A GUIDE TO HOME HYDROPONICS

FOR LEAFY GREENS

Cornell Controlled
Environment
Agriculture

Ryan Ronzoni rjr293@cornell.edu

Neil Mattson neil.mattson@cornell.edu

May, 2020

Objectives

In recent years, hydroponic facilities have become more common, and more research is being done towards better understanding of hydroponic techniques. Research is ongoing in lighting, system design, and energy management, all with the goal of producing more crops with less input. There is however, less research and material to be found on information for the home grower.

Just as commercial hydroponic facilities are becoming more popular, so are home systems. There are several companies that offer hydroponic kits for home use, and many people choose to build their own systems. For a home grower to find information about how to grow crops hydroponically they often have to search through hobby websites, university extension websites, and youtube. There is certainly good information out there, however it is difficult to find all the information in one spot. In addition, there are some sites that can have misleading or wrong information, and not all home growers may be aware of this.

This guide has two goals. 1) To provide a single source of information on home level hydroponics and 2) to show data from experiments done to help a grower decide what systems, tactics, and plant care is right for them. Experiments were conducted on head lettuce as a proxy for general leafy green growing, and specific experiments were done on lights a home hydroponic grower might use, the use of fans in hydroponics, and the use and care of fertilizer in nutrient solutions.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

CEA	Controlled Environment Agriculture
DLI	Daily Light Integral
DO	Dissolved Oxygen
DWC	Deep Water Culture
EC	Electrical Conductivity
HID	High Intensity Discharge
HPS	High Pressure Sodium
LED	Light Emitting Diode
MH	Metal Halide
Mole	A quantity referring to $6.02214078 \times 10^{23}$ of something
NFT	Nutrient Film Technique
PAR	Photosynthetically Active Radiation
pH	potential for hydrogen
PPFD	Photosynthetic Photon Flux Density
PVC	Polyvinyl Chloride
SFW	Square Foot Week

1. Introduction

Hydroponics refers to the method of growing plants in soilless media. While we generally think about growing crops hydroponically as a new idea, the method has been in use for quite some time. Some of the earliest hydroponic like systems were the floating floating gardens of the Aztecs! After that however, there wasn't much in the way of hydroponics until the early to mid 1800's when scientists realized that they could grow crops in water if they gave them nutrients (Resh, 2013). In the early 1900's, greenhouses started to take interest in hydroponics because they were constantly having to replace their soil due to problems with pests, fertility, and soil structure (Resh, 2013). Hydroponics started to gain popularity with scientists who used it as a way to perform experiments on plants in a highly controlled manner.

Today, many commercial facilities use hydroponics as a way to grow consistent quality vegetables year round. The largest operations are in Mexico, Canada, the US, Belgium, and Holland. The most important hydroponic crops for these operations are tomatoes, lettuce, cucumbers, and peppers (Resh, 2013).

The main draw of hydroponics comes from the ability to grow year round, local, and generally pesticide free produce. In addition, hydroponic farms are able to produce higher yields of produce when compared to conventional farms due to efficient use of fertilizers directly to the root zone and spacing (Resh, 2013). Given that most hydroponic farms are in controlled environments, there is a general lack of pests, pathogens, and weeds which leads to a lower use of pesticides and herbicides compared to a conventional farm (Resh, 2013) . Controlled environment also allows for more efficient water use than conventional methods (up to 20 percent) (Mattson, 2020). Once on the market, hydroponic vegetables can have a longer shelf life than non hydroponic plants, even more so when the roots are still attached.

The most common systems include deep water culture, nutrient film systems, and rockwool culture. Nutrient film and Deep Water systems are often used for leafy greens and rockwool culture is often used for vine crops like tomatoes and cucumbers. At the home level, the best success is likely to be found with a small deep water culture or nutrient flow technique system.

This guide aims to give you practical knowledge for maintaining leafy greens in a hydroponic set up, and to provide information on how to construct your own system. There are 10 sections that include topics such as lighting, nutrient solution, and seed starting. Each section includes a detailed discussion on the different aspects of the topic that would be useful for a home grower to know. At the end of each section there is a "quick guide" which aims to both recap the main points of the section and to provide easy steps to follow without having to read the entire section. Furthermore, I have detailed several experiments conducted at Cornell to help visualize and answer some common questions about plant lighting and nutrition in a home hydroponic setting.

2. Lighting

Lighting may be one of the most important aspects when it comes to setting up your hydroponic system. Light is the main driver of plant growth, and controls a plethora of plant functions such as germination, flowering, pigmentation, biomass accumulation, and of course photosynthesis (Peacock, 2015). When it comes to lighting your system, there are a few important factors to consider. The first is light quantity.

Light quantity refers to how much light the plant is receiving. Overall plants require much more light than humans do for vision (perhaps 20 times more to get decent photosynthesis of leafy greens). For plants we use a different unit for measuring light than for humans (in which we can talk about light in lumens or footcandles). For plants we consider all light between the wavelengths of 400 to 700 nanometers (basically all the colors from blue to red in the rainbow). We call this range of light Photosynthetically Active Radiation, or PAR for short. These are the wavelengths that are the drivers of photosynthesis.

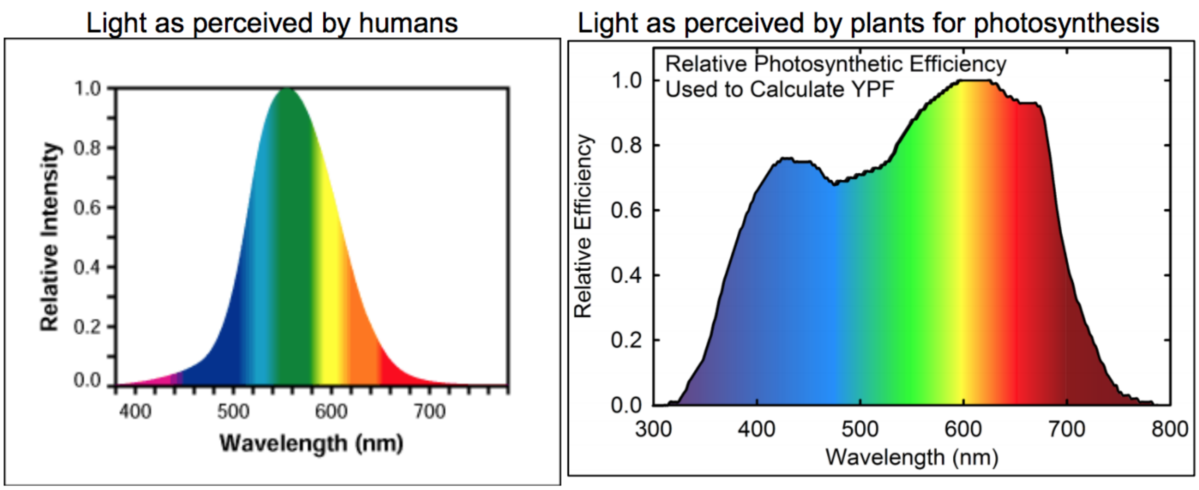

Figure 1. Light perceived by humans and plants

We measure this light by the amount of photons (the smallest particle of light) passing through a square meter every second. This is known as the photosynthetic photon flux density (PPFD) and the preferred units are micromoles per square meter per second (umol m^{-2} s^{-1}). If you were to measure the total number of light particles hitting a square meter for the entire day you get what is known as the Daily Light Integral, or DLI. The DLI is the total amount of light received per day and the prefered units are moles of light per square meter per day (mol m^{-2} day^{-1}). Notice that we look at moles, not micromoles, when it comes to the DLI. This is because if you were to measure micromoles per day you would have an extremely large number as there are 1 million micromoles per mole, and 3600 seconds per hour. For more helpful information check out https://extension.unh.edu/resource/growing-seedlings-under-lights-fact-sheet (Ebba, 2020).

For leafy greens, we generally want 12-17 moles of light per day, or about 12 watts of electricity from a lighting fixture per square foot of growing area if information about DLI is not available (Mattson, 2017). When all else fails, just look at the plants. If they look stretched and thin, then you need more light (either more intensity or longer duration of lights turned on). Too much light will generally show itself in the form of tip burn (see “physiological disorders” section).

Another important factor is light quality. Light quality refers to the wavelengths of light. It is known that certain wavelengths can have different effects on plant growth. For example, far red light tends to stretch plants, and blue light tends to cause shorter and stockier plants (Mattson, 2017). Other wavelengths can induce secondary compounds in plants (Peacock, 2015). And yes, plants do use greenlight for photosynthesis! However, for the purpose of home hydroponics, almost any light will do as long as it can provide the correct quantity of light. In fact, for general purposes, plants tend to grow best under light conditions similar to the sun and you won’t see major benefits of one spectra over another. LED lights will often make claims about how they have the best spectra for growing vegetables, however the main reason you would choose an LED light is its efficiency (the amount of PAR it can generate per unit of electricity) not its spectra.

Three major types of horticultural lights include High Intensity Discharge (HID) lights (including High Pressure Sodium [HPS] and Metal Halide [MH] lights), Fluorescent lights (T5 are the newest fluorescents that are most common), and Light Emitting Diodes (LED). Many commercial growers use High Intensity Discharge lights in greenhouses, and will often have large lamps that are each 1000W. These lights generally have good efficiency when it comes to light output for the electricity used, and have a characteristic peak of intensity in the far-red part of the spectrum.

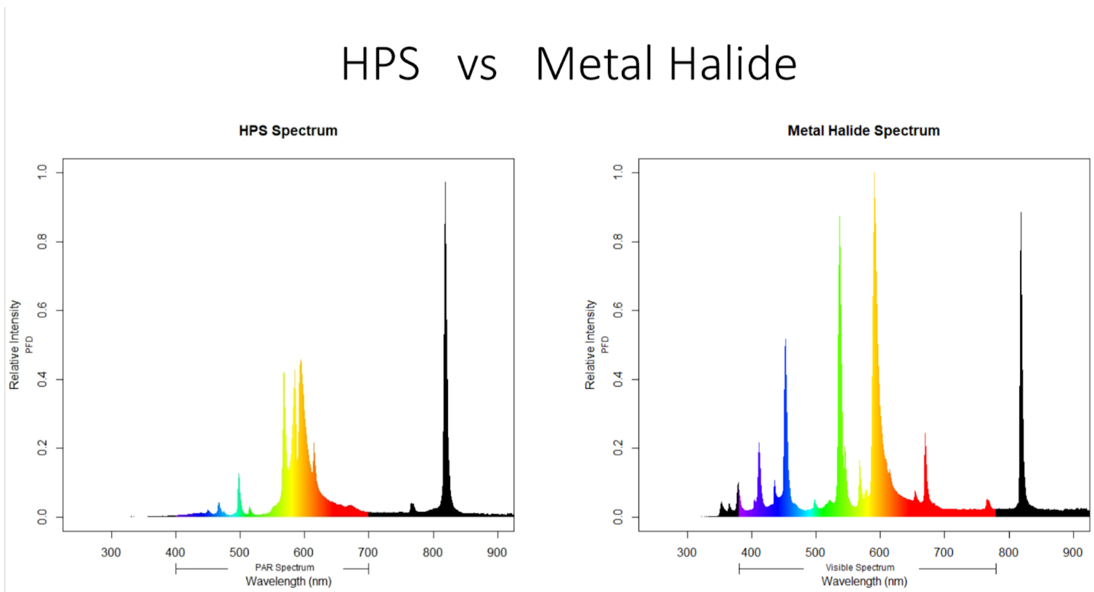

Figure 2. Spectral Output of HPS and MH lights

LEDs have become more common in commercial growing settings as efficiency keeps getting better and better (Both et. al, 2017). Some LEDs even allow you to control the specific waveband (colors) or the light intensity if you desire. There are many types of LED lights out there including panel lights, bar lights, and point source lights (used to replace High Intensity Discharge Lights). The main reason for a home grower to use an LED light would be the cost (when compared to an HID light) and their electrical efficiency.

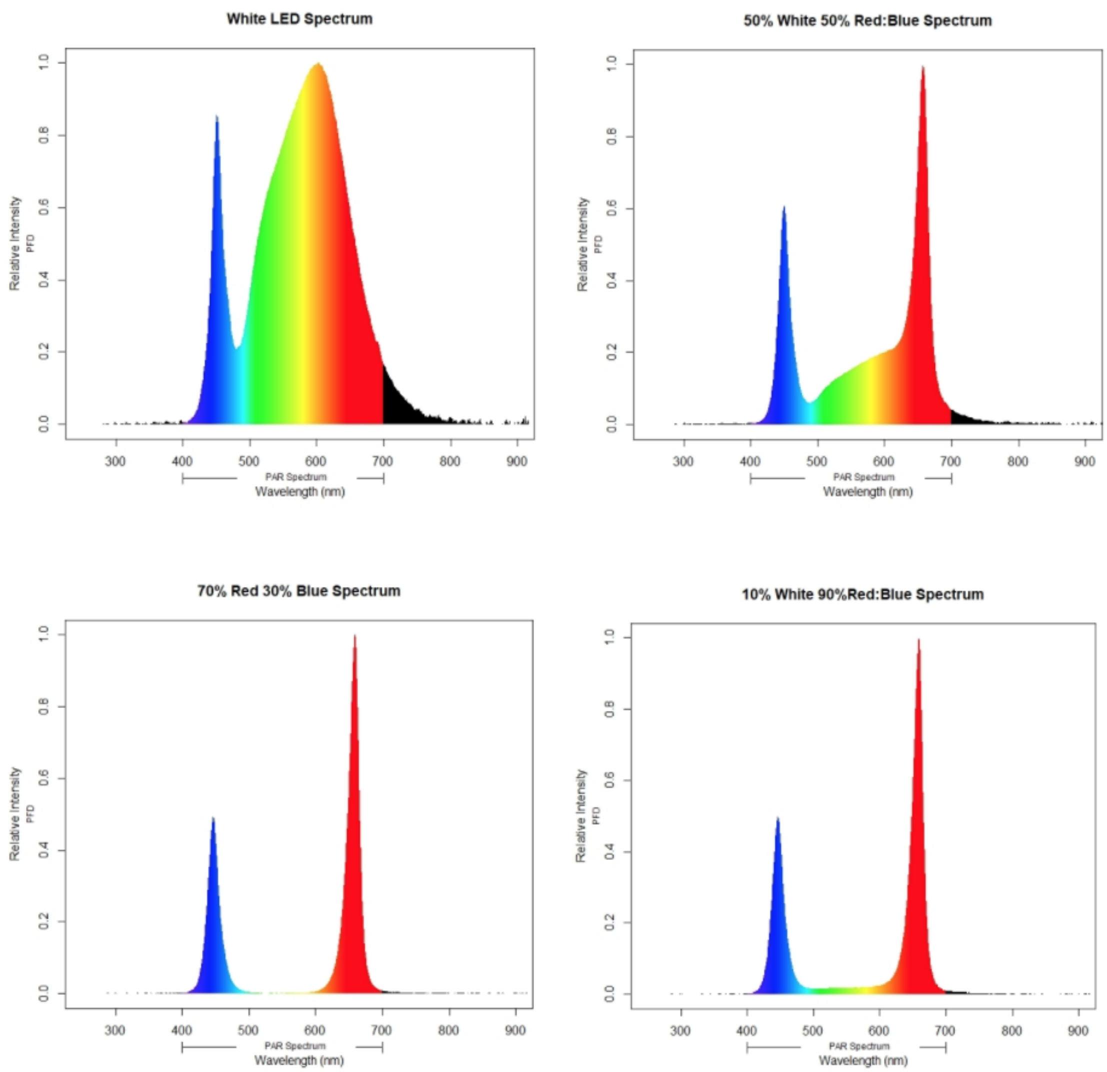

Figure 3. Examples of LED spectral outputs

T5 fluorescent lights are often used for seed starting in commercial operations, but can also be used as the major light source in a home setting. In fact, some might consider them to be the workhorse of home scale grow lighting. They tend to have good efficiency and have a pretty broad spectrum output. However they generally don't produce as much light as a HID or LED fixture would. They look white to our eyes, but have peaks in blue, green, and red light.

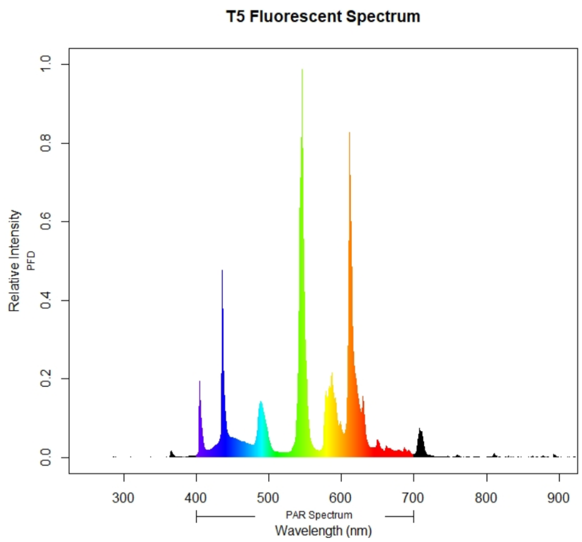

Figure 4. T5 Fluorescent spectral output

How do these light factors relate to home hydroponics? They will help guide you in determining the type of light to use, the height at which to hang it, and the amount of time to leave the light on per day. Spectra will most likely be determined by the type of light you use, and quantity will be determined by a combination of the type of light, height it is hung, and duration it is kept on.

