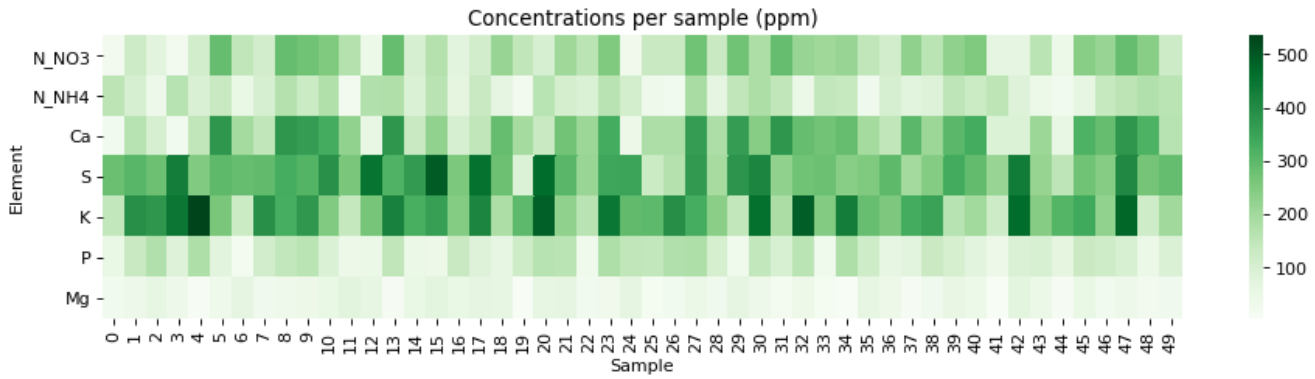
Building a model to predict EC in hydroponic nutrient solutions

Electrical conductivity (EC) is one of the most useful parameters in the practical preparation of hydroponic nutrient solutions. This is because knowing the expected conductivity of a nutrient solution can allow you to prepare solutions without having to measure the total volume exactly, a parameter that is often hard to accurately determine in practice. Although determining the target conductivity is easy to do using small preparation volumes – which can be done accurately – it is often impractical to do so routinely, which is necessary if the actual composition of the nutrient solution is being changed as a function of time. Due to all the above, it is important to come up with accurate models to estimate the EC of nutrient solutions with only information about their mineral composition, without having to measure the value experimentally. In this post I am going to talk about how I created a model to do exactly this, taking advantage of multi-variable experimentation and simple modeling techniques.



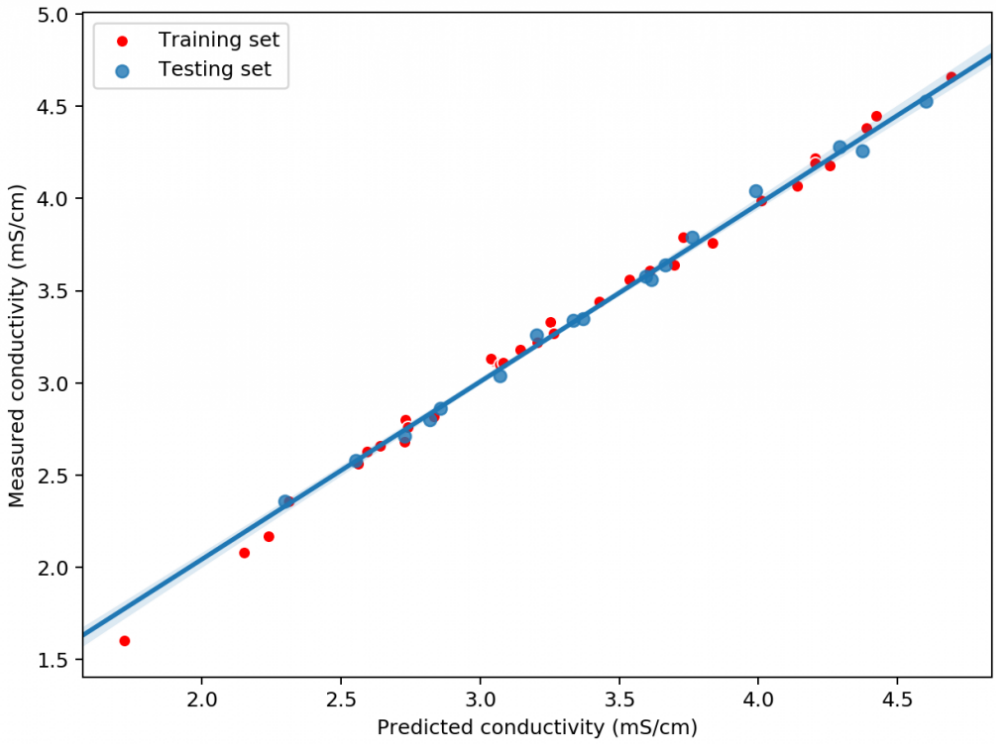
Mineral nutrient concentrations (ppm) of all the samples measured

The problem with conductivity modeling is that not all salts contribute the same to the conductivity of a nutrient solution. For example potassium sulfate can contribute

significantly more to conductivity per gram compared to a salt like monopotassium phosphate. Furthermore, the addition of some salts can affect the conductivity of others (see my previous post on conductivity modeling in Hydrobuddy for more details). In the regime we use in hydroponics, the determination of electrical conductivity using data from limiting molar conductivity can lead to very skewed results, which makes these estimations of little usage in practice.

To solve this issue, I designed an experiment where 50 different EC measurements were made for different hydroponic nutrient solutions within the range of concentrations of nutrients that are reasonably expected in hydroponic culture, with some values being above these in order to ensure that all values encountered in practice will be within the measured ranges. The image above shows you all the concentrations that were measured within the experiment. To prepare the solutions I used calcium ammonium nitrate, potassium sulfate, magnesium sulfate heptahydrate, monopotassium phosphate and ammonium sulfate. All of these were agricultural grade salts in order to reflect the same impurities expected in a normal hydroponic setup. Note that no heavy metal salts were used since their contribution to the EC of a hydroponic nutrient solution is negligible.

Concentrated solutions of all the salts were prepared in 250mL volumetric flasks using a +/-0.001g scale and aliquots of these solutions were drawn using 5mL plastic syringes (+/- 5%) in order to prepare final 250mL solutions using volumetric flasks. Conductivity measurements were done using an Apera EC60 conductivity meter that was previously calibrated using a 2 point calibration method. All the solutions were prepared using distilled water. The target concentrations for the solutions were determined using a pseudo random number generator in order to try to ensure a random distribution of samples within the concentration space of interest.

