>
<tr>
<td>- 5’ of 1/2” PVC pipe, Qty. 1</td>
<td>- Chalk line</td>
</tr>
<tr>
<td>- 1/2” PVC tee, Qty. 16</td>
<td></td>
</tr>
<tr>
<td>- 2” net pot, Qty. 12</td>
<td></td>
</tr>
</tbody>
</table>

Channel Assembly

The nutrient film technique (NFT) hydroponic system was assembled in two runs of equal length from 3” PVC pipe (Figure A-1). PVC is an economical solution for use in hydroponic channels and is a widely accepted building material for research purposes.
Figure A-1. Hydroponic system schematic.

1. Cut the 3” x 10’ length of pipe into two 5’ lengths.

2. Measurements for plant holes: Starting on one end of a 5’ length measure off 5” and mark. Continue to measure off every 10” and mark. When finished, there should be 6 evenly spaced marks down the length of the pipe.

3. Snap a chalk line down the 5’ length ensuring that it is straight and intersects with all marks.

4. Drill 2” holes for plants on the center of each mark.

5. Drill a 1/2” hole at the top end of the 3” cap (Figure A-2).

6. Drill 1/2” and 2” holes, for the pump line and return pipe respectively, in the lid of the 5-gallon bucket.
7. Prepare the lengths to be joined together by applying primer on the 5’ lengths, the 1’ connecting piece, the 3” cap, the 3” to 1 1/2” 90º reducer, and the two 3” 90º elbows.
8. Glue the 3” PVC cap to the end of one of the 5’ lengths of 3” pipe (Figure A-2).
9. Glue the 3” to 1 1/2” 90º reducer to the end of the second 5’ length of 3” pipe, ensuring that it face down from the plant holes.
10. Dry fit the 1’ length to the elbows so that they form a small ‘U’ shape (Figure A-3).
11. Dry fit the 5’ lengths to the elbows creating a large ‘U’ shape. This completes the channel assembly. Do not glue the assembly yet.
Figure A-3. Channel connector assembly.

Stand Assembly

The stands were also made from PVC due to cost (Figure A-4) and ensure proper flow throughout the NFT system, which should be between 1 – 2 L/min.

1. Cut two of the following from the 1/2” pipe: 6” lengths, 5 1/2” lengths, 5” lengths, and 4 1/2” lengths.
2. Cut four 3” lengths from the 1/2” pipe.
3. Dry fit the long lengths to the 1/2” tees.
4. Dry fit the 3” length as a crossbar connecting the two halves.

Upon completion there should be a 6”, 5 1/2”, 5”, and 4 1/2” stand. Additional pieces of 1/2” pipe can be used to create additional support. There is no need to glue the stands.
Figure A-4. Stand assembly.

**Apparatus Assembly**

1. Place the dry fitted channel onto the stands, with the tallest stand at the influent and the shortest at the effluent.
2. Bend the channel assembly at the elbows into resting position.
3. Glue the channel joints together, making sure to maintain proper angles for the resting position.
4. Glue the 2’ length of 1 1/2” pipe to the 1 1/2” end of the reducer, this will serve as the water return pipe (Figure A-5).
5. Place the 5-gallon bucket underneath the 1 1/2” PVC pipe with the pipe entering the 2” hole in the lid (Figure A-6).
6. Place the fountain pump inside of the bucket with the vinyl tubing connected to the pump extending through the 1/2” hole in the bucket lid and securely placed in the 1/2” hole in the 3” cap (Figures A-5 and A-6).
7. Place 2” net pots in all plant holes along the main 3” pipe.
The NFT apparatus is completely assembled.

Figure A-5. Fully assembled NFT system.

Figure A-6. Reservoir apparatus with pump line and return pipe.
Sample Calculation – KH₂PO₄

\[ C_1 \cdot V_1 = C_2 \cdot V_2 \]

1 molar KH₂PO₄ stock solution = 136 g/L
K⁺ in KH₂PO₄ ≈ 29%
PO₄³⁻ in KH₂PO₄ ≈ 70%

CALCULATION 1: Theoretical concentration of KH₂PO₄ (mg/L) in nutrient solution

Per nutrient solution (ns) specifications 0.5 mL of KH₂PO₄ stock solution (ss) per L of water.

\[ C_{ss} \cdot V_{ss} = C_{ns} \cdot V_{ns} \]

\[ (136 \text{ g/L}) \cdot (0.0005 \text{ L}) = C_{ns} \cdot (1 \text{ L}) \]

\[ C_{ns} = 0.068 \text{ g/L} = 68 \text{ mg/L} \]

CALCULATION 2: Sample nutrient solution restoration calculation for KH₂PO₄

Spectrophotometer reading for PO₄³⁻ concentration = 0.182 mg/L. Adjusted for 1:100 dilution: 18.2 mg/L.