2.1 Lighting Calculations

Now that we have discussed the different aspects of light and how they relate to growing plants, let's do some actual calculations to estimate the height at which to hang lights, and how long to keep them running. If you don't enjoy calculations, or wish to spend your time just growing - you can jump directly to the lighting quick guide. However, if you wish to learn more details about lighting plants - read on!

2.1.1 DLI and Run Time

First, let's discuss calculations for Daily Light Integral (DLI) and light run time.

Example: Let's say you have a light that you know produces 200 μmol·m^{-2}·s^{-1} (PPFD) of light at plant canopy when hung at 15 inches above plants. You want to know the DLI if you run your light for 24 hours. To determine the Daily Light Integral (DLI) you will want to use this equation:

$$DLI = \frac{PPFD \times \frac{3{,}600\ seconds}{hour} \times run\ time\ (in\ hours)}{\frac{1{,}000{,}000\ umol}{mol}}$$

For our example:

$$DLI = \frac{\frac{200\ umol}{meter^2 \times second} \times \frac{3{,}600\ seconds}{hour} \times 24\ hours}{\frac{1{,}000{,}000\ umol}{mol}}$$

$$DLI = \frac{17.28\ mols}{meter^2 \bullet day} = 17.28\ \text{mols}\cdot m^{-2}\cdot d^{-1}$$

If you already know the micromoles per second at a certain height, and you would like to figure out how long to run the light based on your desired DLI (mol·m^{-2}·d^{-1}), you can rearrange the formula so that it looks like this: $Run\ time = \frac{DLI \times \frac{1{,}000{,}000\ umol}{mol}}{PPFD \times \frac{3{,}600\ seconds}{hour}}$

Example: Let's say we have the same light with an output of 200 μmol·m^{-2}·s^{-1} at crop level when hung 15 inches above the plant. We know we want 15 mol·m^{-2}·d^{-1} of light per day, so to calculate how long we need to run the lights we do:

$$Run\ time = \frac{\frac{15\ mol}{meter^2 \bullet day} \times \frac{1{,}000{,}000\ umol}{mol}}{\frac{200\ umol}{meter^2 \bullet second} \times \frac{3{,}600\ seconds}{hour}} = \frac{20.8\ hours}{day}$$

One thing to think about is that plants tend to do better with DLIs spread over a longer period of time. For example, lettuce will perform better with 15 moles of light over a time period of 20 hours compared to 15 moles of light over a time period of 5 hours (Both et. al, 1994).

2.1.2 Light Height and Area Lit

Determining the height at which to hang your light can be a little tricky depending on what information the manufacturer gives you. Horticultural grade lamps might give you information on the light intensity ($\mu mol \cdot m^{-2} \cdot s^{-1}$ [PPFD]) at different heights, and if this information is available to you, then it's quite easy. Choose a height that looks like it gives good coverage of all plants and then use the formulas described above to calculate run time based on the height you have chosen.

If you have a commercial grow light, the information you are given could be the total output of the light in umol/sec. In this case, the first thing you will want to do is to calculate the area the fixture can light using this equation. $Area = \frac{total\ output}{desired\ instantaneous\ light}$

Example: You have a HPS light with a total output of 500 μmol/second. You have a desired instantaneous light output of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (the light level at plant canopy) . How much area can the fixture light? $Area = \frac{total\ output}{desired\ instantaneous\ light} = \frac{\frac{500\ \mu mol}{second}}{\frac{200\ \mu mol}{meter^2 \cdot second}} = 2.5\ square\ meters$

Now that you know the fixture can light 2.5 square meters, you should adjust the height so that the area has even light coverage. You can then calculate the run time based on equations previously mentioned and your desired instantaneous light output.

2.1.3 Lights without specified PPFD

Unfortunately, not all light manufacturers provide the PPFD at certain heights for their lights. You could use a PAR light meter (often called a quantum sensor), however these can be quite expensive ranging anywhere from $300 - $1000+. In the case you are not given PPFD, a good estimate to go by is 12 watts of electricity from the light fixture per square foot of growing area, and then adjust the light to a height that seems to give good coverage of the growing area (Mattson, 2017).

Example: You have a growing area that is approximately 2ft x 2ft. What is the light requirement in watts? We know that 2 ft x 2 ft = 4 sqft, and we know we want 12 watts per square foot. So all we have to do is multiply $4\ square\ feet \times \frac{12\ watts}{square\ foot} = 48\ watts.$ This means you want your light, or combination of lights, used for that area to be around 48 watts.

After you have chosen a light based on the area you need to light, and a height based on good light coverage of that area, the next step is to choose a run time for the light. Again, in the absence of PPFD you can’t make exact calculations, but in general, if you follow the 12 W per square foot rule of thumb, to produce enough light for leafy greens, you will want to run T5 fluorescent lights close to 24 hours a day, 150W HPS lights around 16 hours a day, and LED lights also about 16 hours per day (though LED lights are more variable in their output and actual values will depend on their output).

The moral of this story is that grow light manufacturers should report their light output in PPFD (with units of $\mu mol \cdot m^{-2} \cdot s^{-1}$)! (See https://doi.org/10.21273/HORTTECH03648-16 for more details). To recap, if you don’t have PPFD information your best bet is to aim for 12 watts per square foot, adjust the light height so there is even coverage, and aim anywhere from 15-24 hours a day run time. Use your best judgment based on the look of the plants. If they are tall and stringy run the lights longer, and if they have tip burn (see physiological disorders) then they are probably getting too much light and you should decrease the run time.

2.2 Electrical Calculations

Electricity Calculations:

When looking at the cost of your system it's important to think about the electrical cost. Electricity is generally charged based on Kilowatt hours (kWh). You can use this formula to find your electricity usage, and then multiply your usage by your electricity cost to find the total cost of any electrical use for the system including lights and pumps.

$$kWh = \frac{Power\ consumption\ (watts) \times number\ of\ hours\ used}{1000}$$

Example: You are charged $0.21 per kWh used. You run a 150W HPS light for 15 hours a day for 35 days. What is the electric bill charge for that light?

$$\frac{150\ watts \times \frac{15\ hours}{day} \times 35\ days}{1000} = 78.5\ kWh$$

Then multiply the kWh used by the price of electricity $/kWh):

$78.5\ kWh \times \frac{\$0.21}{kWh} = \$16.54$ for the 525 hours you ran the light.

2.3 Case Study

To help in the decision to choose a light, I ran some experiments with a range of lights a home grower might choose to use. In these experiments I measured the light output at different heights using a PAR light meter and made calculations for suggested heights and run times. My results and recommendations are as follows. (Based on a roughly 2 square foot growing area, and goal of 15 $mol \cdot m^{-2} \cdot d^{-1}$ of light)

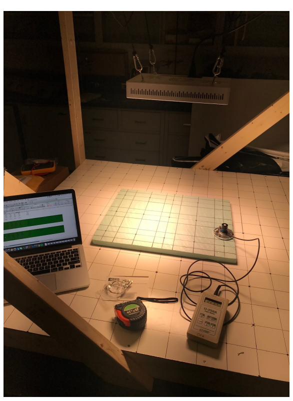

Image 1. PPFD measurements being taken on an LED light with a quantum sensor.

Table 1. Light Recommendations for DLI of 15 mol·m^{-2}·d^{-1} for a 2ft^2 growing area

Light Tested	Height above plants (in inches)	Average umol/(m^2 • s) at specified height	Run time (in hours per day)
SunSystem 150W HPS	15	270.3	15.5
Durolux 48W T5 Fluorescent ****	7	126.3	24
RAB 2X2 40W LED Panel	4	269.7	15.5
iGrowtek 50W (total) LED Bar	6	264.2	15.5
Growstar “50W” LED clip on ****	9	73.8	24
Monios T5 LED	8	260.3	15.5
YGROW LED (“600W HPS equivalent”	18	295.8	14
Aceple LED (“600W HPS equivalent”	18	268.8	15.5

(****Neither the T5 Fluorescent or the LED clip on could reach 15 mol·m^{-2}·d^{-1}, DLIs were 10.92 mol·m^{-2}·d^{-1} and 6.8 mol·m^{-2}·d^{-1} respectively.)

In another experiment, I grew lettuce under 5 types of lights that home growers are most likely to use. The lettuce cultivar Rex Butterhead from Johnny’s Seeds was selected as it is a good representative of lettuce that could be grown in a home hydroponic system. The hydroponic systems used were home made deep water culture systems (approximately 2 ft^2 growing area) that held 6 plants and could easily be constructed for use at the home level (see the DIY section under deep water culture). The lettuce was grown for a 35 day period, with transplanting done on day 11 and then grown for an additional 24 days in the hydroponic systems under the lights. The pH and EC were kept at 5.6 and 1.4 mmhos/cm (from fertilizer) respectively. The treatments and results are as follows.

1) HPS giving 15 mol·m^{-2}·d^{-1}
2) LED Panel giving 15 mol·m^{-2}·d^{-1}
3) LED bar giving 15 mol·m^{-2}·d^{-1}
4) T5 fluorescent giving 10.92 mol·m^{-2}·d^{-1} (This was the max output for 24 hours)
5) Led clip on giving 6.8 mol·m^{-2}·d^{-1} (This was the max output for 24 hours)
    a) This clip on light claimed it was a 50W replacement for a 150W HPS light, however it was found to only draw 12W and did not have the output of an HPS. So be careful if you are looking at cheap lights that promise great results.

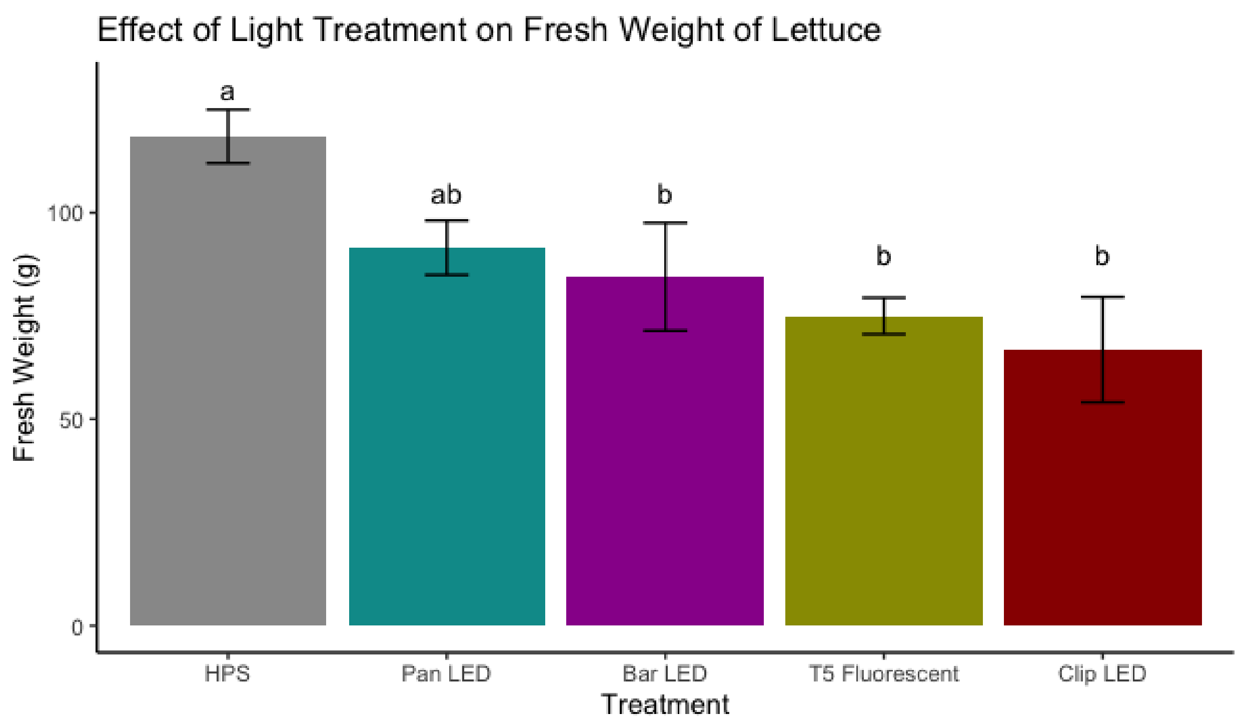

Figure 5. Fresh Weight of lettuce based on light treatment (treatments with the same letters are not significantly different from each other, based on Tukey HSD test with significance level of 0.05)

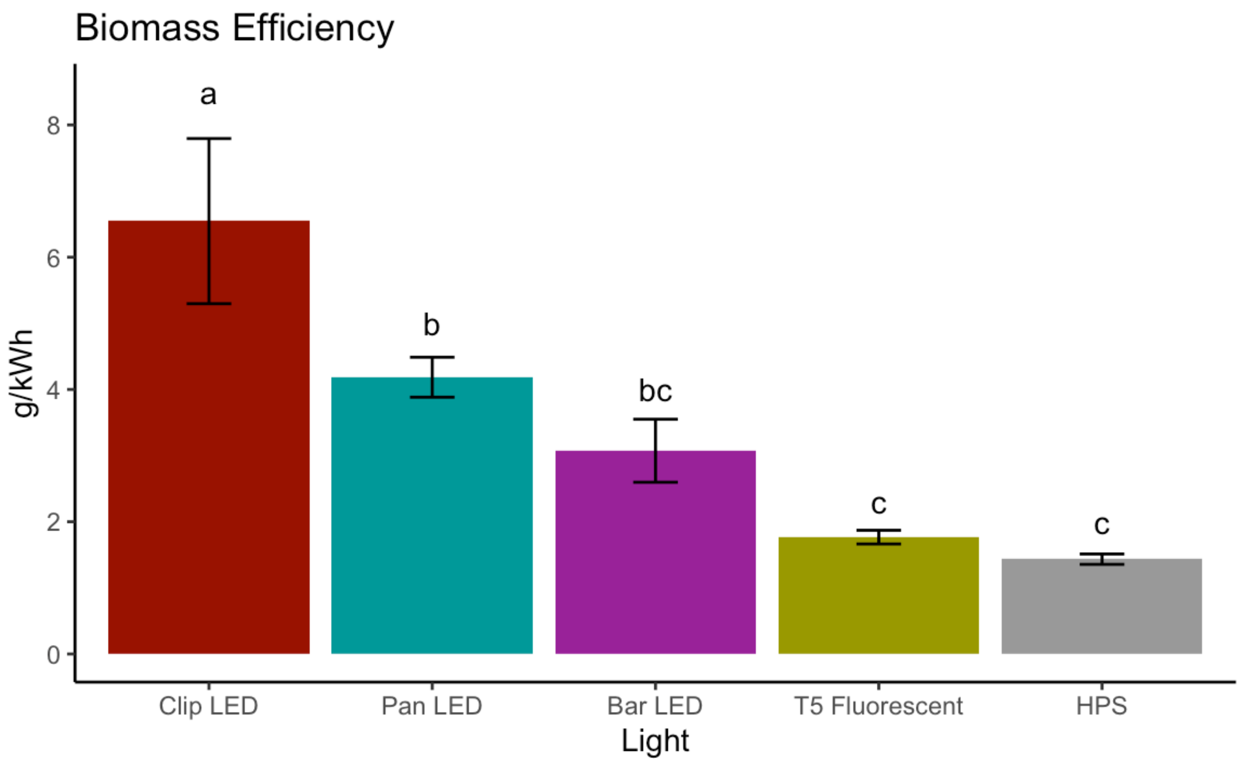

Figure 6. Biomass efficiency of lights based on 2 ft^2 area (treatments with the same letters are not significantly different from each other based on Tukey HSD test with significance level of 0.05)

Image 2. HPS treatment

Image 3. LED Panel treatment

Image 4. LED Bar treatment

Image 5. TR Fluorescent Treatment

Image 6. LED clip on treatment

Image 7. Lettuce heads from LED clip on treatment

The HPS was the clear winner when it came to both fresh weights and dry weights (figure 5. However, the LED Panel and LED Bar lights were not too far behind. In addition, the LED Panel light had a significantly better efficiency in terms of grams of biomass efficiency (i.e. the fresh weight of lettuce produced per kWh of electricity used) than the HPS. The LED Panel and LED bar both had similar electrical efficiency and both cost less than an HPS fixture - making them both fine choices for the home grower. However, almost all of the lights tested would make fine lights for a home grower. You just have to think about what you are looking to get out of your lights(i.e. the highest yield? Or a balance between light cost, electricity use and yield?).