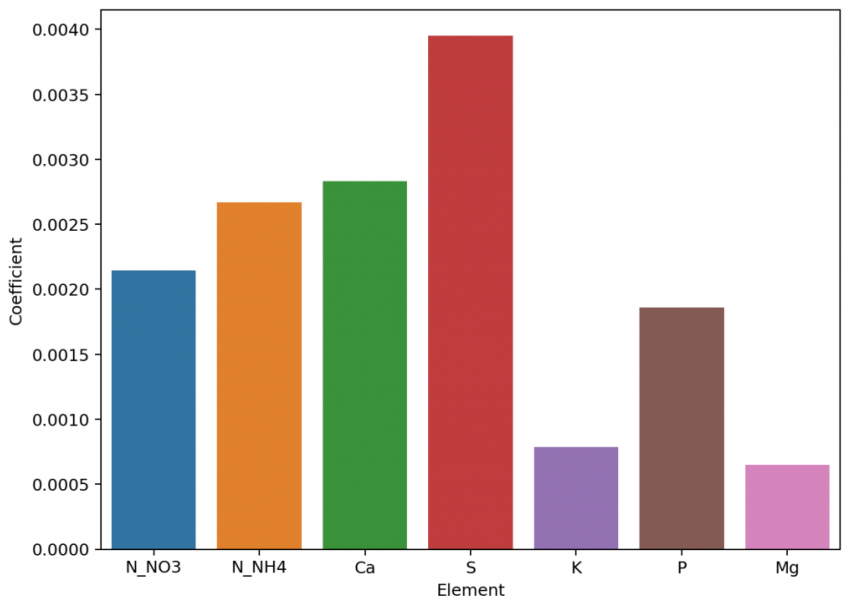


A sample modeling results for a random split with training (33 data points) and testing sets (17 data points)

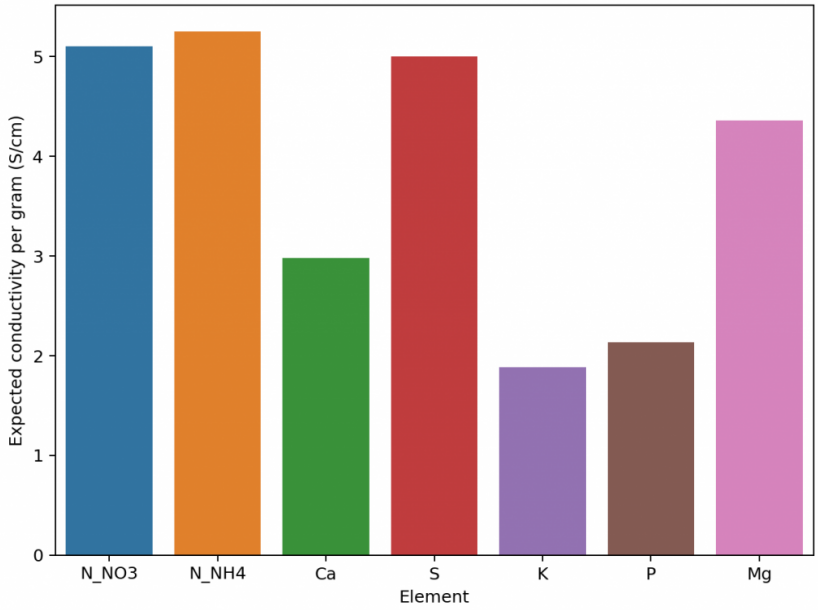
Using this data we constructed a linear model to attempt to predict conductivity. In order to evaluate the model we randomly split the results to get 33 data points used for model construction and 17 points left for model validation. Performing this process 100 times shows that the mean R2 of the model on the training set is 0.995 while the average on the training set is 0.994. This shows that the model is able to properly generalize the conductivity data in order to properly predict the conductivity of the solution across the space studied. **The mean absolute error in the testing set was 0.036 mS/cm. This shows the high certainty with which we can make conductivity predictions.**

Exploring the model coefficients can also show us how different the contributions of the different elements to the conductivity of the nutrient solution can actually be. These results are surprising if you compare them to the conductivity contributions per gram that are expected from the limiting molar conductivity values, which are the conductivity values the ions exhibit on their own under very high dilutions (this

is also the method used in HydroBuddy <=v1.65). We can clearly see here that in reality we are getting way more conductivity out of sulfate compared to the other elements and significantly less from magnesium. This means that at the makeup and concentration values used in hydroponics the Mg ions are not being able to contribute as much as they can when they are alone because their activity is being lowered by the other ions in solution, while the opposite case applies to sulfate.



Linear model coefficients for the different elements (proxy for their contribution to conductivity)



Expected conductivity values per gram using data from limiting

molar conductivity values (taken from here)

The above shows us why conductivity in hydroponics is so complicated, it shows how ions do not contribute equally to conductivity and how they behave very differently in real hydroponic solutions. Thankfully the above also shows how we can create a model using experimental data that is actually able to predict conductivity, since the relationships – although different than expected – are still highly predictable when enough experimental data is available. All the above experimentation took 4 hours to do – with the help of my lovely wife, who is also a chemist – and should allow me to add a very powerful model to predict hydroponic nutrient solution EC values to HydroBuddy.

All the above experimentation data will be open source and available in a github repository soon. We also hope to show you how all of this was done in a youtube video in the near future.

Monitoring the quality of fertilizer stock solutions

Hydroponic concentrated nutrient fertilizer manufacturers are not held to any routine quality standards by regulatory authorities in most countries. Although fertilizers need to be properly registered and their intended minimum compositions are shared with the public, the manufacturer never guarantees that each batch of the product will comply with any sort of quality standard and it's therefore possible for hydroponic nutrients to come out of a factory with compositions that significantly deviate between batches. People who make their own fertilizers are also not free from problems either, as

issues further down the chain – with the fertilizer raw inputs – or issues related with human error, can and will still happen.

Because of these problems, a very important part of every hydroponic grower's process should be to establish some quality guidelines to evaluate whether a given batch of nutrients – either bought or self-made – complies with what is expected and can therefore be used in the hydroponic crop. In today's post I will talk about the properties that you can measure in order to ensure that the quality of your inputs is sustained through time and how these measurements should be done.



These are two measurements that should always be done whenever you receive or prepare a new batch of hydroponic nutrient stock solution:

Density of the stock solution: The density of a hydroponic stock solution should always be measured and recorded. The density needs to be measured accurately, using a pycnometer and an accurate enough balance (+/- 0.01g). A 5 or 10mL pycnometer would be recommended and the balance should be able to measure up to at least 50g, to ensure that the measurement

of the final weight of the pycnometer will be in range. You should first weight the empty and dry pycnometer, then fill it with liquid to the brim, place the stopper – some liquid will spill, this is how it's intended to work – then wipe any spilled liquid and weight the full pycnometer. The difference in weight divided by the pycnometer volume will give you the density. Make sure you also record the ambient temperature when the measurement is made.

pH of the stock solution: You can use a pH meter to determine the pH of a sample of the stock solution. You can use the regular pH tester you use to measure the pH of your hydroponic nutrient solutions, however make sure the pH meter does not remain for too long in the stock solution – more than what's necessary to make the measurement – and wash it with distilled water and store it in pH meter storage solution as soon as the measurement is done. Also make sure the pH meter is calibrated right before making this measurement.

If any compounds are added incorrectly or the composition of the raw inputs was in anyway wrong, the above two parameters – pH and density – will tend to change, as they depend very strongly on the composition of inputs being the same. Of course, there are mistakes that can go undetected in these two domains but a stock solution that always records the same across batches will tend to be the same chemically. Every time you receive or prepare new solution record the above and ensure you never use any solution that deviates more than -/+ 5% from the median you have on your record. The deviation of the above two parameters also serves as a way to control how reproducible the manufacturing process of the stock solution actually is.

If there is a strong mismatch in these measurements when compared with the median of all past values, then you need to continue to actual chemical analysis of the nutrients to figure out what's wrong.

If you prepared the fertilizer yourself then it becomes important to check notes – always keep records of weights that are added when preparing solutions – and see if there were any changes in the chemical suppliers of any of the used inputs. Sometimes the quality and composition of certain chemicals can change dramatically between suppliers, so making changes from one to another can often require chemical analysis to ensure that the composition stays the same. A good example can be potassium silicate, where the exact grade and potassium to silicon ratio of the raw material can change a lot depending on the exact fabrication process used by the company making it.