Find current theoretical concentration of KH₂PO₄:

70% (KH₂PO₄) = 18.2 mg/L of PO₄³⁻

KH₂PO₄ ≈ 26 mg/L \therefore 26 mg/L KH₂PO₄ presently in solution

Find amount of KH₂PO₄ to add:

68 mg/L total KH₂PO₄ is needed in solution. Current theoretical concentration is approximately 26 mg/L.

\[ 68 \text{ mg/L} - 26 \text{ mg/L} = 42 \text{ mg/L} \text{ KH₂PO₄ to be added to nutrient solution reservoir} \]

\[ C_{ss} \cdot V_{ss} = C_{ns} \cdot V_{ns} \]

\[ (136,000 \text{ mg/L}) \cdot (V_{ss}) = (42 \text{ mg/L}) \cdot (24 \text{ L}) \]

\[ V_{ss} = 0.00741 \approx 8 \text{ mL} \text{ KH₂PO₄ stock solution to be added} \]

Addition of KH₂PO₄ contributes additional K, which must be allocated for in subsequent K calculations. This is applicable to all calculations where a prior stock solution addition increases the concentration of a salt yet to be restored.
Hydroponic Survey

Type of Hydroponic System Used:

Frequency of System Flushes (per harvest, all nutrient solution discarded):

Average Total Plant Production (per harvest):

Average Nutrient Solution Consumption (per harvest):

Average Nutrient Consumption (per harvest, nutrient concentrate added to reservoir):

Water Unit Cost (per harvest):

Nutrient Unit Cost (per harvest):
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Table B-1. Summary of C1 and C2 fresh aboveground mass, total water consumption, and total nutrient consumption.

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<thead>
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<th>Cycle</th>
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<th>Fresh Aboveground Mass (g)</th>
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<th>Total $\text{KNO}_3$† (mL)</th>
<th>Total $\text{CaNO}_3$† (mL)</th>
<th>Total $\text{MgSO}_4$† (mL)</th>
<th>Total Trace Elements† (mL)</th>
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Note: Empty cells in Aboveground Dry Mass column were due to the dry biomass of non-viable plants being too low to accurately measure.
† Stock solution
Table B-2. C1 and C2 spectrophotometer readings for test system samples.

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<th>Cycle</th>
<th>Run</th>
<th>Concentration (mg/L)</th>
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<th>System 4</th>
<th>System 5</th>
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<td>K⁺</td>
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*Values were below spectrophotometer range, therefore highest concentration undetectable by particular HACH method assumed

Table B-3. C2 pH buffer additions.

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<td>pH Down</td>
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<td>-</td>
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Table B-4. C2 foliar nutrient concentrations.

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<th>P (%)</th>
<th>K (%)</th>
<th>Ca (%)</th>
<th>Mg (%)</th>
<th>S (%)</th>
<th>Mn (PPM)</th>
<th>Fe (PPM)</th>
<th>Al (PPM)</th>
<th>B (PPM)</th>
<th>Cu (PPM)</th>
<th>Zn (PPM)</th>
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Note: The table continues with similar entries for Run 2.
Figure B-1. C1-R2 total water consumption per system type, test system plants were non-viable.

Figure B-2. C1-R2 total nutrient consumption per system type, test system plants were non-viable.
Figure B-3. C2-R1 total nutrient consumption per system type.

Figure B-4. C2-R2 total nutrient consumption per system type.
Figure B-5. C1-R1 electrical conductivity.

Figure B-6. C1-R2 electrical conductivity.
Figure B-7. C2-R1 electrical conductivity.

Figure B-8. C2-R2 electrical conductivity.
Figure B-9. C1-R1 pH.

Figure B-10. C1-R2 pH.
Figure B-11. C2-R1 pH.

Figure B-12. C2-R2 pH.
Figure B-13. C1-R1 continuous hourly air temperature ± SE.

Figure B-14. C1-R1 continuous hourly reservoir temperature ± SE.
Figure B-15. C1-R1 daily mean air temperature ± SE

Figure B-16. C1-R1 daily mean reservoir temperature ± SE
Figure B-17. C1-R2 partial continuous hourly air temperature ± SE.

Figure B-18. C1-R2 partial continuous hourly reservoir temperature ± SE.
Figure B-19. C1-R2 partial daily mean air temperature ± SE

Figure B-20. C1-R2 partial daily mean reservoir temperature ± SE
Figure B-21. C2-R2 continuous hourly air temperature ± SE.

Figure B-22. C2-R2 continuous hourly reservoir temperature ± SE.
Figure B-23. C2-R2 daily mean air temperature ± SE

Figure B-24. C2-R2 daily mean reservoir temperature ± SE