For example, if your goal is to produce as much lettuce as possible (similar to a commercial greenhouse grower) than the HPS is the way to go. The downside with the HPS is that it is the most expensive, and also will cost the most in terms of electricity use. The 150 W HPS fixture could have been used to light a bigger space than the 2' x 2' area in our experiment so a solution might be to use the one HPS to light 2 DWC bus bucket systems.

If you would rather save some money (both in initial costs, and electrical costs), knowing that it will take a little longer to grow your heads of lettuce to your desired weight (a week more at most), then finding some sort of lower wattage (when compared to the HPS) LED (but still aiming for the 12 watts per square foot rule of thumb) is the way to go. In addition, many LED lights will have good light coverage of your growing area (based on their design). I really like the panel and bar options because they are a good way to have even distribution of light throughout your growing area.

Or maybe you have a smaller system with only one row of crops. In this case, you could think about using a T5 Fluorescent light. You won't have to worry as much about light distribution in a smaller system, and hanging the light directly over the crops will provide higher light levels than if you were trying to light several rows.

Even the little clip on LED (which in our experiment only used 12 W) could have its place. Let's say you are only growing 1 or 2 heads of lettuce, or just a couple small herbs in a one square foot area, then you could put this light directly over them and get good results. In our experiment the LED clip on produced the lowest biomass, but because it also used by far the least amount of electricity it had the greatest biomass efficiency (grams produced per kWh electricity). It produced two mediocre heads of lettuce and four thin and stretched heads of lettuce.

2.3.1 Fans

Some airflow to the plants can be used to prevent the environment around the plant staying too humid which can promote leaf diseases or the disorder tipburn. Tipburn is a physiological disorder (described more in section 10.5) whereby under high light, or high humidity, plants can't take up enough calcium (Mattson and Merril, 2015). In commercial greenhouses the solution is to add more airflow (Both et. al 1994). Therefore, in another experiment, I took the highest performing lights, pushed the light output to 17 $mol \cdot m^{-2} \cdot d^{-1}$, and added a fan into the mix (all other parameters from the previous experiment were kept the same). I used a small computer fan and mounted it 4 inches above the crop canopy in order to promote horizontal airflow above the lettuce. In the case of the LED Panel light, I positioned the fan so that it would blow air in between the light and lettuce (as the Panel was only 4 inches above the lettuce).

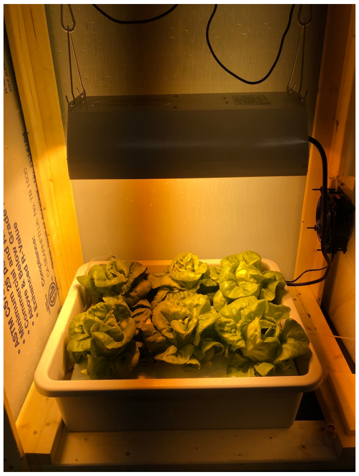

Image 8. HPS treatment with fan

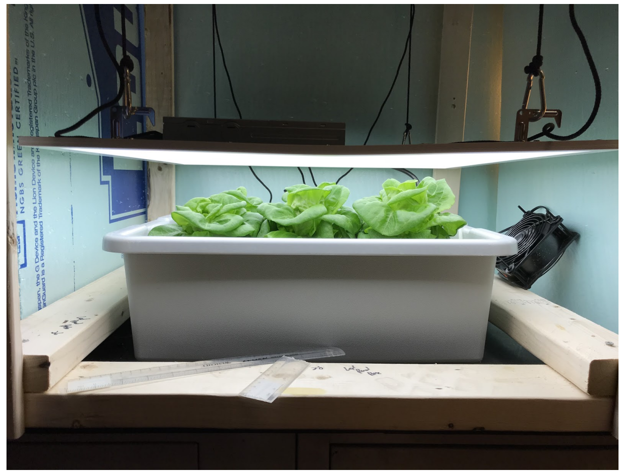

Image 9. LED Panel treatment with fan

In general, I found that pushing to 17 mol·m^{-2}·d^{-1} in such a small enclosed area caused tip burn in the lettuce (see image 10 below). Treatments with fans produced lettuce heads with less tip burn, however the downside of the fan was that it tended to decrease the fresh weight at the end of 35 days. However, if you let the lettuce grow a few days longer it should make up the weight. The treatments and results are as follows.

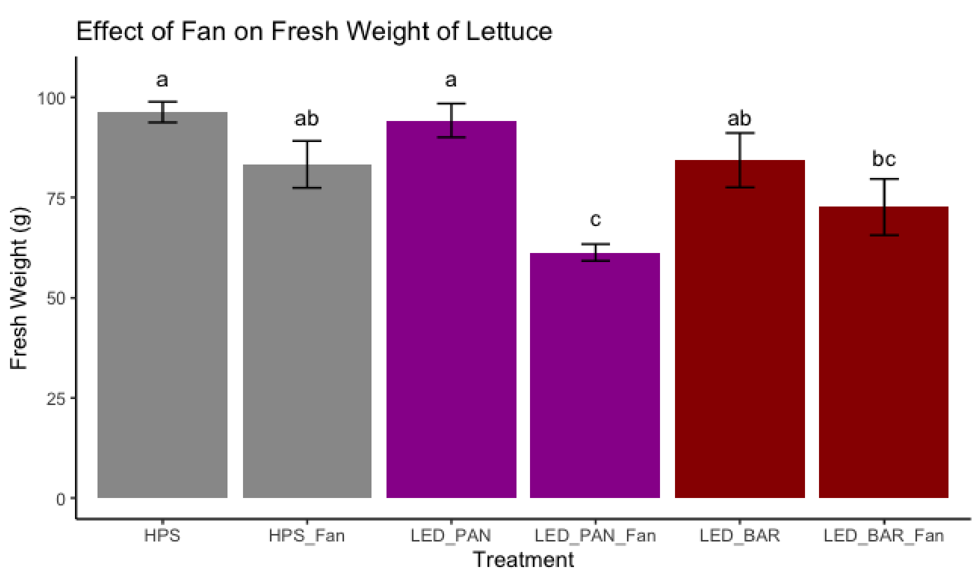

Figure 7. Fan vs. no fan treatments. (Treatments with the same letter are not significantly different from each other, based on Tukey HSD test with significance level of 0.05)

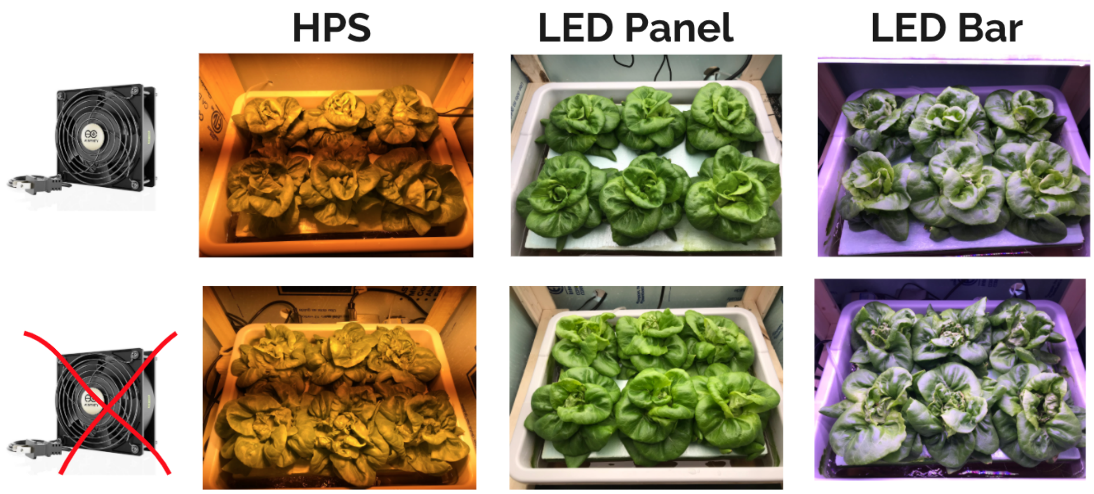

Image 10. Lettuce treatments with and without fans

In general, treatments with fans had lower fresh weights at the end of the 35 day growing cycle, although the only significant difference in fresh weight occurred in the LED Panel treatments. If you really want to push your crops with light levels, a fan will help to decrease tip burn in lettuce and also promote healthy air flow (good for reducing moisture on leaves). However, as noted, the fan may increase the amount of time you have to grow your plants to get desired fresh weights. In that case, it seems that the best option is to just lower light levels (by raising up lights a bit) so that tip burn does not occur, and wait a little longer for your plants to reach desired weights.

The biggest reason to use a fan would be if you are noticing moisture on leaves. Stagnant moisture on leaves is the perfect place for a pathogen to infect your plants so a fan would really come in handy there.

2.4 Lighting Quick Guide

When choosing a light for your system here are some things to think about.

1. Where you are going to put the light (Does it have a place to hang? Will it fit?)

2. The area you want to light

   a. If you know the umol/second output of the light use the equation

   $$Area\ capable\ of\ being\ lit\ = \frac{total\ output}{desired\ PPFD}$$

   b. If you don't know the output in umol/second you can use the metric of 12 W per square foot of growing area.

   c. The manufacturer may also give an estimate for the area the specific fixture can light.

3. The height at which to hang the light

   a. If you know the PPFD at certain heights you can choose a height based on your desired PPFD.

   b. If you don't know the PPFD at certain heights, a good idea is to aim for even light coverage of the growing area.

   c. If you have a similar light to one I mentioned (and you have a similar growing area) I would recommend a similar height

4. The duration of time to run the light

   a. If you know PPFD you can use the equation: $Run\ time\ = \frac{Desired\ DLI \times \frac{1{,}000{,}000\ umol}{mol}}{PPFD \times \frac{3{,}600\ seconds}{hour}}$

      i. A DLI of 12-17 mol·m^{-2}·d^{-1} is common for leafy greens

   b. Sometimes the manufacturer will give a suggested run time, usually this is pretty accurate but I would take it as a conservative estimate.

   c. If you have a similar light to one I mentioned (and you have a similar growing area) I would recommend a similar run time .

d. In general, be mindful of your plants. If they look stretched and thin they need more light, and if there is noticeable tip burn the light quantity should be scaled back.

5. To calculate electrical use and cost use the formulas:

   a. $kWh = \frac{Power\ (watts) \times number\ of\ hours\ used}{1000}$

   b. $Cost\ in\ dollars = kWh \times local\ electrical\ cost\ per\ kWh$

3. Nutrient Solution

The nutrient solution is the source of essential mineral elements plants need to carry out cellular functions including growth, photosynthesis, and respiration. There are 14 essential elements that plants need including 6 macronutrients: Nitrogen, Phosphorus, Potassium, Sulfur, Calcium and Magnesium; and 8 micronutrients: Iron, manganese, zinc, boron, copper, molybdenum, chloride and nickel (Mattson and Peters, 2014). Micronutrients are just as important to the plant as macronutrients, they just aren't needed in the same quantity. There are many hydroponic fertilizers available, and most will do a good job supplying these nutrients so it doesn't matter too much which one you choose. What matters most is the correct mixing of the solution based on the specific fertilizer you chose. However, before we get into specific recipes, let's discuss several important factors when it comes to maintaining the nutrient solution.

3.1 pH

The first factor is the pH of the solution. The pH of the solution is the measure of how acidic or basic the solution is based on the number of hydrogen ions. pH ranges on a scale from 0 to 14, where 0 is the most acidic, 7 is neutral, and 14 is the most basic.The more hydrogen ions the more acidic the solution is, and the more hydroxide ions the more basic the solution. (Both and Brechner, 2013). Common acids (not for use in hydroponic systems, just examples) include lemon juice and vinegar, a neutral solution is milk, and basic solutions include drain cleaners and milk of magnesia. pH is important because it controls the nutrients available to the plants. Too high or too low of a pH will make certain nutrients unavailable to the plants. An Ideal pH for hydroponic solution is between 5.5 - 6.0 (Mattson, 2016).

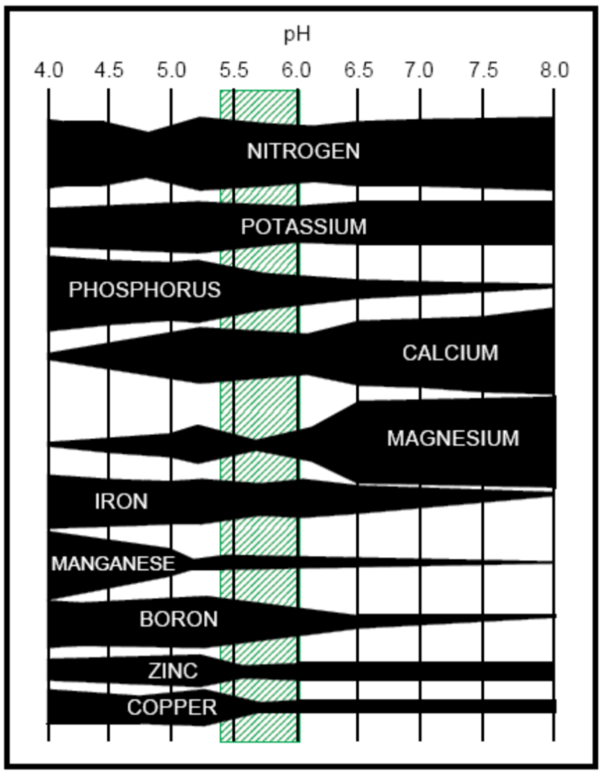

Figure 8. Nutrient availability at different pH

The pH of the solution should be checked regularly, as it can change within a matter of days often due to fertilizer used and the plant's uptake of that fertilizer (Mattson and Leith, 2019). Generally, fertilizer with Ammoniacal Nitrogen will tend to decrease pH, and fertilizer with Nitrate Nitrogen will tend to increase pH (Mattson and Leith 2019).

3.2 Electrical Conductivity

The next factor to look at is the EC of the solution. EC stands for electrical conductivity and is a measure for the amount of dissolved salts in the solution. The units can be a bit confusing, but EC is typically measured in mmhos/cm which is the same as mS/cm (Mattson and Peters, 2014) or dS/m. Occasionally meters will report 1,000 times higher in µS/cm. For example, your nutrient solution may have a fertilizer strength of 1.8 mmhos/cm (or mS/cm, dS/m) which is the same as 1,800 µS/cm. You can use EC as an approximation for the fertilizer strength (concentration). An important thing to note is that EC measures all salts in the solution, not just the ones in your fertilizer, so it is important to measure the EC of your water before adding fertilizer. Knowing the EC of your water beforehand allows you to better control your fertilizer input. Generally you want a starting EC of 1 mmhos/cm or less, although at the home scale, unless you are starting with a really high EC of say 2, you are probably ok. In addition, most people don't regularly have access to an EC meter and thus while it is important for a commercial grower to keep up with EC (often they use continuous EC sensors connected to computer controlled dosers to supply nutrients), for the home grower, pH is more important to take care of. In fact studies have shown that if pH is not controlled, then the EC won't matter as much because certain nutrients won't be available to crops (see figure 9) (Mattson and Hansen, 2011) . Thus, the suggestion for a home grower is to monitor your pH because that will have more of an impact on your crops than worrying about EC. As long as you mix the fertilizer correctly your EC should be okay.

If you want to get more in-depth and track EC you can purchase hand-held meters for \$60-100+, and you can always send samples out to a lab for testing. Ex. J.R. Peters Laboratory.

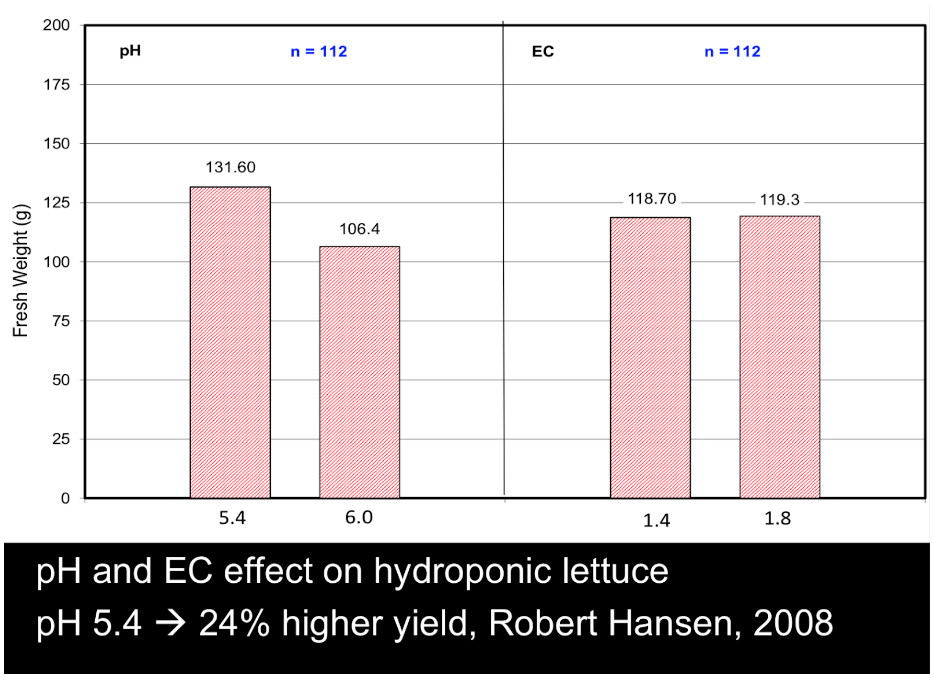

Figure 9. pH and EC effects on lettuce yield

3.3 Oxygenation

Plants need oxygen for cellular respiration, and in a hydroponic system the roots get this through dissolved oxygen in the nutrient solution. Generally we want a dissolved O_2 content of 7-10 ppm (this is generally at saturation in water, depending on water temperature) (Goto et. al, 1996). In a deep water system this can be achieved by using a pump and an airstone. In an NFT system oxygenated water is achieved through the constant flow and agitation of the water (Adams, 1981). Generally you want 10L of water flow per plant per hour in an NFT system (based on general commercial systems and Jackson, 1979) .