Another important point is the accuracy of the instruments used for the preparation of solutions. Sometimes the problem is that a scale or a volume measuring device lost calibration and generated errors in a previously unseen range. This can be particularly problematic if different instruments are used to measure different inputs, which can make some inputs subject to bigger errors that others and can therefore change the ratio between different nutrients in the hydroponic solution.

Using calcium sulfate in hydroponics

Calcium is a very important element in plant nutrition and can be supplied to plants through a wide variety of different salts. However, only a handful of these resources are significantly water soluble, usually narrowing the choice of calcium to either calcium nitrate, calcium chloride or more elaborate sources, such as calcium EDTA. Today I am going to talk about a less commonly used resource in hydroponics –

calcium sulfate – which can fill a very important gap in calcium supplementation in hydroponic crops, particularly when Ca nutrition wants to be addressed as independently as possible and the addition of substances that interact heavily with plants wants to be avoided.



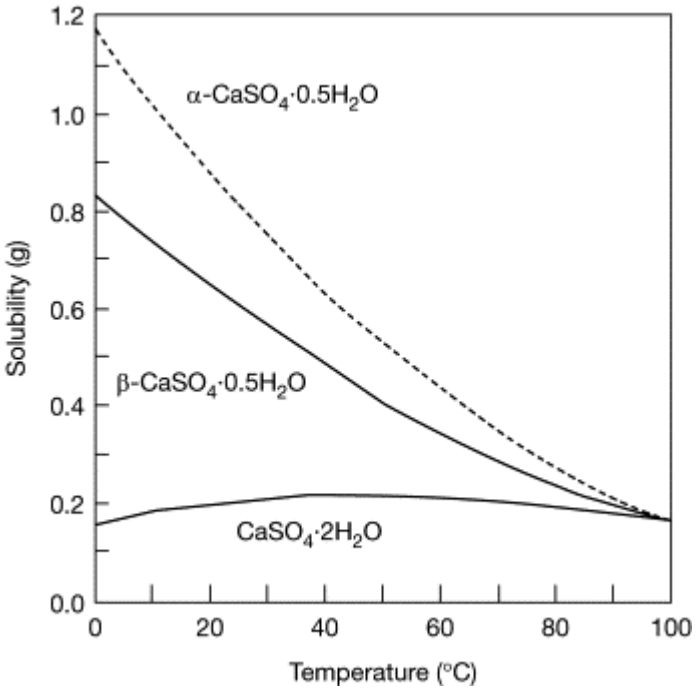
Calcium sulfate dihydrate (gypsum)

There are some important reasons why you don't hear too much about calcium sulfate in hydroponics. Some websites actually recommend heavily against using this substance in hydroponic nutrient solutions. Why is this the case? The core issue is calcium sulfate's solubility, with this substance traditionally considered "insoluble" in chemistry. However all substances are soluble to one or another degree – even if to an extremely small degree – but calcium sulfate is actually at the very border of what is considered a soluble substance in regular aqueous chemistry.

At 20C (68F), calcium sulfate dihydrate – the form most commonly available – has a solubility of around 2.4 g/L. In practice this means that you can have up to around 550 ppm of Ca in solution from calcium sulfate dihydrate before you observe any precipitation happening. This is way more than the normal 150-250 ppm of Ca that are used in final hydroponic nutrient solutions that are fed to plants. You could supply

the entire plant requirement for calcium using calcium sulfate without ever observing any precipitate in solution. *At the normal temperature range that hydroponic nutrient solutions are kept, the solubility of calcium sulfate is just not an issue*. To add 10 ppm of Ca from calcium sulfate you need to add around 0.043g/L (0.163g/gal). You should however avoid using calcium sulfate for the preparation of solutions for foliar sprays as it will tend to form precipitates when the foliar spray dries on leaves, the leaves will then be covered with a thin film of gypsum, which is counterproductive.

Calcium sulfate has a great advantage over other ways to supplement calcium in that the anion in the salt – sulfate – does not contribute as significantly to plant nutrition. Other sources, such as calcium chloride or calcium nitrate, will add counter ions that will heavily interact with the plant in other ways, which might sometimes be an undesirable effect if all we want to address is the concentration of calcium ions. Other sources such as Ca EDTA might even add other cations – such as sodium – which we would generally want to avoid. Calcium sulfate will also have a negligible effect in the pH of the solution, unlike other substances – like calcium carbonate – which will have a significant effect in the pH of the solution.



Solubility (g per 100mL) of calcium sulfate as a function of temperature for different crystalline forms (see more here)

A key consideration with calcium sulfate is also that its dissolution kinetics are slow. It takes a significant amount of time for a given amount of calcium sulfate to dissolve in water, even if the thermodynamics favor the dissolution of the salt at the temperature your water is at. For this reason it is very important to only use calcium sulfate sources that are extremely fine and are graded for irrigation. This is sometimes known as "solution grade" gypsum. I advice you get a small amount of the gypsum source you want to use and test how long it takes to dissolve 0.05g in one liter of water. This will give you an idea of how long you will need to wait to dissolve the calcium sulfate at the intended temperature. Constant agitation helps with this process.

An important caveat with calcium sulfate is that its relatively low solubility compared with other fertilizers means that it cannot be used to prepare concentrated nutrient solutions. This means that you will not be able to prepare a calcium sulfate stock solution or use calcium sulfate in the preparation of A and B solutions. As a matter of fact the formation of calcium sulfate is one of the main reasons why concentrated nutrient solutions usually come in two or more

parts, to keep calcium and sulfate ions apart while they are in concentrated form. *Calcium sulfate should only be added to the final nutrient solution and adequate considerations about temperature and dissolution time need to be taken into account.*

Can you use regular soil fertilizers in hydroponics?

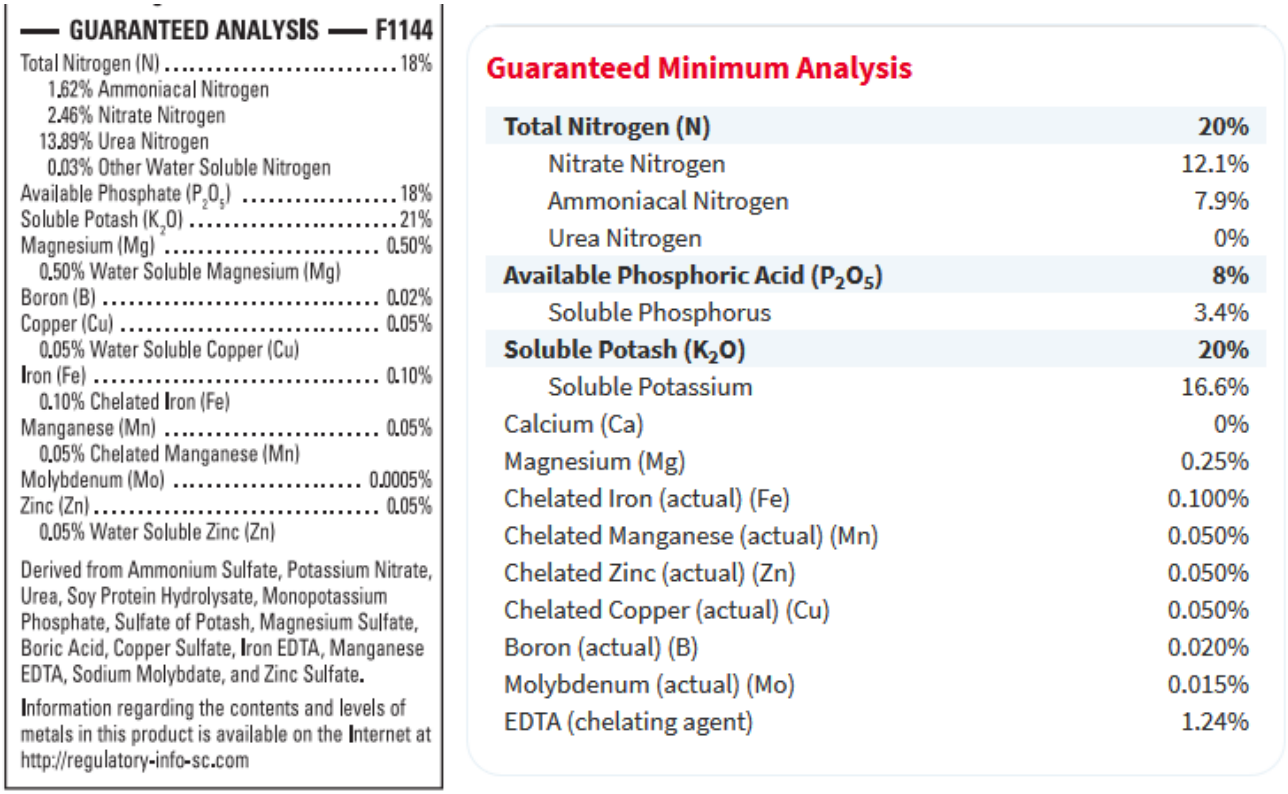
If you have just started your journey into hydroponics you're probably wondering why you need to spend your money in hydroponic specific nutrients when there are so many cheaply available soil fertilizers sold out there. Certainly there are all plant food and there must be some way you can use all these cheap soil fertilizers to create a suitable replacement to feed your hydroponic crop. In this post I want to explain some of the key differences between hydroponic and soil fertilizers, when soil fertilizers can be used in hydroponics, how they can be used and when it is definitely a bad idea to try to use them.