One other important factor for a high dissolved oxygen content in your nutrient solution is temperature. Generally speaking, colder water is able to have a higher dissolved oxygen content (Adams, 1981). This might not be a huge problem indoors, but if you set up your system outside, you will want to do your best to try to keep your reservoir cool. For an NFT system, this might mean keeping the reservoir in the shade, and for a deep water culture system this most likely means having an opaque material for the reservoir and trying to let as little light in the reservoir as possible.

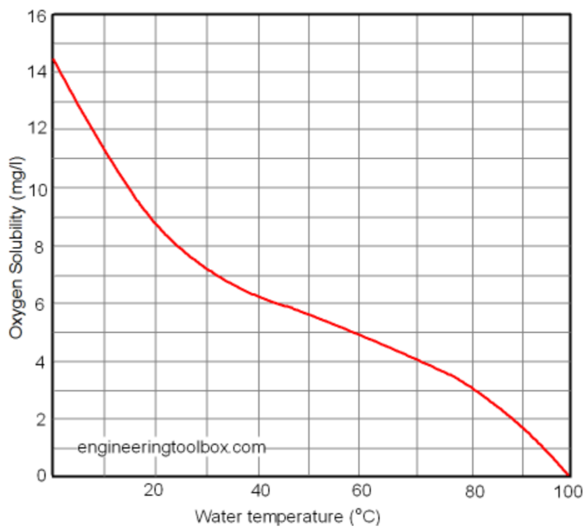

Figure 10. Dissolved oxygen solubility based on temperature

3.4 Mixing a Solution

To mix a nutrient solution there are two main things you need to know. First, you need to know the volume of the solution you want to make. Second, you need to know how much fertilizer to add per liter/gallon of water. The first step is easy, as that is pretty much the volume of your reservoir and how much you intend to fill it. Most reservoirs/containers you purchase will list their volume (or you can calculate it based on their dimensions). For example, maybe you have a 25L reservoir and you decide to put 20L of water in the reservoir. Step two requires a little reading from the fertilizer bottle, but you should be able to find how much fertilizer to use per unit volume fairly easily. For example, if you have a liquid fertilizer, your bottle may say something to the effect of, “add 2 mL of fertilizer for every 1 L of water”. In our example, this means we need to at 2 mL $\times$ 20 = 40 mL of fertilizer. If you have a powdered mix, it might say something to the effect of “add 1.5 grams of fertilizer for every 1 L of water”. In this case you would need to add 1.5 g $\times$ 20 = 30 grams of fertilizer.

Should your fertilizer come in several parts, make sure to mix the correct amount from each part into your nutrient solution (as addressed below, be sure to completely dissolve/mix one part of the nutrient solution before adding the next). In the case that your fertilizer has different suggestions for different stages of growth, I would recommend choosing the prescribed amount for a stage that might be called something like “general purpose” or “vegetative growth”. If that sounds good enough for you (your plants will be fine with this!) then feel free to skip the next two sections. However, if you are getting really excited and just want to do some custom mixing then read on!

3.4.1 Reading a Liquid Fertilizer Label and Making a Custom Mix

Sometimes a fertilizer will suggest different feed rates for different weeks based on growth stages of plants. This strategy can be useful, and is often employed, when growing a fruiting crop such as a tomato or a flowering crop such as hemp. However, for leafy greens and herbs, only one solution recipe is generally used throughout the entire growth cycle. If you find yourself in this position you may need to make a mix from several different fertilizers. For example, General Hydroponics’ Flora Series is a three part mix that could be used in stages, but for leafy greens we mix all three parts into one solution. In order to make that one solution you first need to understand how to read a fertilizer label. A fertilizer label tells you the percentage of each element contained, and will look something like this.

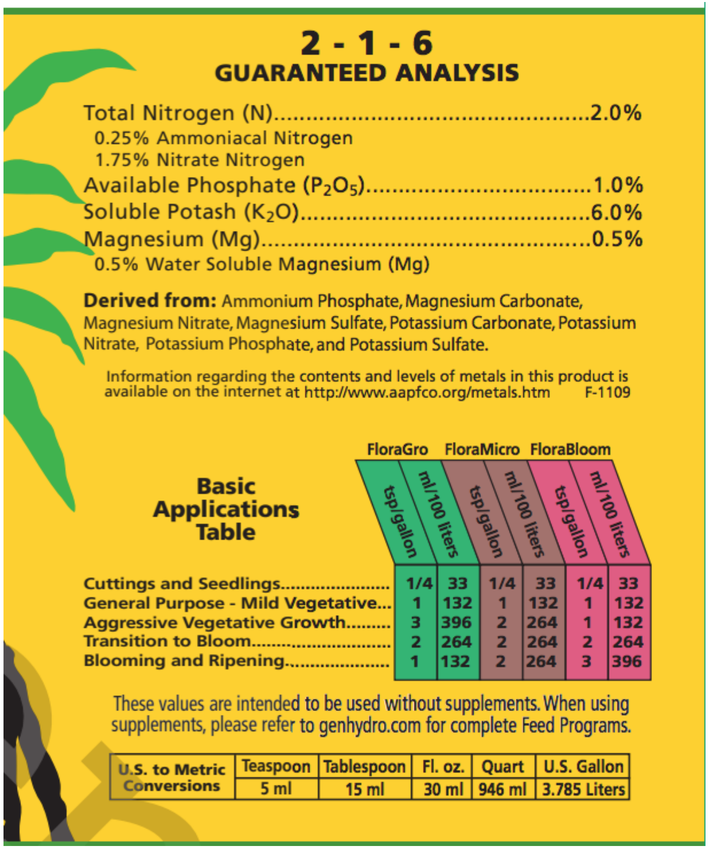

Image 11. Liquid fertilizer label

In this example we can see that this fertilizer is 2.0% total nitrogen, 1.0% phosphate, 6.0 % potash, and 0.5% magnesium. The first three nutrients listed here (N,P,K) are also listed at the top in bold numbers because those are the main macronutrients. Other fertilizer bottles will also follow the same procedure of listing N,P,K in bold or large numbers in that order. One thing that is a little confusing is that phosphorus (P) and potassium (K) are listed as phosphate (P_2O_5) and potash (K_2O). This means that the actual percentage of P and K is actually lower. To figure this out you need to know the atomic mass of each element and then you need to find the percent of the desired element in each molecule. So for phosphate we want the percent P, and for potash we want percent K. The calculations are as follows.

Atomic mass of P = 30.97 | Atomic mass of K = 39.10 | Atomic mass of O = 15.99

Then for P_2O_5…

$\% P = \frac{(30.97 \times 2)}{(30.97 \times 2) + (15.99 \times 5)} \times 100 = 43.7 \% P$ (generally we just use .44 as our conversion factor)

So now we multiply whatever the percent phosphate is by .44, and in our case we will do:

$1\%P \times .44 = 0.44\%P$

Then for K_2O…

$\% K = \frac{(39.10 \times 2)}{(39.10 \times 2) + (15.99 \times 1)} \times 100 = 83.2 \% P$ (generally we just use .83 as our conversion factor)

So now we multiply whatever the percent potash is by .83, and in our case we will do:

$6\%K \times .83 = 4.98\%K$

The rest of the elements listed are the actual percentage of that specific element. In this example we have a final percentages of 2%N , 0.44% P, 4.98% K, and 0.5% Mg. Now that we know the percentages we can figure out how much fertilizer to use based on some target value we have. Let's say we have a target value of 150 ppm (parts per million) nitrogen for a 20 L nutrient solution. There are a few key points that you need to be aware of when completing these next steps.

1) In a liquid fertilizer, 1% = 10,000 ppm
2) 1 ppm = 1 mg/L
3) 1 L = 1000 ml
4) (initial concentration) x (initial volume) = (final concentration) x (final volume)
5) We are interested in the volume of fertilizer to use or "initial volume"

First, I would figure the amount of fertilizer to use for one liter and then multiply that number by 20. So now we use this formula solving for the “initial volume” (mL of the fertilizer product we need to add to our reservoir):

$$Initial\ volume\ = \frac{(final\ concentration) \times (final\ volume)}{(initial\ concentration)}$$

$$Initial\ volume\ = \frac{(150\ \frac{mg}{L}) \times (1000\ ml)}{(20{,}000\ \frac{mg}{L})} = 7.5\ ml\ of\ fertilizer\ per\ 1\ L$$

So now that we know 7.5 ml of fertilizer will provide 150 ppm of nitrogen for 1 liter of water, we multiply $7.5ml/L\ \times 20\ L\ =\ 150\ ml\ of\ fertilizer$ is needed for a 20 liter nutrient solution at 150 ppm Nitrogen.

Now you have to to figure out how much of the other nutrients you are supplying with the fertilizer. You can rearrange the formula to find final concentration and do a calculation like this:

$$Final\ Concentration\ = \frac{(initial\ concentration) \times (initial\ volume)}{(final\ volume)}$$

If we were looking to find the amount of phosphorus supplied to 1L of solution we would do:

$$Final\ Concentration\ Phosphorus\ = \frac{(4{,}400\ \frac{mg}{L}) \times (7.5\ ml)}{(1000ml)} = 33\ ppm$$

Another way to do it would be to say that we know we supplied a total of 150 ppm nitrogen, and the fertilizer is 2% Nitrogen and .44% phosphorus. So we could find the percent of phosphorus relative to nitrogen and then multiply that by 150:

$$\frac{(.44)}{2} = 0.22$$

$150\ \times 0.22\ =\ 33$ ppm (mg/L) P

You would then have to do this for all the elements, and in addition you would have to factor in how to use the other parts of the fertilizer mix as well. This could get very drawn out, so for ease of calculations I am including an excel spreadsheet where all you have to do is enter the percent of each element (enter the percent phosphate and potash, the excel chart will handle the conversion), and adjust with the ml/L of each part of the mix until you find a final mix you are happy with:

https://blogs.cornell.edu/cornellcea/files/2020/05/Useful-Home-Hydroponics-Excel-Sheets.xlsx

3.4.2 Reading a Powder Fertilizer Label and Making a Custom Mix

When making a custom mix of powdered fertilizer, some of the steps will be the same as making a custom mix from a liquid fertilizer. You will still need to find the percent of your desired element, and 1 mg/L still = 1 ppm. However, when calculating how much fertilizer to use based on your target ppm you will now use the formula:

$$mg\ of\ fertilizer\ = \frac{target\ ppm\ (mg/L)}{\%\ of\ desire\ element\ in\ compound}$$

Example: we are using commercial calcium nitrate to supply nitrogen, and we want 150 ppm (mg/L) nitrogen in our nutrient solution. The chemical formula for commercial calcium nitrate is $Ca(NO_3)_2 \bullet 3H_2O$. According to the product label the product is 18.5% Ca and 15.5% N. So to calculate how much calcium nitrate fertilizer to use to get 150 ppm N::

$mg\ of\ fertilizer\ = \frac{150\ ppm}{.155} = 968\ mg$ of calcium nitrate in 1liter of water to supply 150 ppm N.

You can find the amount of calcium supplied by doing (968 mg calcium nitrate) x (0.185) = 179 mg/L calcium (179 ppm). (Mattson, 2018).

Once again you would need to do this for all the sources of elements you are using, and don't forget to take into account that when you are supplying one element you are most likely also supplying another element! (If you enjoy these sorts of calculations, one resource that walks you through the calculations is: http://e-gro.org/pdf/E305.pdf)

3.5 Organic Fertilizers

Organic Fertilizers are ones in which the elements are derived from natural substances. Unfortunately, it is often difficult to create an organic mixture that doesn't precipitate when mixed together. Organic fertilizers will often form an organic film that can clog pumps, airstones, tubing, and generally is quite messy. In the first few days, organic fertilizers will often bubble and seem to ooze out of the reservoir. This can take several days to a week to settle down depending on the size of the reservoir. Most of the mineral elements in organic fertilizer require quite a bit of time to be released and made available to the plant. This process requires naturally occurring microbes to become established to process these complex organic compounds and turn them into plant available nutrients. In addition, pH often drastically changes due to the sources of nutrients thus limiting the amount of nutrients actually available to the plant. While growing organic can be a great farming practice in the field, it may not yet be suitable for use in hydroponics. In addition, it's unclear if you can actually grow crops "organically" (as in have them labeled organic) in a hydroponic system due to many of the materials used, and the obvious lack of soil which is paramount to the organic label (Mattson and Leith, 2019).

However, it's worth noting that some of the big reasons for growing organic in the field include zero use of synthetic pesticides or herbicides. Commercial hydroponic growers will not be using synthetic herbicides, and will have little to no use of synthetic pesticides. Certainly home growers should not be using synthetic pesticides on their crops. In addition, even though conventional nutrients are most commonly used in hydroponics - they are recirculated (i.e. reused) typically for the whole crop cycle which limits environmental concerns about nutrient use and runoff.

Image 12. Bubbling from organic Fertilizer

Image 13. Organic Fertilizer Biofilm

3.6 Conventional Fertilizers

Conventional Fertilizers are ones where elements are synthetically derived from natural substances or isolated from naturally occuring materials. They are more easily formulated to be water soluble and available to plants immediately. In general, they are easier to handle and require less maintenance than organic fertilizers. Examples of conventional fertilizer brands include: General Hydroponics, FoxFarm, AeroGarden Liquid Plant Food, Jack's hydroponic mixes.

3.7 Case Study Conventional (General Hydroponics Flora Series) vs Organic (General Hydroponics Organic)

The objective for this experiment was to grow heads of lettuce with different levels of nutrient solution care to see what kind of commitment would provide the best results for a homeowner. Four different care levels were established ranging from no care at all after the initial set up, all the way to checking and maintaining pH and EC 3 times a week. In addition, I looked at a conventional fertilizer and an organic fertilizer to see what the best option for a home grower would be.

The set up for the experiment and results are as follows

- 35 day growing cycle in restaurant bussing tubs (21x17x7 inches, with a total volume of 27 liters, tubs were initially filled with 25 liters of nutrient solution)
- In a greenhouse with supplemental light (daily light integral held constant at 12.5 $mol \cdot m^{-2} \cdot d^{-1}$)
- pH and EC held constant at targets for different treatments
- 4 treatments of a single Conventional fertilizer (a 3-part liquid hydroponic fertilizer) with different levels of care
- 4 treatment of Organic fertilizer (a 4-part liquid organic hydroponic fertilizer) with different levels of care

Different Levels Of Care:

Treatment 1 :Control (pH and EC were adjusted 3 times weekly to desired levels) (labels: GHC [conventional] and GHOC [organic])

Treatment 2: Fertilizer was added and then left alone the entire growing cycle (labels: GHN [conventional] and GHON [organic])

Treatment 3: Tubs were topped off with fertilizer water when needed (no pH or EC adjustment) (labels: GHFNopH [conventional] and GHOFNopH [organic])

Treatment 4: Tubs were topped of with fertilizer when needed and pH was adjusted (no EC adjustment)

(labels: GHFYespH [conventional] and GHOFYespH [organic])

Nutrient Solutions were mixed with the goal of getting as close as possible to a modified Sonneveld's solution for leafy greens - which is what we recommend at Cornell for leafy greens. The conventional fertilizer was mixed from the 3 part General Hydroponic Flora series based on each part's guaranteed chemical analysis, and the organic fertilizer was mixed froma 4 part General Hydroponics' Organic series based on each part's guaranteed chemical analysis. I happened to use a four part mixture, although the organic series has a wide range of products. I found that the best mixture for this solution would come from a combination of "Bio Grow", "Bio Bloom", "Ca Mg", and "Diamond Black".

Table 2. Fertilizer concentrations

Element	**Target PPM (Modified Sonneveld's Solution for leafy greens)**	**PPM Supplied by Conventional Fertilizer**	**PPM Supplied by Organic Fertilizer**
Nitrogen (N)	150	150	140
Phosphorus (P)	31	44	61.1
Potassium (K)	210	191	132.8
Calcium (Ca)	90	100	100
Magnesium (Mg)	24	35	40
Sulfur (S)	32	15	20
Iron (Fe)	1	2	0
Boron (B)	0.25	0.20	0
Manganese (Mn)	0.13	1.00	0
Zinc (Zn)	0.16	0.30	0
Copper (Cu)	0.023	0.20	0
Molybdenum (Mo)	0.024	0.02	0.08

Image 14. Fertilizer treatments. Conventional fertilizer on the left, treatments 1-4 from back to front. Organic fertilizer on the right, treatments 1-4 back to front.

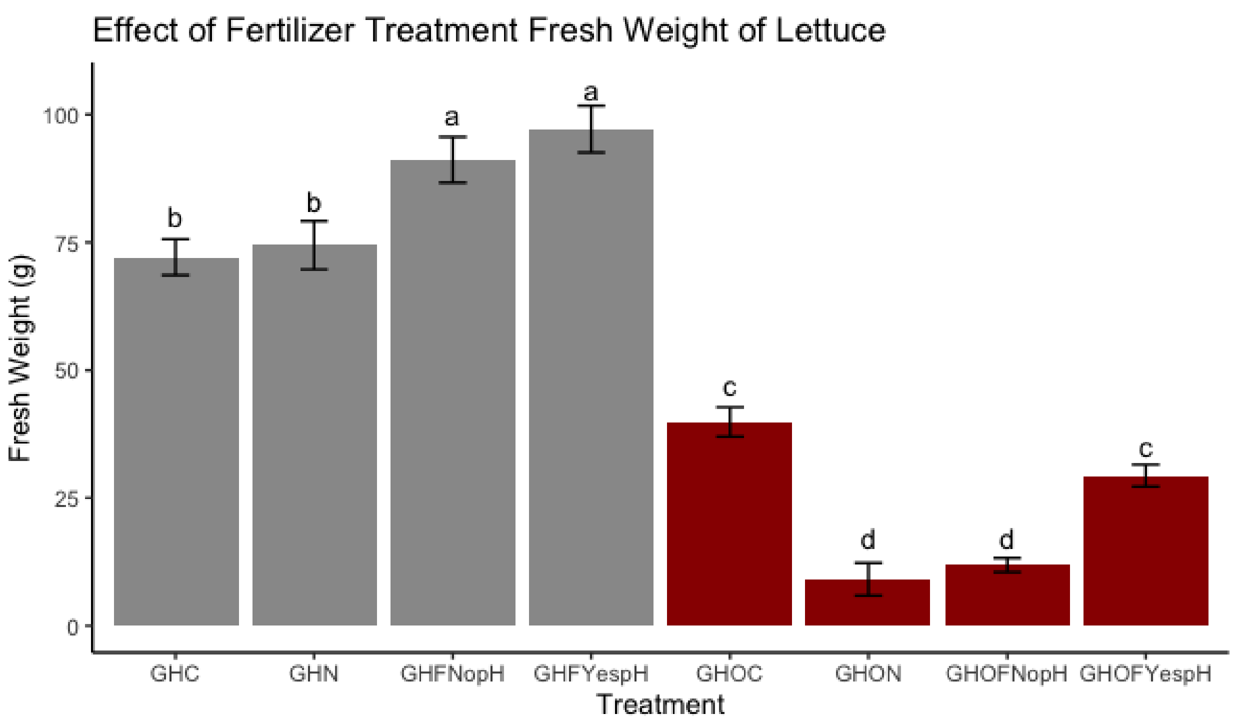

Figure 11. Conventional and Organic Fertilizer treatments. (Treatments with the same letters are not significantly different from each other, based on Tukey HSD test with significance level of 0.05)

All conventional treatments had significantly higher fresh weights compared to the organic treatments. In the conventional section, treatments 3 and 4 (where nutrient solution was topped off each week) had significantly higher freshweights than treatments 1 and 2. In the organic section, the treatments where pH was controlled (treatments 1 and 4) had significantly higher freshweights than the others.

Basically, if you have the choice you should use a conventional fertilizer to get the best plant performance. Not only will the plants have a higher fresh weight, but the system will be cleaner and have less maintenance. In this specific experiment, controlling the pH did not have a significant impact on the fresh weight in the treatments with conventional fertilizer. This is most likely because the conventional fertilizer already had a pH buffer in the mix. That being said, many other studies have shown pH is an important factor in the health and development of hydroponic plants so I would still recommend checking the pH at least once a week if you can. However if you can't, it's not a huge deal as the plants will still grow (albeit perhaps a bit smaller than if pH were controlled, or they may eventually develop nutrient deficiencies from high pH such as iron or manganese deficiency). This experiment did show that topping off with nutrient solution each week could be beneficial to plant growth. Once again, if you decide not to do this the plants will still be healthy, they may just take a little longer to get to your desired fresh weight.

On the other hand, if you decide to grow using organic fertilizer you will certainly want to keep track of, and adjust, the pH of the solution several times a week. The organic solutions had wild swings in pH, most often increasing to pH levels of 8 and above, and at these levels of pH nutrients become unavailable for the plants to use. It's clear from the photos that the roots of treatments where pH was controlled were much healthier than those treatments where pH was not controlled, and plants tended to be larger in pH controlled treatments. Note: this experiment was conducted during 1 crop cycle, it could be that after a longer time (multiple crop cycles) the organic nutrient solution will stabilize (as naturally occurring microbes get established and process the organic nutrient forms to make them available to plants).

Control Treatments (Conventional on left, organic on right)

(Image 15.)

(Image 16.)

(Image 17.)

(Image 18.)

Treatment 2. No care after the initial solution was mixed. (Conventional on left, organic on right)

(Image 19.)

(Image 20.)

(Image 21.)

(Image 22.)

Treatment 3. Nutrient solution was topped off each week. But there was NO pH maintenance.(Conventional on left, organic on right)


(Image 23.)


(Image 24.)


(Image 25.)


(Image 26.)

Treatment 4. Nutrient solution was topped off each week AND pH was maintained. (Conventional on left, organic on right)


(Image 27.)


(Image 28.)


(Image 29.)


(Image 30.)

3.8 Fertilizer Quick guide

When choosing a fertilizer, I highly recommend using a commercially available pre-blended conventional hydroponic fertilizer. Fertilizers can come in both a liquid or powder form. For home hydroponic use, liquid fertilizers tend to be easier to measure and mix (i.e. dissolved in water). However, a powdered form might be the way to go if you want a cheaper fertilizer (you are not paying to ship all the water as in a liquid fertilizer) or if you want a more specific fertilizer mix (as a commercial grower might). As an aside, the reason you often have to mix fertilizers together into a solution is because if they were stored together in concentrated form some nutrients would precipitate out (i.e. recombine into an insoluble form). The main culprit is calcium. Calcium doesn’t mix with sulfates or phosphates in concentrated solution (Mattson and Peters, 2014). However, once diluted into the nutrient solution that the plants will receive, precipitation should not be a problem.

1. Mix a solution based on the volume of water you are using and the instruction on the label.
    a. Sometimes the suggested fertilizer schedule wants you to put different mixtures in during different weeks. This is useful when growing flowering or fruiting crops, however when growing leafy greens it’s common practice to have one solution for the entire growth cycle. In this case, use the suggested mixture for a growth stage that is labeled something like “general purpose” or “vegetative growth”, and if the fertilizer comes in several parts don’t forget to mix the appropriate amount together from each one.

    b. If you want to do a more detailed comparison of nutrient values, you can fill in the excel chart provided based on the guaranteed analysis on the bottle.
    c. In terms of precipitation - you want to avoid combining materials together in their concentrated form. First fill the reservoir at least half full, add the first material and stir (or run the pump) until it is fully dissolved in water, then add the second material and fully dissolve and so on.
2. Check the pH of the solution to make sure it falls within the 5.5-6.0 range and adjust. The easiest way to check and adjust pH is to buy a pH up and down kit. It should come with both a way to measure pH (typically a color indicator) and chemicals to adjust pH. (If you want to track pH in a more detailed way you can purchase a handheld pH meter for $60-100+, be sure to also buy reference solutions - so you can adjust your handheld meter for accuracy).
    a. Note, if you are trying to grow totally organic you need to use citric acid (it should say suitable for organic, or OMRI)
    b. If you are using an organic fertilizer I would recommend checking the pH several times a week
    c. If you are using a conventional fertilizer, checking the pH once or twice a week should do.
3. I would recommend topping off the system with nutrient solution every 1-2 weeks.
4. If you are using organic fertilizer, I would suggest keeping the same solution for several crop cycles (still topping off with fertilizer as needed) in order to promote the establishment of beneficial microbes.

a. You may see better results with organic fertilizers in later crop cycles after the beneficials have established.

4. Seed starting

When buying seed, it's a good idea to source your seed from a reputable commercial source. These companies will generally tell you the % germination on the packet (as tested within the last few months), and while this won't necessarily be the actual germination percentage you will get based in your conditions, it's nice to know and it shows the companies have taken the time to actually test the seeds. Some examples of notable companies for sources of seed include Johnny's Seed, Ball Seed Company, Harris Seed, and High Mowing (an all organic brand).

After purchasing seeds, it's a good idea to store them in a cool place such as a refrigerator to help increase the longevity of seeds. In addition, be sure to keep any seeds you are not using dry (sealing in a container with a silica/desiccant packet can help to keep out moisture) , otherwise they will be compromised!

When you are ready to start your seed, there are a few materials that you will want to have. First off, you need a media to plant the seeds in. If you were planting outside the media would be soil, but in hydroponics we use soilless media. Two common media types are Rockwool and Coco Coir.

Image 31. Rockwool cubes

Image 32. Coco coir cubes

Rockwool is heated and spun basalt that is then typically formed into 1 or 1.5 inch cubes (Resh, 2013). Rockwool is an inert media and has good water holding capacity which makes it useful for starting seeds (Resh, 2013). Coco Coir is ground coconut husk which means that it can be composted (Resh, 2013). For seed starting you can find compressed coir cubes with a paper-like wrap that will keep coir particles from falling into your hydroponic system.

A seeding flat is used to hold the media while the seeds germinate. The most common is a 10” x 20” seeding flat, and this can easily be ordered online or picked up at a local garden center. Although for a home grower, a smaller flat will also work just fine. After planting, the seeds will need nutrients (as described in the Nutrient solution section) and light (as described in the Light section).

Now comes the fun part! Pre-soak the flat of rockwool in nutrient solution for 10-15 minutes. Rockwool can often start at a pH around 7-8.5 and soaking helps lower the pH to a more suitable range. If you are using coco coir, it’s best to soak overnight so that 1) compressed coir cubes have time to expand and 2) because coco coir cubes can have excess salts, and soaking helps to leach some of them out. After soaking, plant seeds into the media. If you are planting lettuce or kale, one seed per cube will do as those species can grow quite large. However with most other herbs you can get away planting around 3-4 seeds per cube.

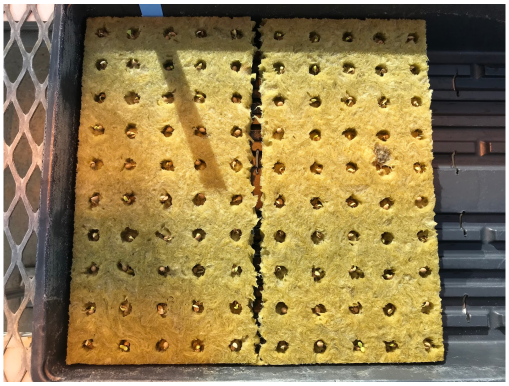

Image 33. Seedlings in rockwool cubes

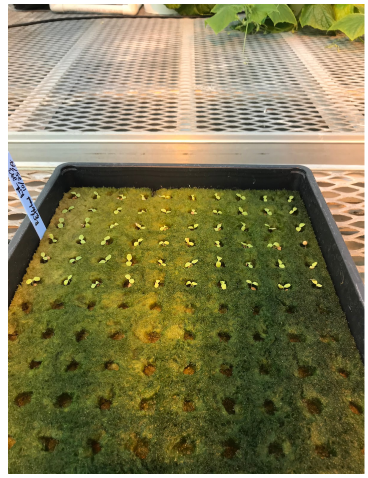

Image 34. Seedlings in rockwool cubes

Make sure to water the seedlings with nutrient solution once a day or at least enough so that the media doesn't dry out. In a commercial setting, seeds are germinated at 68°F, and then after germination the temperature is set for 75°F days and 65°F nights (Both and Brechner, 2013). At the home scale, these specific temperatures are not necessary, but it would be a good idea for the seeds to generally have these conditions. Around the 4 to 5 day mark look for any accidental doubles in the lettuce plugs and remove them (Both and Brechner, 2013).

The duration of time before transplanting depends on both the type of seed, your preference for what stage to harvest at, and environmental conditions. For example, many commercial operations aim for a 35 day growing cycle to get 5 ounce (150 gram) heads of lettuce under ideal environmental conditions. Following this schedule, you should try to transplant your seeds into your hydroponic system around day 11 (Both and Brechner, 2013). When growing herbs from seed, the seedlings tend to be ready anywhere from 2-3 weeks (C. Currey, personal communication, 2019). If environmental conditions are not optimum (such as cooler temperatures and lower light) it will take longer for seedlings to develop. In general, a good time to transplant is when you see the formation of 3-4 true leaves, or the plants are starting to crowd each other (Mattson, 2016). In addition, you should start to see the roots at the bottom of the rockwool or coir cell. Leaving the plants in the rockwool longer could cause stem elongation and tangles between plants.

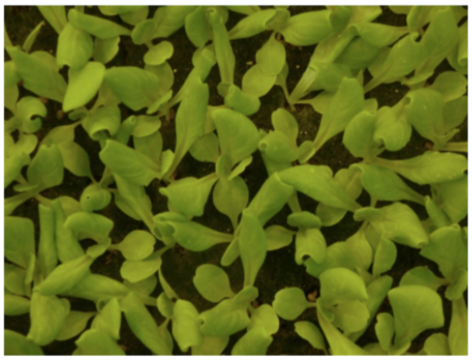

Image 35. Lettuce seedlings ready for transplant.

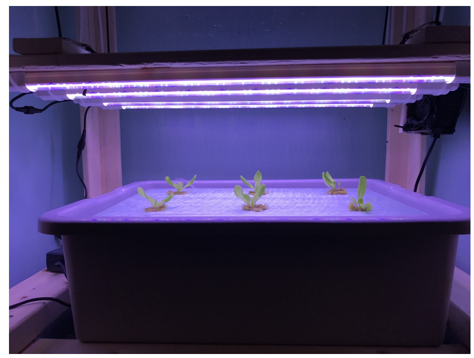

Image 36. Seedlings transplanted into DWC system

Another option for seeding would be to plant directly into the hydroponic system. This wouldn't be realistic at the commercial level due to spacing and scheduling concerns. However, at home level it certainly can be done. Just make sure the rockwool cubes don't dry out before the roots make contact with the nutrient solution

4.1 Seed Starting Quick Guide

<u>Materials:</u>

- Seeds
- Seeding flat
- Media to plant seeds into (Rockwool or Coco Coir cubes)
- Nutrient solution (as per directions in the nutrient solution section)
- Light (as per directions in the lighting Section)

Directions:

1. Place Rockwool in the seeding flat and pre-soak in nutrient solution for 10-15 minutes, overnight for coco coir.
2. Plant one seed per cube if lettuce, 3-4 per cube for other herbs
3. Place seeding flat with media and seeds under light
    a. You can also decide to plant directly into your system at this point if you wish
4. Water once a day, or enough so that the media doesn't dry out
5. At about day 4 or 5 remove any accidental lettuce doubles from plugs
6. If you have left your seeds under a light in the seeding flat, around Day 11 transplant lettuce into your hydroponic system (if you want to stick to a 35 day growing cycle). For other herbs, wait to transplant until you see 3-4 true leaves and/or roots coming out the bottom of cubes.

5. Deep Water Culture

Deep water culture hydroponics consists of a reservoir to hold nutrient solution that the plant roots will be in direct contact with, a floating panel to hold plants, an airstone and a light. This type of system is great for home hydroponic users as it is easily constructed and cared for. In addition, it can be used to grow many different crops such as lettuce, basil, kale, and sorel.

5.1 Kits

There are many kits to be found online, here are some examples:

1. https://www.aerogarden.com/
2. https://backtotheroots.com/collections/top-sellers/products/watergarden

3. https://www.amazon.com/DWC-Hydroponic-System-Growing-Kit/dp/B07FYS5BTJ/ref=sr_1_7?crid=8X83K406F6D&dchild=1&keywords=hydroponic+kit&qid=1587863178&sprefix=hydopnic+kit%2Caps%2C170&sr=8-7

Many of these kits are "plug and play" (ready to use) and all you have to do is plug them in, add water/fertilizer and plant seeds. However, some are quite expensive (especially when they include their own light source) so you might decide to make your own.