Some slow release soil fertilizer being added to plants

To understand the difference between soil and hydroponic fertilizers we must first understand the difference between both growing setups. In hydroponics we try to grow plants in sterile and chemically neutral supporting media where all the nutrients are expected to be provided by the nutrient solution while in soil the media is not intended to be inert – it contains organic matter, minerals that can dissolve and living microbes – and we expect some of these to provide nutrition to our plants. Fertilizers for soil are intended to aid this process – provide material for microbes to process and supplement some of the lacking elements in the soil – while hydroponic fertilizers intend to provide all required nutrition in the forms that are mostly favorable for plants. Fertilizers for soil are often also meant to be applied once or very occasionally, while fertilizers for hydroponics are expected to be fed to the plant very frequently.

In chemistry terms, this means that fertilizers for soil will tend to contain forms of nitrogen that can be processed slowly by microbes in soil – urea and ammonium salts – while hydroponic fertilizers contain mostly nitrate salts. It is rare for soil fertilizers sold to home growers to contain large amounts of nitrates because these are easily washed aware by rain, are strong pollutants of underwater ground sources and are only shortly available for plants due to their high mobility in soil. However ammonium and urea are a terrible idea in hydroponics since ammonium fed frequently strongly acidifies the media and plants supplied their nitrogen only from ammonium in solution will tend to show toxicity issues quickly. Soil fertilizers rely on bacteria to convert this ammonium and urea to nitrate in a slow process, hydroponic fertilizers do not, they contain nitrate which is the final form of nitrogen that plants prefer for healthy growth.



— GUARANTEED ANALYSIS — F1144

Total Nitrogen (N) 18%
1.62% Ammoniacal Nitrogen
2.46% Nitrate Nitrogen
13.89% Urea Nitrogen
0.03% Other Water Soluble Nitrogen
Available Phosphate (P_2O_5) 18%
Soluble Potash (K_2O) 21%
Magnesium (Mg) 0.50%
0.50% Water Soluble Magnesium (Mg)
Boron (B) 0.02%
Copper (Cu) 0.05%
0.05% Water Soluble Copper (Cu)
Iron (Fe) 0.10%
0.10% Chelated Iron (Fe)
Manganese (Mn) 0.05%
0.05% Chelated Manganese (Mn)
Molybdenum (Mo) 0.0005%
Zinc (Zn) 0.05%
0.05% Water Soluble Zinc (Zn)

Derived from Ammonium Sulfate, Potassium Nitrate, Urea, Soy Protein Hydrolysate, Monopotassium Phosphate, Sulfate of Potash, Magnesium Sulfate, Boric Acid, Copper Sulfate, Iron EDTA, Manganese EDTA, Sodium Molybdate, and Zinc Sulfate.

Information regarding the contents and levels of metals in this product is available on the Internet at http://regulatory-info-sc.com

Guaranteed Minimum Analysis

Total Nitrogen (N)	**20%**
Nitrate Nitrogen	12.1%
Ammoniacal Nitrogen	7.9%
Urea Nitrogen	0%
Available Phosphoric Acid (P_2O_5)	**8%**
Soluble Phosphorus	3.4%
Soluble Potash (K_2O)	**20%**
Soluble Potassium	16.6%
Calcium (Ca)	0%
Magnesium (Mg)	0.25%
Chelated Iron (actual) (Fe)	0.100%
Chelated Manganese (actual) (Mn)	0.050%
Chelated Zinc (actual) (Zn)	0.050%
Chelated Copper (actual) (Cu)	0.050%
Boron (actual) (B)	0.020%
Molybdenum (actual) (Mo)	0.015%
EDTA (chelating agent)	1.24%

Comparison between a couple of typical water soluble soil (left) and hydroponic (right) fertilizer labels.

The image above shows you a comparison between the labels for a water soluble soil and hydroponic fertilizer. In terms of NPK they both seem to be similar fertilizers, but the hydroponic fertilizer will have most of its nitrogen as nitrate while the other fertilizer has most of its nitrogen as urea. There are some other differences, mainly that the amount of phosphorous in the soil fertilizer is more than double that of the hydroponic fertilizer, which is also common given that phosphate is fixed rapidly in soil and therefore a higher excess is often added to ensure plants get enough supply. At an application of 1g/L the soil fertilizer would provide 75+ ppm of phosphorous while the hydroponic one would provide around 35. Also note that none of these two fertilizers would be enough to provide total plant nutrition since they both lack a source of Ca, which is commonly provided via a separate product in both cases.

So can any soil products be useful in hydroponics? Yes. First you need to completely avoid products that contain N mainly as urea or ammonium. Useful products to get for your hydroponic

grow will be fully water soluble and will either contain nitrogen solely as nitrate or no nitrogen at all. A very coarse DIY formula can usually be put together using something like a micro nutrient containing 0-10-10 bloom fertilizer (which contains no nitrogen) coupled with a source of nitrate, like agricultural grade calcium nitrate. You can use Hydrobuddy – my open source hydroponic nutrient calculator – to figure out the nutrient contributions of each one of the products you decide to get or have easily available and create an acceptable formulation from their use. The program also contains a long list of readily available raw salts that you can use to make your own fertilizer formulations from scratch if you wish to do so.

In the end, soil products for home growers are not designed for hydroponics use and should therefore be avoided except as a last resort if raw salts or hydroponic specific nutrients cannot be purchased. If you're interested in saving money, learning how to prepare your own fertilizers from raw salts will always be the best and cheapest option, provided you have the time and desire to learn how to do it properly.