5.2 DIY Materials

When constructing your own deep water culture system these are the components you will need to acquire. First you need to acquire a reservoir for your plants. There is quite a large range of reservoir volumes that could be used for your system. In a commercial setting, ponds are usually 8-12 inches deep which corresponds to around 2 gallons of nutrient solution per plant (based on the 3.5 plants per square foot standard). However, at the home level a lower volume is certainly okay. Plants are routinely grown with a gallon per plant and turn out fine. However, the larger your reservoir the more buffering you have when it comes to water temperature, EC, and pH (Goto et. al, 1996). This means there is more stability in the nutrient solution and those factors are less likely to change as rapidly in a larger reservoir as they would in a smaller reservoir. In addition, you may want to think about how often you will have to refill the reservoir. A general guideline for lettuce (and you could probably use this as a guide for most leafy greens) is that you will lose 100 ml of water due to evapotranspiration per plant per day (Ciokolz et. al,). This comes to around 0.7 liters (or one-fifth of a gallon) of water per week per plant.

In terms of actual reservoirs, restaurant bussing tubs work great (I have used bus tubs that are 21" × 17" × 7"), and plastic storage boxes (such as ones you might use to store clothing) can also work equally well. You just want to make sure that whatever you choose as a reservoir it is constructed with opaque material. The reason for this is that you don't want light to be able to get to the nutrient solution. Light will almost certainly cause algal growth and could even degrade some of the nutrients.

The next thing you will need is a raft for the plants to float on. Insulation boards (for example 4'x8'x1" Polystyrene Foam Board Insulation) are often used, but a lid with holes will also do. However, it is important to note that a lid with holes will not drop with the water level, and if left unchecked, especially in the beginning of the plant's life, the roots may no longer be in contact with the nutrient solution. This could lead to both a nutrient deficiency and a lack of oxygen for the plant. If you choose to use a lid with holes, make sure you are vigilant in keeping the roots in contact with the nutrient solution.

In addition, you will need a light (as described in the Light section), an airstone and air pump for oxygenation, and rockwool (or some type of media) for the seeds to germinate in.

5.3 DIY Construction

1. Reservoir (example restaurant bussing tub, or plastic storage box)
2. Floating insulation board.
    a. Insulation is easily found at most hardware stores like The Home Depot and Lowes. The insulation we use can be found here: https://www.lowes.com/pd/Kingspan-Insulation-Common-1-in-x-4-ft-x-8-ft-Actual-1-in-x-4-ft-x-8-Feet-R-5-Unfaced-Polystyrene-Foam-Board-Insulation/999972966

b. Cut the board to the appropriate size for your reservoir. Cutting can be done using a saw or a box cutter. Using a box cutter tended to create a smoother cut, and produced less of a mess. You will want to cut the board as close to the inner area of the reservoir as possible so as to prevent light from getting to the nutrient solution. This will help stop algal growth. One caveat is that if your reservoir gets smaller towards the base you may want to decrease the size of your float just a little so that it can sink down with the water

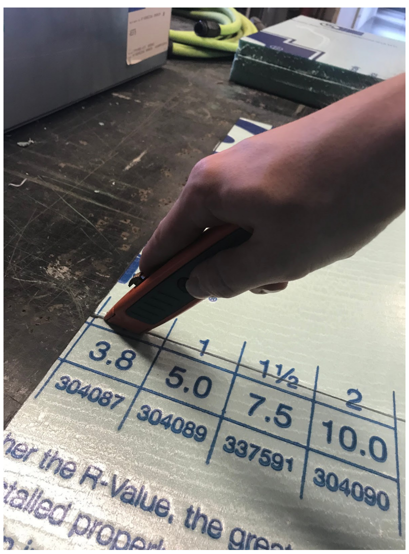

Image 37. Using a box cutter to cut insulation **Image 38. Breaking apart insulation board**

c. Drill the appropriate amount of 1 inch in diameter holes (for one inch rockwool cubes, 1-inch holes or slightly smaller [⅞”] tend to work well) for the area of the board. One thing to consider when drilling holes might be to drill a test hole and try placing a wet rockwool cube in it. See if you are comfortable with the fit. If it feels too loose to you drill a hole that is slightly less than 1 inch in diameter. This is also a good strategy if you are using a different size rockwool cube.

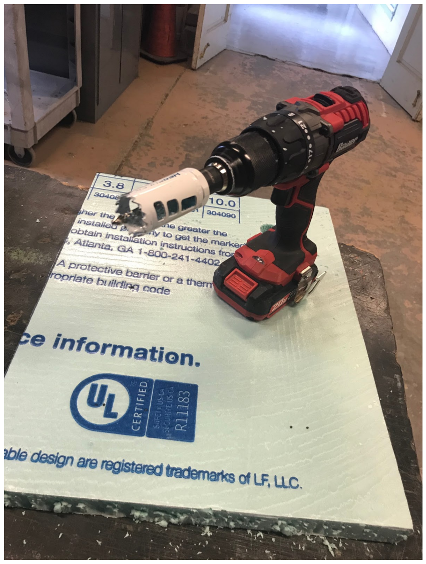

Image 39. Drill and ⅞” attachment for drilling holes in insulation board

The standard density for hydroponic head lettuce (which works well for kale, arugula, and other hydroponic crops is) 3.5 holes per square foot (Both, 2002). This equates to around 6.5 inch spacing between plants. When growing a larger plant like lettuce or kale, it's probably best to stick to this kind of spacing. However, if you are growing a smaller herb you can have closer spacing without too much of an issue.

Research by Chris Currey, of Iowa State University, has shown that plants that are spaced close together will have a lower fresh weight per plant, but the fresh weight per square meter of growing area will actually be higher than plants spaced further apart (C. Currey, personal communication, 2019). This can be a problem for commercial growers because customers generally don't want to buy small plants. However, at the home level this might not bother you if you are getting more fresh weight overall.

Other things to consider include: plants spaced really close together are more at risk for disease, as there is less airflow between plants and they are more likely to tangle with other plants making harvesting more difficult.

3. Place an Airstone connected to a pump in the nutrient solution reservoir. There are pumps made specifically for hydroponics, but a cheap one for a fish tank will also do just fine. You should leave the airstone running all the time as you always want the nutrient solution oxygenated. In addition, you will probably want to check the airstone and tubing for clogs each week just to make sure everything is working properly. It is common to replace the airstone every few crop cycles.
4. Lighting is probably the most difficult part as you need to find some way to hang a light over the plants. I have found doing so in a way that allows the height of the light to be adjustable is quite useful. Although this is not a requirement. One way to do this would be to hang the light with adjustable cables. These are easily found with a quick google search, or through sites like Amazon. For my experiments, I built a wooden cage that would fit around the reservoir to hold up my lights. Some lights may require you build an additional fixture if you wish to make the light adjustable in height. For example, the bar lights I used needed a fixture to hold all of them so that I could adjust in height.

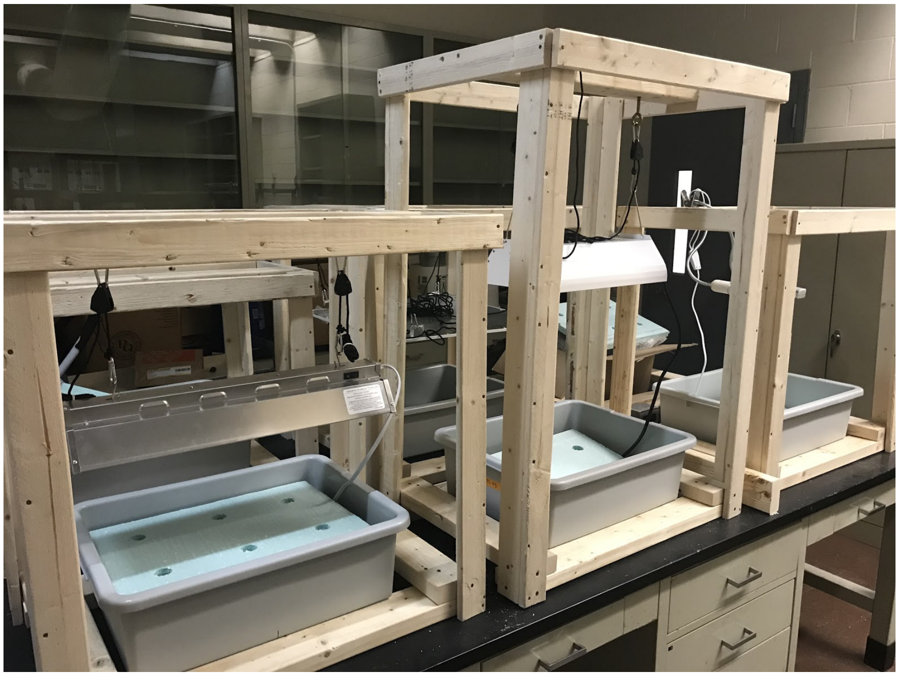
Image 40. Frames with adjustable light hangers

5.4 Mechanical Maintenance/Troubleshooting

The good thing about DWC is that there aren't that many parts to go wrong. The main things to check on are that the airstone is not clogged, and that adjustable lights are at the correct height.

5.5 Deep Water Culture Quick Guide

<u>Materials:</u>

1) Reservoir (Generally around 1 gallon per plant)
    a) You tend to lose around 100 ml per plant per day, or around 0.7 L (.18 gallons) per plant per week.
    b) Opaque material
2) Floating raft to hold plants (generally 1"-thick insulation board)

a) A bucket lid will do, but it will not go down with the water so you need to be vigilant about making sure the roots are in contact with the nutrient solution

b) Plants spaced close to 3.5 plants per square foot (that's around 6.5 inch spacing between plants for lettuce/kale; or use 4-inch spacing for basil and other herbs)

3) Airstone connected to a pump (constantly running)
4) Light (as per lighting section)
    a) Possibly light frame and adjustable cables
    b) Timer
5) Nutrient solution (as per nutrient solution section)
6) Rockwool (typically 1 inch cubes)
7) Seeds

<u>Construction and Plant Care:</u>

1) Construct raft and/or drill holes appropriately spaced in raft or bucket lid
2) Construct frame for light if needed
3) Fill reservoir with nutrient solution and place airstone in solution
4) Place seedlings in the raft or lid making sure that the bottom of media is in contact with the nutrient solution.
5) Check pH and EC 1-2 times per week if possible
6) Top off nutrient solution every 1-2 weeks or as needed

6. NFT Systems

NFT stands for Nutrient Film Technique and refers to plant roots being bathed in a thin layer (film) of nutrient solution that is recirculated. NFT systems consist of a reservoir to hold nutrients, a channel to hold plants, a pump and tubing to transport nutrients to and from the reservoir, and of course some sort of light. NFT is great for leafy greens and herbs, however you would not want to grow a vine crop such as a tomato plant in an NFT system because the long term roots would likely clog up the channel and disrupt the flow of nutrients in addition to creating anaerobic (low oxygen) conditions for the roots (Resh, 2013).

6.1 Kits

There are fewer NFT kits available for sale. Here is one from cropking.

1. https://www.cropking.com/catalog/nft-introductory-systems/nft-desktop-system

In addition, most of these systems tend to be quite expensive and you still need to factor in components that not all kits have such as lighting pumps and structural components.

6.2 DIY Materials

The first component you will want to acquire is the reservoir. Just like with the deep water culture reservoir you will want some sort of dark container that light can't penetrate through so that there is less of a chance of algal growth. In terms of the volume, the larger reservoir you have the better buffering capability you will have for pH, EC, and temperature. In addition, you will tend to lose around 100 ml of water per day per plant (based on research done on head lettuce), so you will want to think about how often you will have to refill the reservoir when considering the size (Ciolkosz et. al,). A lid is ideal and can easily be fashioned out of an insulation board if it doesn't come with the reservoir container.

The next component to think about is the pump and tubing that goes along with it. A pump and tubing can usually be found with a quick Amazon search. When choosing a pump you will want one that is able to pump at least 10L an hour per plant in your system (Jackson, 1979). Another factor to consider is the height you will need to pump the liquid up (you will often have to pump water from a reservoir up to a channel).

When it comes to tubing, there are typically two types: 1) a wider tube which serves as the manifold tube that carries water from the reservoir to alongside the channels (typically 0.5-1.0” tubing based on the number of channels) and 2) smaller tubing that supplies water from the manifold tube to each channel - ¼” tubing that is 16 inches long (with an associated gromet that plugs into the manifold tube) seems to work well, as narrower tubing has been found to occasionally clog up. Each channel is placed at a 1 to 4% slope and then drains into a return line - wide PVC piping and fittings tend to work well for the return line. These setups tend to work well for commercial operations, or smaller home systems modeled after those set ups.

Image 41. Commercial NFT system

Image 42. Commercial NFT system

In an A frame system, there is typically one smaller tube or PVC that runs from the pump to the highest channel. Each channel is then connected with PVC piping and fittings, and a return line (usually PVC) is fashioned back to the reservoir.

Image 43. Homemade NFT system on an A-frame

As far as the channel goes, it can be made from PVC piping or sourced from a hydroponics supplier like cropking, amhydro, or farmtek. These channels are generally not that expensive and can easily be cut to an appropriate size (and then you will glue on end caps). If you are using PVC piping as a channel it's important to make sure that the base of the rockwool cube is in contact with the nutrient film (in the commercial channels, rockwool cubes are placed directly on the base of the channel to come in contact with the nutrient film). Many people choose to use net cups to hold the media the seed has grown in. This can work, but once again you need to make sure that you choose the correct diameter PVC piping so that the bottom of the net cup is touching the nutrient film.

The channels should have a slope of 1-4% (Mattson and Leith, 2019). For example, over an 8’ (96-inch) channel length there should be a difference in height of 1 to 4 inches between the water supply side and drain side. Flat channels will promote stagnant water, especially when roots grow. This can lead to both hypoxic (low oxygen) and low nutrient conditions for some plants. The usual commercial spacing for holes in the channel is 8 inches apart (Resh, 2013). This works well for plants like head lettuce where you can get an 8inch or more diameter plant. Spacing is important because it allows for airflow between plants which is important in protecting against pests and pathogens However, at the home level I have found that 4 inch spacing can be useful for smaller herbs so as to get more plants in a smaller space. If you choose to then grow a plant like lettuce, you can plant in every other hole. Support for channels can come in the form of a wood frame, shelving, or even PVC piping. Common supports include A frames and simple tables.

Lastly, as always you need a light source (as per the lighting section)!

6.3 DIY Construction

1. I would construct the frame for the channels first. For larger projects this could be an A frame or a support table. For smaller indoor systems, it’s possible a shelf or desktop will do. Make sure to think about where you are going to put the reservoir and how piping and tubing will go to and from the reservoir.

2. Place the pump in the reservoir and connect pump tubing to the higher end of the channel. If you make your own channels you will likely have to drill a hole into the channel for the tubing.
3. Fabricate a return line back to the reservoir. PVC piping works well for return lines.
4. If the system is indoors you will need to hang lights overhead. Once again, you may have to build a cage for the lights to hang from. Small pulleys/cables are a great way to hang lights if you want to hang them from a structure that is already in place (such as a shelf, or ceiling, etc.) but is not the correct height above the plants for the light requirements. A search on amazon for greenhouse light hangers should yield good results. Here is one example:
https://www.amazon.com/Pairs-inch-Adjustable-Heavy-Hanger/dp/B07XKLLVL7/ref=sr_1_2?dchild=1&keywords=greenhouse+light+hangers&qid=1587245411&sr=8-2

Example of homemade NFT System


Image 44. Shelving NFT system


Image 45. Shelving NFT system

In this example, a shelving NFT system was created from an old AmHydro NFT channel, 2 homemade shelving units, PVC piping, a garden planter as a reservoir, insulation board as the reservoir cover, and a Monios T5 LED light. A 95 GPH fish tank pump was used to pump the nutrient solution, however we had it on the lowest setting which was 35 GPH, a better flow rate for the number of plants in the system. The AmHydro channel was cut to 2 feet in length and additional holes were drilled in between existing holes due to the home nature of this system, and the desire to grow basil and other herbs. However, if lettuce was to be grown, every other hole (or the original holes) would have to be used in order to achieve good spacing. The pump came with enough tubing to reach the channel so no extra was purchased. ½ inch PVC piping and fittings were used to create a return to the reservoir (if you have multiple channels or longer channels you'll need a wider drain return).

6.4 Mechanical Maintenance/Troubleshooting

The main sources of problems in a NFT system comes in the form of leaks which most frequently occur in piping and piping connections. To help stop leaks you can use PVC cement, just make sure it is not a part you want to take apart later. Another option is to tightly screw in connections, using teflon tape. In addition to looking for leaks, make sure to check the system for clogs every once in a while.

6.5 NFT Quick Guide

<u>Materials:</u>

1) Reservoir with lid (the larger the size the better buffering capabilities for pH, EC, and temperature)

a) You will tend to lose around 100 ml of water per plant per day due to evapotranspiration (useful for thinking about size and how often you would like to refill).

2) Pump and tubing (with the ability to pump 10 L per hour per plant)

a) If you have multiple channels you will have a wider manifold tube (½-1") and then a gromet and small tubing (¼" to supply water from the manifold tube to each channel).

3) Return tubing and/or PVC piping and couplings

4) Channel (1-4% slope, 8 inch hole spacing for lettuce, 4 inch for smaller herbs)

5) Frame for channels to be placed

6) Light and timer (as per lighting section)

7) Planting media (rockwool)

8) Nutrient solution (as per nutrient solution section)

<u>Construction and Plant Care:</u>

1) Construct frame for channels, think about space for reservoir and tubing

2) Construct fixture for light if indoors

3) Construct return flow to reservoir

4) Place pump in reservoir and connect to channels (leave running throughout until harvest)

5) Place rockwool with seeds in channels making sure that the bottom of the rockwool is in contact with the flow of nutrient solution.

6) Check pH and EC if you are able 1-2 times per week

7) Top off nutrient solution every 1-2 weeks or as needed

7. NFT vs. Deep Water culture

Both of these systems are great for home hydroponic use, and both can be used to grow leafy greens and herbs. In fact, in a comprehensive study comparing the two systems sides by side (Walters and Currey, 2015) there were no major differences in crop yield from one system to another. They recommend that the decision for which system to use should be based on the "ease of maintenance, and ergonomics" (Walters and Currey, 2015). As noted above, be aware that NFT requires more maintenance due to potential for leaks, and if channels run dry (due to leaks or electrical outage) plants can quickly experience drought stress. Deep water culture has less chance for leaks, and if the electricity goes out the plant roots are still bathed in nutrient solution. In short, choose a system that best fits the area you would like to put it and the degree of risk tolerance you have related to leaks and electricity outages.

8. Useful Equipment

Here is a list of tools and equipment I found useful when constructing my DWC systems. You should keep a list of the equipment you find useful and what it is useful for, that way when a new problem arises you might have an idea about what equipment could be helpful!

1. Drill with up to 1-inch wide drilling attachments.
    a. Screws tend to work very well for support frames. Be sure to pre-drill screw holes.
2. Saw (Hacksaws tend to work well with PVC and plastic channels)
3. Box cutter (useful for cutting insulation board without the mess of a saw)
4. Tape measure
5. Level

6. Square (extremely useful for cutting insulation float boards and cutting wood for supports)
7. Sharpie (for marking insulation) and pencil (for wood and paper drawings)
8. Safety equipment (Gloves, Goggles, Respirator)

9. Total System Cost Examples and Crop Costing

When thinking about the total cost of your system there are several components that you need to think about including material costs, electricity costs, and opportunity costs (i.e. what else you could spend your time and money on instead of building and maintaining a system). It should be expected that building and maintaining a system might not be as cheap as you expect. For example, lighting fixtures can cost a fair amount, and you still have to pay to run those lighting fixtures.

However, it's also important to think about all the returns you will get from a hydroponic system. The first and most obvious return is actual produce, and that's not too shabby. A hydroponic lettuce head at the store will cost you around $2.50 (Wegmans, 2020). So if you were to buy a head of hydroponic each week of the year, it would cost you around $130. In addition, you might want to think about the positive effects of having fresh produce and greenery in your house all year long. There are many studies showing how greenery makes people happy and can improve relaxation (Grinde and Patil, 2009). And lastly, think about the skills and knowledge you will gain from this type of project. First, you might gain some handy work skills, and second, a hydroponic system could spark your interest in some field related to the project. Maybe you will find out you really like plant science, or maybe you realize that greenhouse management is something you enjoy. Maybe building a system will inspire you to do more research into sustainable design and engineering, or maybe you will decide to take up gardening because you want some colorful plants too! It's certainly worth thinking about all the benefits of undertaking a project like this that may not have exact monetary values.

And now for some examples:

1) Small DWC system with HPS light as described in section 5.2 and 5.3 (DIY DWC system) (2 ft^2 growing area, 6 heads of lettuce, 35 day crop cycle, target DLI = 15 $mol/(m^2 day)$).
    a) Material Costs: (There could be a range in prices depending on what you buy, the prices listed here are of the specific items I used in my experiments unless otherwise noted)
        i) 150W HPS light ($100.95)
        ii) Timer ($12.99)
        iii) Light Hangers ($12.59 for 4)
        iv) Restaurant Bussing Tub as the reservoir ($17.34)
        v) Insulation board for plant floats ($5.98 for 2ft x 2ft panel at home depot)
        vi) Air Pump ($20.99)
        vii) Fertilizer ($45.45) (General Hydroponics Flora Series)
        viii) pH up and down ($18.59)
        ix) Rockwool ($19.31 for 200 cubes)
        x) Seeds ($11.25 for 250 seeds from Johnny's seeds)
        xi) Wood for light frame (Let's say you need 30 ft: around $9)
        xii) Miscellaneous (let's say $20)

b) Electrical Costs (For one year based on an average NY state cost of $0.21 per kWh, and a goal of DLI = 15 mol/(m^2day))

i) 150W HPS Light ($172) (running for 15 hours a day)

ii) 1W Air pump ($1.84) (running continuously, 24 hours a day)

In total, this comes to $294.44 for materials, and $173.84 for electrical costs for the year. It's important to realize that you will be able to use many of the components for more than one growing cycle. In fact, the only components you won't be able to use more than once are rockwool cubes and seeds, and in this example you would have 200 and 250 of each respectively. All of the other materials will carry over for future crop cycles. Another important thing to realize here is that some of the major costs come from lighting and electricity. Let's look at an example where both the initial lighting costs and electrical costs associated with lighting are much less.

2) Small DWC system with 40W LED Panel light. (2 ft^2 growing area, 6 heads of lettuce, 35 day crop cycle, target DLI = 15 mol/(m^2day)).

a) Material costs (same as before except a different light)

i) 40W LED Panel light ($69)

ii) All else ($193.49)

b) Electrical Costs (For one year based on an average NY state cost of per $0.21 per kWh, and a goal of DLI = 15 mol/(m^2day))

i) 40W LED Panel light ($45.99) (running for 15 hours a day)

ii) 1W Air pump ($1.84) (running continuously, 24 hours a day)

In this case, the total for the first year is $262.49 for materials, and $47.83 for electricity for the year. Again, it's worth noting again that almost all of the materials will be reused for more than one crop cycle. In addition, the cost could fluctuate based on the specific materials you buy. Furthermore, you may already have some of the materials to begin with (for example a storage crate, wood, screws, or a timer). Or maybe you don't need equipment to hang a light as you already have a perfect mount!

Now you might say, "Hold on one second there, Ryan. Fertilizer, pH up and down, rockwool, and seeds are not just upfront costs. We will have to replenish them at some point. How does that affect the calculations?" And to that, I say fasten your seatbelts.

Engaging some serious greenhouse math:

Let's get specific. We want to know how much the system will cost us to run per crop cycle, and even more than that, per plant. To do that we need to separate some of the initial costs out into costs that can be attributed to each plant. These will be known as direct costs, and we will consider the Fertilizer, pH up and down, rockwool, and seeds to be direct costs (Uva et. al, 2002). The other type of cost we will need to consider is our overhead cost. In a greenhouse, overhead costs are the ones that you will be paying whether or not you are growing plants and include things like electricity, labor, and taxes, but we will only be looking at electricity for our hobby system (Uva et. al, 2002). You could probably consider electricity to be a direct cost in this sort of system, but let's get fancy and do it the right way. First, let's look at direct costs.

- $19.31 for rockwool 200 cubes. Let's call it $20. That means $\frac{\$20}{200\ cubes} = \frac{\$0.10}{cube}$
- $11.25 for 250 seeds. That means $\frac{\$11.25}{250\ seeds} = \frac{\$0.045}{seed}$

- Fertilizer is a little more tricky, so bear with me here. Our cost for fertilizer is $45.45. It's a 3 part mix that comes in 3 bottles that are each 946 mL. That means there is a total of 2,838 mL of fertilizer. That means $\frac{\$45.45}{2{,}838\ mL} = \frac{\$0.016}{1\ mL}$. Our specific fertilizer mix calls for 6mL of fertilizer per L of water. Our initial starting volume of water is 25L, and then we expect to add 4.2L of water each week (for 6 heads of lettuce) starting week 2 (see previous sections), and that means for a 5 week growing cycle we expect to have to add an additional 16.8 L of water. This brings us to a total of 41.8 L of water. That means we will use $41.8\ L\ of\ water\ \times \frac{6ml\ of\ fertilizer}{L\ of\ water} = 250.8\ ml$ of fertilizer per cycle. We know that our fertilizer costs $0.016 per mL so, 250.8 mL × $0.016 = $4.01 for fertilizer per crop cycle. If we break that down even further to each plant we have ($4.01)/6 plants = $0.668 per plant. Thanks for sticking with me. If you are still reading, I'm proud of you.
- pH up and down is also quite tricky because it's very unclear how much of the pH buffer you will have to use. It really depends on your plants, your growing conditions, and the water source you have. So for this calculation, we are going to assume that for some reason you have to buy a new kit each year. To calculate the pH buffer cost per crop (based on the explanation above), we need to know it's cost per crop cycle. In our specific case, there are approximately 10.4 crop cycles per year (365 days ÷ 35 days/crop cycle = 10.4 crop cycles). That means each crop cycle will cost $18.59/10.4 crop cycles = $1.79 per crop cycle. To calculate the cost per plant we divide $1.79 by 6 to get $0.0298 which we will call $0.30.
- So our total direct cost per plant = $0.10 (rockwool) + $0.045 (seed) + $0.668 (fertilizer) + $0.30 (pH up and down) = $1.11.

Now let's move to our overhead costs. In our case, it's just electricity. When calculating overhead costs, it's important to understand the concept of the square foot week (SFW). The square foot week is a concept that helps us to transfer our yearly overhead costs to per plant costs. The basic idea is that you take the amount of square feet you are using to grow plants, and then multiply that by the amount of weeks you could be growing them (Uva et. al, 2002). So for our example, we have 2 square feet of growing area and we could grow our crops all year round, or 52 weeks (If we had done our electricity costs for half the year then we would say 26 weeks). This means we have (2 square feet) $\times$ (52 weeks) = 104 square foot weeks (SFW). Once you know your SFW, you take your overhead costs and divide them by your SFW to get a price per SFW. Okay, now back to some greenhouse math.

- Our electricity (as noted before) costs \$47.83 yearly.
- Now we divide our yearly cost by our SFW. $\frac{\$47.83}{104\,SFW} = \frac{\$0.46}{SFW}$

That means it is costing us \$0.46 per square foot each week to run our system no matter what. In terms of how to use this information to calculate our overhead cost per plant we think about it like this. We know that each square foot costs \$0.46 a week, and we know we will be growing 6 heads of lettuce for 5 weeks, and we know that 6 heads of lettuce per 2 square feet equals 3 heads of lettuce per one square foot. So to find out the overhead cost per plant per cycle we do $\frac{\frac{\$0.46}{SFW} \times 5\ weeks}{\frac{3\ heads}{square\ foot}} = \$0.77$ per head of lettuce in overhead costs per growth cycle. We are almost there! I hope you are still with me!

Let's now add our direct cost per head of lettuce, which was \$1.11, and overhead cost per head of lettuce, which was \$0.77, to get a total of \$1.88 per head of lettuce. Given that we have

6 heads of lettuce, let's multiply $1.88 by 6 to get $11.28. This means our 5 week crop of lettuce cost us $11.28 in direct and overhead costs.

Now, I know what you are thinking. You are thinking, "Ryan, that seems like a lot of extra work when all I had to do was calculate the monthly electricity cost and add that to the direct costs for 6 plants to find out the monthly cost of the system." Yes, you are correct. BUT, now you know exactly where all the costs are coming from. In addition, you can see which ones are the most expensive (I'm looking at you fertilizer and electricity) so you know that's where you need to be the most informed consumer. Also, we just found out that even though the system may have been expensive to build, it still costs us less (in this specific system) to grow hydroponic lettuce than to buy it from the store (our $1.88 per head compared to the store's $2.50 a head)!

Lastly, using this information, we can calculate how long it would take us to "break even" in terms of the amount we are saving per head of lettuce produced. Now I will warn you it's going to seem like a long time because we are only saving $0.62 per head, and we have to make up all of our initial costs. To calculate the number of crop cycles it will take us to "break even" we want to see at what point our expenditures will equal our theoretical gross profit from lettuce. We said before that a head of hydroponic lettuce at the store will cost $2.50, so we will say that our crop of 6 lettuce heads is worth $15.

$$Upfront\ cost\ +\ \frac{\$\ spent}{crop\ cycle}(number\ of\ cycles)\ =\ \frac{\$\ gained}{crop\ cycle}(number\ of\ cycles)$$

Upfront costs = $167.81

C = number of crop cycles

$$\frac{\$\ spent}{crop\ cycle}\ =\ \$11.28$$

$$\frac{\$\ gained}{crop\ cycle} = \$15$$

$$\$167.89\ +\ \$11.28(C)\ = \$15(C)$$

$$C\ =\ \frac{\$167.89}{\$3.72} = 45.13\ crop\ cycles$$

Given that our specific crop cycle is 35 days, this means it will take 46 $\times$ 35 days = 1,610 days, or a little under 4 and a half years to “break even”. You can find a helpful spreadsheet for these calculations here:

https://blogs.cornell.edu/cornellcea/files/2020/05/Useful-Home-Hydroponics-Excel-Sheets.xlsx

First, I would like to congratulate you for sticking with me and getting all the way to the end of that calculation. It was a lot of work, and in the end we learned it’s gonna take a while to break even for this set up. But it was a fun journey! Once again, I would like to point out that these calculations were for my specific set up. Your setup and costs might be a little different, and as we demonstrated there could be lots of ways to save money (such as energy efficient LEDs, cheaper powdered fertilizer, and using materials you have available) and optimize production (for example my bussing tub system was 2 ft^2, but the lights - especially the HPS would be good for lighting 4 ft^2), and now you have the tools to figure out what your costs will be.

I would like to point out that in this example we were only thinking about growing lettuce. You could throw other herbs into the mix that have higher market values than lettuce such as mint or basil, and these other herbs could be spaced closer together which would change some of the calculations (for the better) (and you now have the ability to crop cost all sorts of herbs and setups!).

And of course, let's consider for a moment the reasons for building such a system. Let's be honest, the reason you are building a small DWC system probably isn't to grow enough food to stop shopping at the supermarket, and it probably isn't to grow the cheapest lettuce possible. If that's the case, then you should probably just go to the supermarket and by iceberg lettuce (or grow outdoors in summer time and not have lettuce in winter). Hopefully, your reasons have something to do with it being cool to be able to grow fresh greens in your house throughout the entire year and being able to pick them whenever you want! In addition, it's pretty fun to know that you built the whole system yourself and now you are producing fresh awesome tasting food! And, as I mentioned before, there are many studies that show having plants indoors improves happiness. Especially greenery you can eat!

10. Diseases, Insects, and other Disorders

As a home grower, the problems you are likely to have with diseases and insects should be much smaller than in a commercial setting. For this reason, it does not make sense to use pesticides, but rather cultural control practices - mainly cleanliness and sanitation of systems. A clean system with the removal of any infected plant material should be enough to keep pests and diseases at bay at the home level.

When looking at disorders of plants, it's important to know whether what you are seeing is caused by biotic or abiotic factors. Biotic disorders are ones caused by pathogens and insects, and abiotic disorders are ones caused by environmental conditions such as a lack of nutrients or a lack of light. Biotic disorders tend to have patchy distribution throughout crops (both individual plants and groups), and abiotic disorders tend to have uniform distribution throughout crops.

The list of disorders below is by no means comprehensive, but should give a good idea of the main issues a home hydroponic grower could face.

Definition of terms:

Chlorosis: yellowing of leaves

Necrosis or Necrotic material: Dead leaf material

Marginal: On the edge of the leaves

Interveinal: between the veins

10.1 Common Diseases

1. *Powdery Mildew* is a fungal disease that will appear as a white powdery substance on leaf surfaces (typically the upper surface of leaves)and can often cause leaf wilting. It is found on a variety of leafy greens and herbs.

Image 46. Powdery Mildew on lettuce

2. *Basil Downy mildew* is a fungus that can be found on basil plants. It is identified by chlorotic leaves, spots of necrosis, and spores on the underside of the leaf. Sometimes this pathogen is confused for a nutrient deficiency which is why it's important to check the underside of the leaves for spores (McGrath, 2019).