Accurately preparing large quantities of concentrated hydroponic nutrients

When preparing concentrated solutions for hydroponics it is important to have a reproducible process that always generates the exact same results. If this is not done, you'll obtain different nutrient concentrations between different batches and the concentrated nutrient additions to create the final

nutrient solutions will yield inconsistent results. To address the potential variability of the concentrated solution manufacturing process we need to understand the different sources of error present and come up with ways to modify the process to generate more reproducible results. In this blog post I will talk about the largest source of error when preparing larger batches of concentrated nutrient solutions and how this error can be greatly reduced in order to obtain both more precise and accurate results.



Picture of a type A 250mL volumetric flask.

The process of preparing hydroponic concentrated solutions involves two steps. First, you dissolve raw fertilizer salts into some volume of distilled or RO water and then you take this volume of solution to a desired final volume of solution using the same source of water. In a small scale setup this process is very simple to carry out, since we can just weight and dissolve all our salts in some fraction of the desired final volume and then use a precise instrument to measure total volume – most typically a volumetric flask – to take our solution to the final desired volume. For example if we desire to prepare 250 mL of concentrated nutrient solution and we use

a well calibrated scale with +/- 0.001g of precision and an A grade volumetric flask with a precision of +/- 0.3mL, the error we expect to get from a 500mg salt will be +/- 4.77 ppm with a 99% confidence. Since the concentration of this salt in the concentrated solution is 2000 ppm, we get a final result of 2000 +/- 4.77 ppm. If both instruments are calibrated this is a very precise and accurate result.

When we move to larger amounts of solution we usually get better on the side of mass. This is because we can still get scales that weight with +/-0.1g precision even at weights exceeding 50kg, so our error as a fraction of the total measurement remain in the 0.01% to 1% region pretty easily. However things get way worse in terms of volume. If you are preparing 100 gallons of nutrient solution – around 378 liters – you will be able to weight the salts precisely and accurately but when it comes to measuring final volumes of solution, you are not going to be very lucky. The volume marks in tanks are widely inaccurate and are not even standardized to any level of significant precision or accuracy plus accurately measuring whether water is at a given level in a tank is a very error prone process because of how wide the tank area is.

Although we don't usually have a way to adequately measure final volume, we do have a way to measure volume going into a tank in the form of flow meters, which can give us significant accuracy and precision. However, to be able to properly use the flow meter – know how much volume we need to actually get to the final volume we want – we must obtain information from a precise and accurate low scale process. To do this you can carry out the following steps:

- Get a precise and accurate scale (calibrated and at least +/- 0.001g in precision)
- Get a scale that can weight up to 500g that can measure with at least +/- 0.1g precision (if the one above does not).

- Get a 250 mL type A volumetric flask (should be around +/- 0.3 mL in precision).
- Get a 250mL beaker
- Get a plastic lab washing bottle and fill it with distilled water
- Calculate the salts you would need to dissolve to arrive at your desired concentrations at a 250mL final volume of concentrated solution
- Weight those salts and put them in a beaker, take note of all the exact weights added.
- Weight the dry, empty volumetric flask
- Add approximately half the volume of distilled water to the beaker and dissolve the salts
- Transfer to the volumetric flask, use the washing flask to fill the volumetric flask up to the calibration line (bottom of water meniscus is touching the line when viewed at eye level).
- Weight the flask with the solution
- Calculate the weight of water (weight of flask with solution – weight of flask – sum of weight of salts)

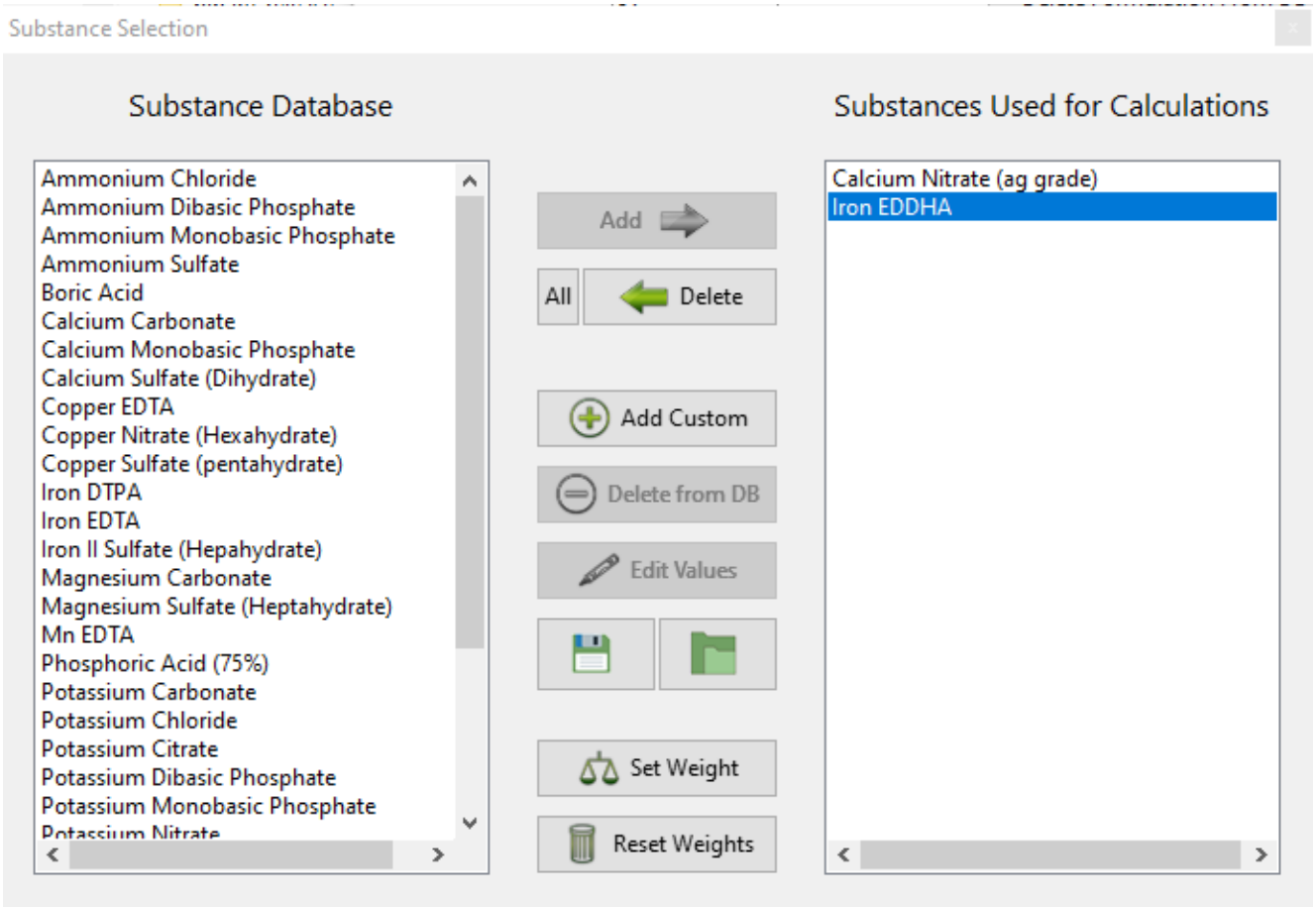
If the procedure above was carried out between 10-25C (50-77F) we can approximate the density of water to 1.0g/mL with little error (around 0.003g/mL). This means that we know the volume of water that was required to get to the desired final volume and we can then transfer this volume to our preparation procedure when we use a large tank. If the volume of water required for the preparation of the 250mL solution was just 230mL, then we can assume that the volume required to prepare 100 gallons will be 92 gallons, as the salts, when proportionately scaled, will take up the same volume and will require the same amount of water proportionately to reach the final desired volume.

When this type of procedure is done and an accurate and precise flowmeter is used, we can usually achieve concentration values at large scales that will be in the

0.1-1.0% error range, which is way better than anything that can be achieved by just using lines in tanks or procedures that use flow meters but ignore what the actual amount of water added needs to be in order to reach the desired concentration (many people achieve the salts take up no volume, which is a mistake). Having low errors in concentrated solutions means there will be less variability in final nutrient solution composition and therefore more reproducibility in crops.

HydroBuddy has now been updated to v1.70: New features and modifications

My free and open source hydroponic nutrient calculator has been available since 2010, going through many iterations and changes through the years. The latest version as of May-24-2020 is now 1.70, which you can download here. This new release implements some important updates and modifications. In this post I will write about these, the reason why they have been made and the features that I am implementing for the next version of the software.



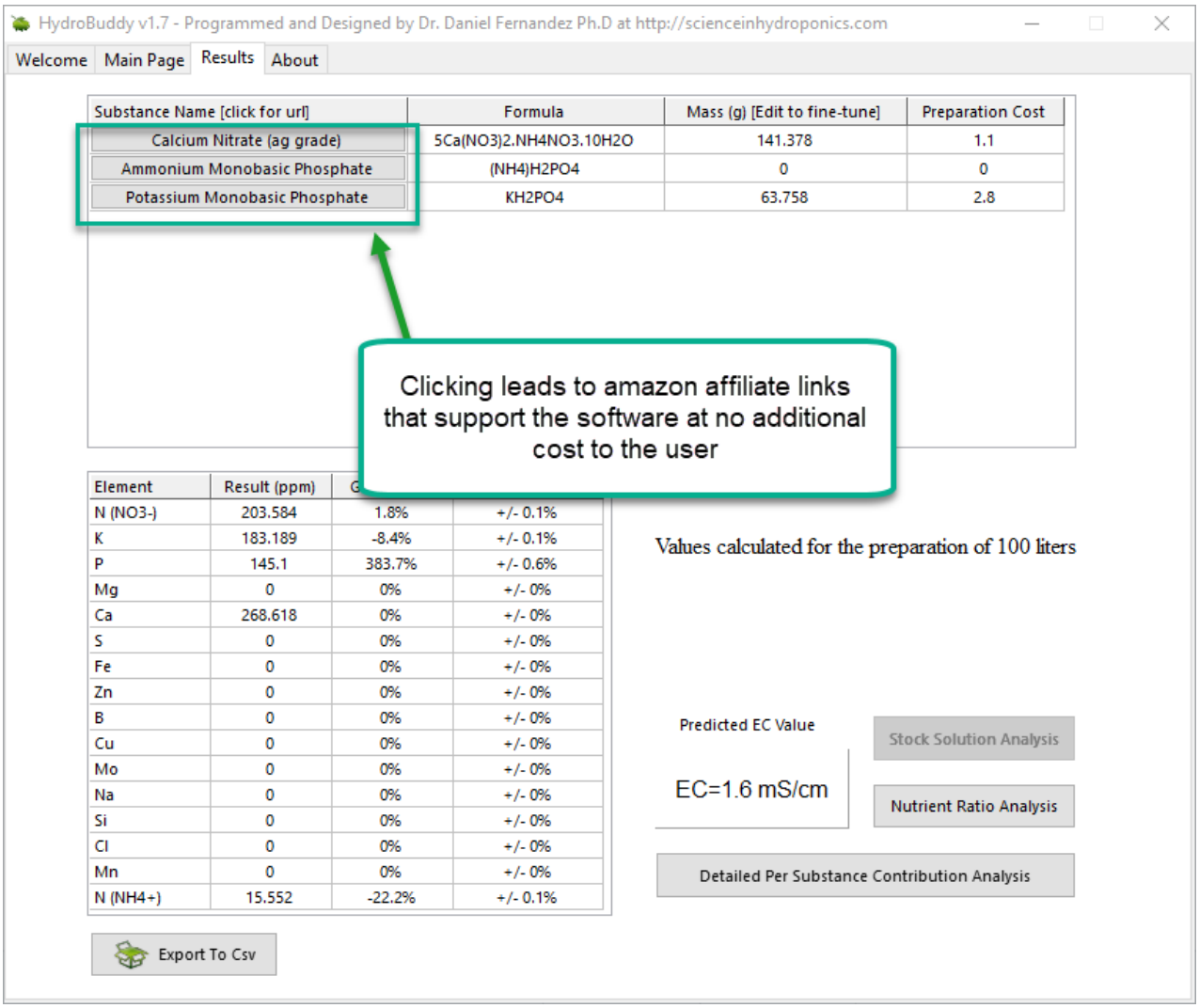
New substance selection screen in HydroBuddy v1.70

Most changes in this version have been done in the “Substance Selection” section of the program, which is accessible through the button of the same name in the “Main Page” tab. This is the “heart” of the program as this is where users decide what raw inputs they want to use and where they can manage the library of inputs that are actually available for calculations. In previous versions a very wide library of inputs was available by default, including many inputs that were rarely of any practical use in hydroponics and were there for illustrative purposes. A good example of this is a salt like “Calcium Nitrate (Tetrahydrate)” which is very rarely used by hydroponic growers as commercial “Calcium Nitrate” is actually a calcium ammonium nitrate salt that is very different in chemistry and composition to pure calcium nitrate tetrahydrate.

To solve the problem mentioned above I have completely rebuilt the substance database to include only commercially available raw fertilizers that make sense and are actually used in

common situations in hydroponics. This included adding a lot of different metal chelates and salts that were previously ignored but are now part of the HydroBuddy default database.

Another issue I wanted to address was the confusion some users have about where to buy these chemicals and potentially get some revenue to support the development of the software at no additional cost to the user. For this reason I have added manually selected links to all the raw fertilizers that are included with the DB so that users who want to buy small quantities of those can also support the software when they do so.



HydroBuddy v1.7 contains clickable substance names in the result tab that take you to amazon affiliate links that sell the products mentioned at no additional cost to the user.

The “Substances Used” tab has also been enhanced with a new

“Save/Load” functionality that enables users to save or load lists of substances used to avoid the hassle of having to go through and select substances whenever they want to prepare a certain solution. This has also been very annoying for me in the past as having to go through different sets of inputs used for different purposes can be a very time consuming exercise. With this new feature all I have to do is save one list for each one of my needs and a single click of the “Load” button can easily change a list of 5+ inputs without the need for any tedious and – mistake prone – manual changing. Another small manual enhancement has been the addition of a small “All” button next to the “Delete” button, which allows you to delete all the substances present in the “Substances Used for Calculations” list.

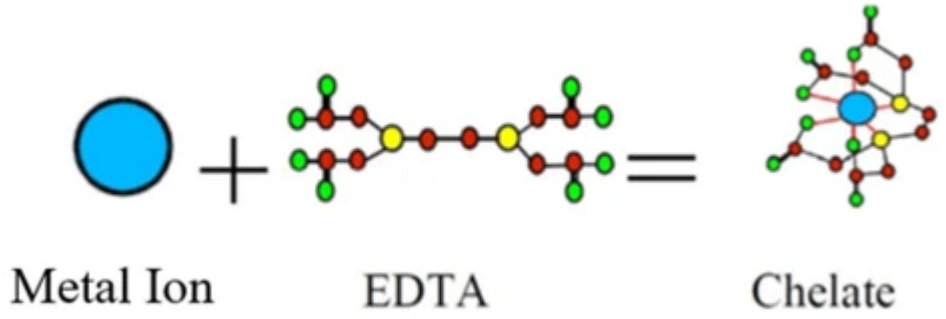
Another change in this version was a decision to go with a 32 bit compiler in Windows in order to ensure that the variables for this operating system are all 32 bit. This will enable users who are using both 32 and 64 bit operating systems to use the software without problems. This was an issue in the past as many uses still use old 32 bit systems and they were having problems having to manually compile Hydrobuddy in some of their old machines. Sadly I still do not own a Mac, so HydroBuddy has yet to be available as a download for MacOSX and the software will need to be individually compiled by all of those who wish to use it in their MacOSX setups.