Image 47. Basil Downy Mildew Chlorosis.

Image 48. Basil Downy Mildew spores on the underside of the leaf.

3. *Botrytis (Gray Mold)* is a fungus found on a variety of leafy greens and herbs, diagnosed by brown/gray fuzzy growth and browning stems and leaves.

Image 49. Botrytis on lettuce.

4. *Pythium Root Rot* is a water mold especially common on spinach, basil, and arugula roots but occasionally also on lettuce. It is diagnosed by brown and discolored roots. Due to the decline of the root system it can also cause leaf wilting and chlorosis. One control method more specific to Pythium is to keep water temperatures below 68°F (Thompson et. al, 1998).

Image 50. Discolored roots from Pythium root rot.

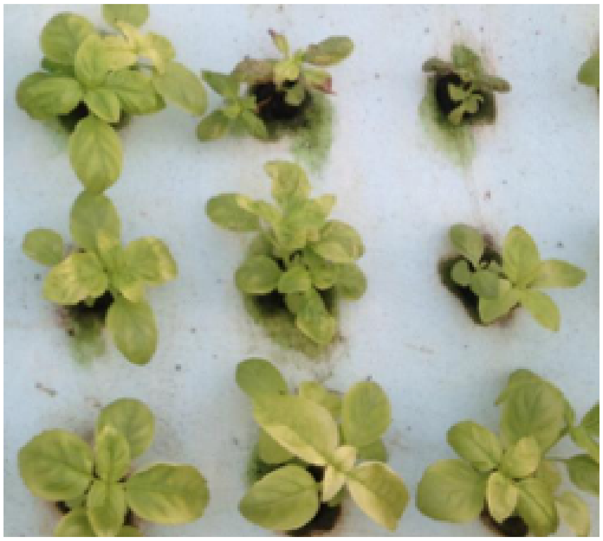

Image 51. Wilting from Pythium root rot

5. *Sclerotinia blight (white mold*) is a fungus that often affects lettuce and is diagnosed by soft rot, white mycelium, and wilting of plants.

Image 52. Sclerotinia blight on lettuce

Image 53. Sclerotinia blight on lettuce

10.2 Pathogen Control Methods

These control methods will work for most of the pathogens mentioned. First, when buying seed, try to get cultivars that are resistant to diseases like downy and basil downy mildew (McGrath, 2019). Second, make sure to keep the system clean. This means remove any debris and dead material from the system and sanitize the system after each growth cycle (Raudales, 2018). As soon as any pathogen is detected be sure to remove any infected plants (and in the case of root rot - it can rapidly spread to all the plants that share the same water so consider halting growth now, sanitizing, and restarting with new plants and new nutrient solution). Finally, try to maintain low humidity and good airflow through proper spacing between plants. Some commercial growers will use a preventative fungicide to help stop infections, however this is not very realistic for a home grower.

10.3 Common Pests

1. *Shore Flies* are common in commercial greenhouses and could show up in a home system. Shore flies are small black flies with 5 white spots on their wings. They feed on algae and can leave frass (droppings) on leaves. They are mostly a nuisance for people, but have also been known to transmit root diseases between plants.

Image 54. Shorefly

2. *Fungus gnats* are a common small mosquito like fly that feed on naturally occurring microbes in the root zone. They are mostly a nuisance for people, but have also been known to transmit root diseases between plants, and at high levels they can damage the roots and base of the stem by feeding on them.

Image 55. Fungus gnat

10.4 Pest Control Methods

Shore Flies are more common when algae is around as the larvae love feeding on algae in rockwool cubes. Fungus gnats are more of a problem with soilless potting mixes such as coco coir cubes. We suggest the following methods for a home grower trying to control shore flies and fungus gnats. Try to keep algae to a minimum by keeping the system clean, sanitizing it between growth cycles, and blocking the nutrient solution from light as much as possible. This should eliminate the food source for shore flies. Fungus gnat larvae thrive in wet root-zones - for example if you are starting seeds in coir cubes, avoid overwatering of the cubes so the rootzone does not stay oversaturated with water. In addition, general cleanliness of the system, removing any debris and dying leaves, and sanitizing between crop cycles is a great way to reduce pests. Commercial growers will often use bio controls such as predatory mites and beneficial nematodes, however this probably isn't not be needed for a small home system.

10.5 Physiological Disorders

1. *Leaf tip burn* is a disorder that often affects head lettuce especially when it is approaching maturity with a compact head forming. The symptoms include marginal leaf necrosis and

distortion of young leaves at the center of the head. Tip burn is caused by a lack of calcium most often caused by poor plant uptake and inadequate supply of calcium to the young leaves due to poor transpiration, or a lettuce head nearing maturity that is growing too fast (such as under too high light levels). Tip burn is not normally caused by a lack of calcium in the nutrient solution (Mattson, 2016). Control methods include promoting good air flow (possible with a fan), and decreasing the amount of light supplied to the plant (increase light height or decrease running time).

Image 56. Leaf Tip Burn in lettuce

2. *Outer leaf edge necrosis* is mostly found on lettuce and shows symptoms of necrotic spots on older leaves. This disorder is caused by a leakage of water and salts often due to high relative humidity during the night. Control methods include promoting good airflow, avoiding high night time humidity, and also avoiding a high salt content (EC) in the nutrient solution.

Image 57. Outer leaf edge necrosis in lettuce.

3. *Bolting* is the early development of the flower stalk and is typically caused by excessive air temperature. Both lettuce and spinach are sensitive to it - and for spinach a long day length (lights on longer than 12 hours) also promotes early bolting. Keeping the air temperature below 80 °F, or keeping the water temperature below 68 °F are both effective control measures.

Image 58. Bolting in Lettuce

Image 59. Bolting in Spinach

4. *Stringy and Stretched Plants* are most likely due to a lack of light (or an overcrowding of plants). Under low light conditions, plants naturally grow tall and stringy in an attempt to grow above their neighbors to access light. If you see these types of plants they need more light!

Image 60. Stretched lettuce plant lacking sufficient light

10.6 Nutrient Deficiencies

The first signs of nutrient deficiency in plants will often occur as discoloration (often chlorosis), distortion, or marginal necrosis of leaves (mattson). If these symptoms occur in older leaves (lower leaves), you probably have a deficiency in N, P, K, or Mg. These are called mobile nutrients and thus the plant can relocate them to new growth (McCauley et. al, 2009). If symptoms occur in the middle of the plant it is possible that you have a deficiency in S or Mo, as these are semi-mobile nutrients. Symptoms occurring in newer leaves (towards the top of the plant), are likely to be a lack of Ca, B, or Fe. These are immobile nutrients, so if the plant isn't getting any then there will be none for new growth (McCauley et. al, 2009).

For a commercial grower, knowing the specific nutrient deficiency is important because they will most likely adjust their custom nutrient solution. However, at the home level, if a nutrient deficiency is to occur, it's probably going to be an iron deficiency in the upper (newer) leaves with signs of interveinal chlorosis due to a high pH, or a more general N,P,K, or Mg deficiency due a lack of nutrients in solution. In the case of an Iron deficiency, the best course of action is to check the pH of the solution and make sure it is between 5.5-6. In the case of a deficiency from one of the other nutrients it's best to check the EC of the solution if you can and adjust, or in the case that the nutrient solution is several weeks old, it's probably a good idea to mix a new nutrient solution (you can use the old nutrient solution for water other plants you may have).

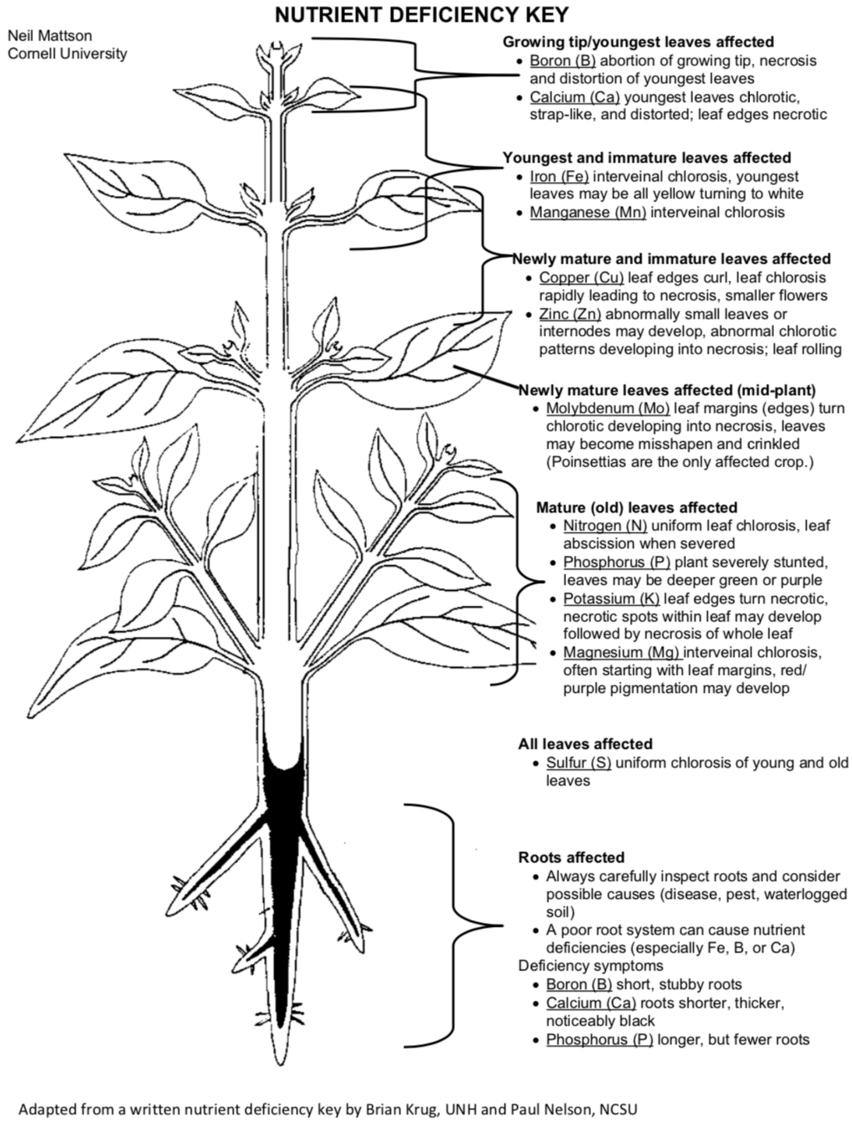

Image 61. Diagram of nutrient deficiencies.

Disclaimer: Mention of trademarks or brand names is for informational purposes only and does not imply its approval to the exclusion of other products that may be suitable.

References

Adams, P. (1981). Nutrient-film culture, Agricultural Water Management, Volume 4, Issue 4, Pages 471-478, ISSN 0378-3774, https://doi.org/10.1016/0378-3774(81)90035-4. (http://www.sciencedirect.com/science/article/pii/0378377481900354)

Both, A. J. (2002). Ten years of hydroponic lettuce research. *The State University of New Jersey, New Jersey*.

Both, A. J., Albright, L. D., Langhans, R. W., Reiser, R. A., & Vinzant, B. G. (1994, January). Hydroponic lettuce production influenced by integrated supplemental light levels in a controlled environment agriculture facility: experimental results. In *III International Symposium on Artificial Lighting in Horticulture 418* (pp. 45-52).

Both, A.J. and Brechner, M. (2013). Hydroponic Lettuce Handbook. Cornell University. Cornell CEA. Retrieved from https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/8/8824/files/2019/06/Cornell-CEA-Lettuce-Handbook-.pdf

Both, A. J., Bugbee, B., Kubota, C., Lopez, R. G., Mitchell, C., Runkle, E. S., & Wallace, C. (2017). Proposed product label for electric lamps used in the plant sciences. *HortTechnology*, *27*(4), 544-549.

Ciolkosz, D. E., Albright, L. D., & Both, A. J. (1997). Characterizing evapotranspiration in a greenhouse lettuce crop. *II Modelling Plant Growth, Environmental Control and Farm Management in Protected Cultivation 456*, 255-262.

Ebba, J. (2020). Growing Seedlings Under Lights [Fact Sheet]. UNH. NH Extension. Retrieved from https://extension.unh.edu/resource/growing-seedlings-under-lights-fact-sheet

Grinde, B., & Patil, G. G. (2009). Biophilia: does visual contact with nature impact on health and well-being?. *International journal of environmental research and public health*, *6*(9), 2332-2343.

Goto, E., Both, A.J., Albright, L.D., Langhans, R.W. and Leed, A.R. (1996). EFFECT OF DISSOLVED OXYGEN CONCENTRATION ON LETTUCE GROWTH IN FLOATING HYDROPONICS. Acta Hortic. 440, 205-210. DOI: 10.17660/ActaHortic.1996.440.36 https://doi.org/10.17660/ActaHortic.1996.440.36

Jackson, M.B., 1979, September. Aeration in the nutrient film technique of glasshouse crop production and the importance of oxygen, ethylene and carbon dioxide. In *Symposium on Research on Recirculating Water Culture 98* (pp. 61-78).

Mattson, N. (2018). Fertilizer Calculation Basics. *E-Gro.* Edible Alert. Retrieved from http://e-gro.org/pdf/E305.pdf

Mattson, N. (2011). Greenhouse Lighting. Cornell University. Cornell CEA. Retrieved from https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/8/8824/files/2019/07/Greenhouse-Lighting.pdf

Mattson, N. 2016. Growing hydroponic leafy greens. Greenhouse Product News. 26(10):16-20.

Mattson, N. (2017). Using LEDs for Starting Vegetable/Flower Seedlings. Cornell University.

Mattson, N. and Lieth, J. (2019). Chapter 12 - Liquid Culture Hydroponic System Operation, Editor(s): Michael Raviv, J. Heinrich Lieth, Asher Bar-Tal, Soilless Culture (Second Edition), Elsevier, Pages 567-585, ISBN 9780444636966, https://doi.org/10.1016/B978-0-444-63696-6.00012-8. (http://www.sciencedirect.com/science/article/pii/B9780444636966000128)

Mattson, N. and Merril, T. (2015). Symptoms of Common Nutrient Deficiencies in Hydroponic Lettuce. *E-Grow.* Research Update. Retrieved from http://www.e-gro.org/pdf/Mattson_Lettuce_2015_9.pdf

Mattson, N. S., & Peters, C. A. R. I. (2014). A recipe for hydroponic success. *Inside Grower Ball Publishing, Chicago, IL*, 16-9.

Mattson, N.S. and R.C. Hansen. 2012. Manage pH and soluble salts in hydroponics. Greenhouse Grower Magazine. 30(10):43-46.

McCauley, A., Jones, C., & Jacobsen, J. (2009). Plant nutrient functions and deficiency and toxicity symptoms. *Nutrient management module*, *9*, 1-16.

McGrath, M. (2019). Managing Basil Downy Mildew in the Greenhouse. *E-Grow.* Edible Alert. Retrieved from http://www.e-gro.org/pdf/E407.pdf

Raudales, R. (2018). Sanitation: Start Clean, stay clean!. *E-Grow.* Edible Alert. Retrieved from http://www.e-gro.org/pdf/2018_731.pdf

Resh, H. M. (1995). *Hydroponic food production. A definitive guidebook of soilless food-growing methods* (No. Ed. 5). Woodbridge press publishing company.

Pocock, T. (2015). Light-emitting Diodes and the Modulation of Specialty Crops: Light Sensing and Signaling Networks in Plants, *HortScience horts*, *50*(9), 1281-1284. Retrieved May 11, 2020, from https://journals.ashs.org/hortsci/view/journals/hortsci/50/9/article-p1281.xml

Thompson, H. C., Langhans, R. W., Both, A. J., & Albright, L. D. (1998). Shoot and root temperature effects on lettuce growth in a floating hydroponic system. *Journal of the American Society for Horticultural Science*, *123*(3), 361-364.

Uva, W. F. L., & Richards, S. T. (2002). New York Greenhouse Business Summary and Financial Analysis, 2000.

Walters, K. J., & Currey, C. J. (2018). Effects of Nutrient Solution Concentration and Daily Light Integral on Growth and Nutrient Concentration of Several Basil Species in Hydroponic Production, *HortScience horts*, *53*(9), 1319-1325. Retrieved May 11, 2020, from https://journals.ashs.org/hortsci/view/journals/hortsci/53/9/article-p1319.xml

Walters, K. J., & Currey, C. J. (2015). Hydroponic Greenhouse Basil Production: Comparing Systems and Cultivars, *HortTechnology hortte*, *25*(5), 645-650. Retrieved May 11, 2020, from https://journals.ashs.org/horttech/view/journals/horttech/25/5/article-p645.xml

Wegmans. (2020). Hydroponic Boston Lettuce. Retrieved from https://shop.wegmans.com/search?search_term=hydroponic%20lettuce

IMAGE REFERENCES

TABLE REFERENCES

FIGURE REFERENCES