One of the features that is lacking most now is an ability to import databases from previous versions, as each time the software is updated users haven’t been able to take advantage from previous custom databases built using the software due to problems with compatibility across releases (new DB fields being added, edited, etc). For the next version of the software I am working on a DB importing feature that should eliminate this issue so that users can benefit from the latest HydroBuddy releases without having to tediously add all their old substances to the new release.

With all the above said, I hope you enjoy this new version of the software. If you have any suggestions or comments about the above please feel free to leave your comments in this post!

How to prepare a low cost chelated micronutrient solution

Micronutrients constitute only a small portion of a plant's nutritional requirements but are still vital to growth and development. They are mainly comprised of heavy metals (Fe, Zn, Mn, Cu, Mo) as well as a single non-metal, boron (B). Since they are used in such small concentrations – normally in the 5 to 0.01 ppm range – they are normally put into concentrated nutrient solutions in small proportions and included with other components such as Ca and Mg, which are present in concentrations much more in line with macro nutrients like N, P and K.



Simple model of the metal chelating process

The advantage of micro nutrients is that they are available cheaply and in high purities as heavy metal sulfate salts.

These however have the problem of leading to relatively unstable cations in solution, making the preparation of concentrated micro nutrient solutions with pure sulfates impractical (unless you want to see how a gallon of rust looks like). However we can chelate the cations as they come out of these sulfates, using a chelating agent, in order to prevent any precipitation issues. In this article I am going to walk you through the preparation of a DIY chelated micronutrient concentrated solution. This is much cheaper than buying the heavy metal chelates, which can be 3+ times more expensive. To prepare this solution you'll need to buy the chemicals shown in the table below. The table includes links to buy all the different substances mentioned plus their cost (without shipping).

Link	Price USD/lb	Weight g/gal
Disodium EDTA	22.96	17.0600
Ferrous sulfate heptahydrate	15.99	9.4211
Zinc sulfate monohydrate	9.49	0.1039
Manganese sulfate monohydrate	14.99	1.1646
Copper sulfate pentahydrate	20.99	0.0595
Sodium Molybdate	19.99	0.0191
Boric acid	10.95	3.3384
Total Cost	115.39	

List of salts to prepare a DIY chelated micronutrient concentrated solution. This concentrated solution is to be used at 5mL per liter of final feeding solution.

In order to prepare the solution you also need a scale that can weight with a precision of +/- 0.001g (this is my low cost recommendation) and a container where you can store 1 gallon of solution. Please note that these solutions *have to be prepared with distilled water*, with RO water you might still run into some issues in the process. To prepare the solution carry out the following steps (the weights to be used are specified in the table above):

1. Wash your container thoroughly with a small amount of distilled water
2. Fill your container with half its volume of warm distilled water (30C, 86F)
3. Weight and add the disodium EDTA, stir until it is completely dissolved (this can take a while).
4. Weight and add all the remaining micro nutrients one by one in the order given above, stirring till each one is fully dissolved before adding the next.
5. Fill the container to its final volume using warm distilled water.
6. Let the solution cool before closing the container.
7. For longer half-life transfer to a container that is opaque to UV light.

This solution is prepared to give you the heavy metal concentrations of the Hoagland nutrient solution (a very common set of ratios used in scientific research for growing plants) when used at a ratio of 5mL per every liter of final feeding solution (18.92mL per gallon). The links given above are for 1lb of each product, with this you should be able to prepare at least 53 gallons of the concentrate, which will allow you to prepare 10,600 gallons of final feeding solution. The first salt you will run out of is Fe, but some are used so sparingly that you should be able to use them for the rest of your life without needing to buy any more (like copper sulfate and sodium molybdate). For less than 120 USD you will be able to have enough solution for probably the rest of your life – if you're a hydroponics aficionado – or even an entire crop cycle if you're a commercial grower.

This preparation is not without problems though, since the chelates are all prepared *in situ* they will take a substantial amount of time to reach their thermodynamic equilibrium, meaning that it cannot be used to soon or some of the metals might not be fully chelated. To obtain the full metal chelating effect an excess of around 25% of disodium EDTA is

also used, which means that this micro nutrient solution contains more free EDTA than a solution prepared with the chelates. Another issue is that all heavy metals are chelated with EDTA, which might not be optimal depending on your growing conditions. The EDTA chelates are also less stable against UV light and are also more easily attacked by oxidants. Another final issue is that the solution above contains no preservatives and fungi generally like to feast on this sort of micronutrient containing solutions. It is therefore reasonable to avoid preparing any large amounts of the above, as a solution prepared as instructed is normally expected to spoil in 3-4 weeks.

With this in mind, the above is not a perfect but a low cost and practical solution for those who want to start preparing their own nutrient solutions and avoid paying the high prices of some commercial nutrients just because of their micro nutrient contents. The above gives you a versatile micro nutrient concentrate that is bound to be adequate for growing almost all plants.

Why TDS is NOT equal to Total Dissolved Solids in hydroponics

Electrical conductivity is a very commonly used measurement in hydroponics, yet a very poorly understood one. I have written several posts about conductivity in the past (1,2,3) and today I want to talk about the use of the term “Total Dissolved Solids” and the poor usage of the unit “ppm” in order to express a measurement of electrical conductivity. In this

article I will walk you through why this term exists in the first place and why its use in hydroponics is terribly misleading for growers.

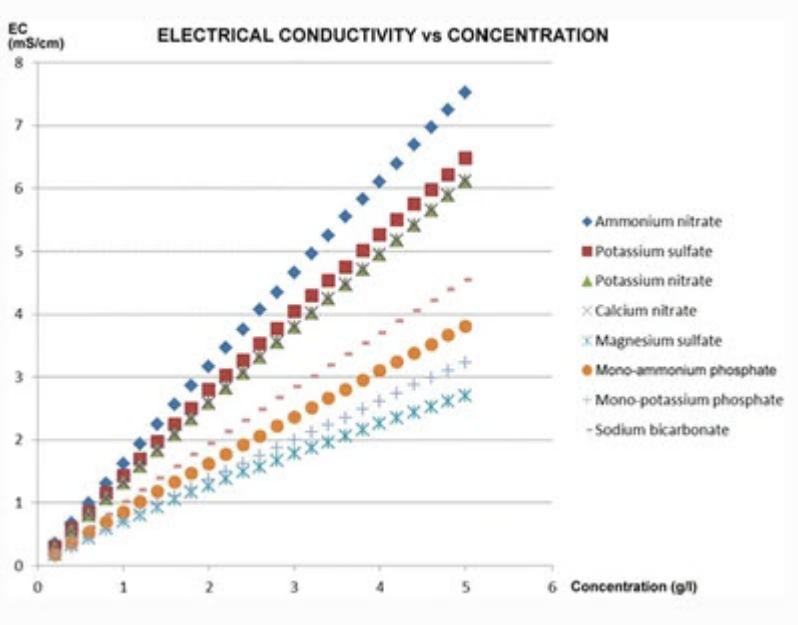


Conductivity as a function of NaCl concentration (taken from here)

Conductivity is just a measure of how easy it is for an electrical charge to go from one electrode of a certain area to another. It's generally expressed in mS/cm, which is a measurement of conductance (the opposite of resistance) and area (the area of the electrode). How in the world do we get from this to a measurement like "ppm", which measures the concentration of something in mg/L? What does a measurement of 500 ppm even mean? What is it that we are expressing a concentration of?

The answer lies in the practical uses of conductivity and a simplification to make the evaluation of water sources easier. Conductivity is generally linearly proportional to the amount of a pure salt dissolved in solution at low concentrations. For a pure salt like table salt (NaCl) the higher the concentration of the salt in solution the higher the conductivity (you can see this in the image above). People working on water quality realized that they generally dealt with similar salt combinations (Mg and Ca carbonates and possibly some Na and K chlorides) so they decided to use some standard salt mixtures (say KCl, NaCl or some mixture of Ca/Mg/K/Na salts) and then use conductivity as a proxy for the concentration of these things that are actually in solution. So the "ppm" that your EC meter reads is just the equivalent conductivity of some standard. A meter reading 500 ppm in conductivity is telling you "your solution has the same conductivity as a solution of the standard at 500 ppm". The "standard" can change – as mentioned before – which is why there are several different TDS scales. One meter might be telling you it's the same conductivity as a solution of KCl

with that concentration, while another might be in NaCl.



Conductivity curves of different salts used in hydroponics (taken from [this article])

The above is very useful when you're measuring things that tend to be similar but this becomes a complete nightmare when the composition of what you're measuring can change substantially. *In hydroponics you have a wide variety of different salts, all with very different conductivity values at different concentrations*. Look at the graph above, which shows the conductivity as a function of concentration for 8 different salts commonly used in hydroponic culture. If you prepare three solutions, one with 1000 ppm solution of potassium sulfate, another with 1000 ppm of monopotassium phosphate and another with 1000 ppm of ammonium nitrate and measure them with your conductivity meter they would *all* give very different results. The meter might be close to 0.95mS/cm for the monopotassium phosphate, but it might read almost 1.5 mS/cm for the potassium sulfate. Both solutions have 1000 ppm of "total dissolved solids" but the conductivity meter is telling you one has 500 ppm and the other almost 800 ppm, none of them even close. This is because "total dissolved solids", as used in water quality measurements, is a meaningless measurement in hydroponics as it relates to the actual ppm values of things dissolved.

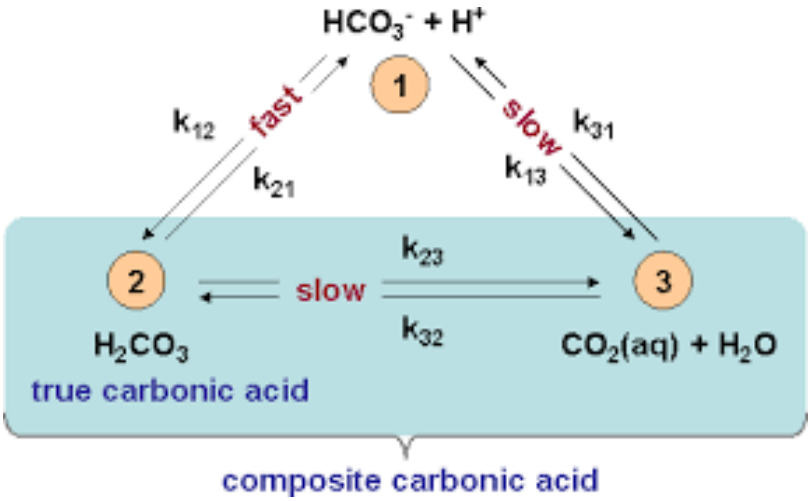
This is the main reason why you should never compare the EC values of nutrients that contain different ratios of salts, because they are simply not the same. One nutrient might give you 100 ppm of potassium at some EC level, while another might give you 200 ppm. Thinking that having the same EC level means that both are at the same “strength” is a big mistake, since this is never going to be the case when two nutrient solutions are mixed with different ratios of nutrients. This is also why comparing vegetative and bloom formulation EC values is not correct. A solution in veg might contain a lot more of nitrates while a solution in bloom might contain more phosphates. As we saw above this might mean that a solution of the “same strength” might actually have a significantly lower measured EC value.

Since the TDS measurement is not telling you anything about “total dissolved solids” in hydroponics, you should avoid using it to avoid confusion. This is important since nutrient concentrations are usually expressed in ppm as well, ppm of actual nutrients dissolved in solutions. Instead use the normal conductivity measurements of your meter in conductance per area. You should also take care to only use EC values to talk about comparative strength when you’re talking about a formulation where the ratios of nutrients remain the same. If that’s not the case, then you should not talk in comparative terms between the two solutions as this might deviate a lot from reality.

My advice is to not think in EC terms to begin with, but to think about nutrient concentrations, prepare solutions that match the concentrations you want and then use the EC of those solutions as references to know whether they are prepared correctly or not. The conductivity should be a measurement used for confirmation but not as a guiding principle. For example the aim should be to “prepare a solution containing 150 ppm of N and an K:N ratio of 1.2” not to “prepare a solution with an EC of 1.2 mS/cm”.

Understanding the carbonic acid/bicarbonate buffer in hydroponics

I have written several articles before about pH and it's importance in hydroponic culture (1, 2, 3, 4). However I have yet to write a detailed explanation of one of the most important buffering systems in hydroponics, which is the carbonic acid/bicarbonate buffer. This buffer is significantly more complicated than the simpler buffer created using phosphoric acid species, as it not only relies on ions present in solution but also on the partial pressure of carbon dioxide in the atmosphere. In this article I will attempt to explain this buffering system in detail, shining some light into the limitations of this buffer and how changing different key variables can fundamentally affect the way it works in hydroponics.



Chemical reactions involved in the carbonic acid/bicarbonate buffer. Taken from here.

A buffer is nothing more than a pair of chemical species in solution that are present at a certain pH, that can react with

additional H_3O+ or OH- ions that are introduced into the solution. Since these ions control the value of pH, anything that prevents their concentration from changing will keep the pH stable. Distilled water, for example, has absolutely no buffering capacity since within it there is nothing that can react with incoming H_3O^+ or OH^- ions that are added to the solution. Distilled water should therefore have a pH of 7.0, it does not because we live in an environment where an acid can always be generated from the air. This acid – carbonic acid – is generated in water whenever it's put into contact with a carbon dioxide containing atmosphere. *This makes distilled water have a pH of around 5.6*.

To be able to calculate the pH we need to consider all the chemical equilibrium reactions that happen, these are summarized here and in the image above. We must consider that carbon dioxide will dissolve in water to always satisfy Henry's law, that dissolved carbon dioxide will be in equilibrium with carbonic acid, that carbonic acid can dissociate into a H_3O^+ ion and a bicarbonate ion and that a bicarbonate ion can further dissociate into an additional H_3O+ ion and a carbonate ion. To solve all of this we must also consider that charge neutrality must be preserved, meaning that the sum of all molar charges of all positive ions must be equal to the molar charges of all negative ions. To carry out these calculations I routinely use the freely available Maxima software. Below you can see the code I use to solve this system in Maxima (constants are taken from here):

```
[kw : 10^(-14.0), kh: 1.7*10^(-3.0), kc1: 2.5*10^(-4.0), kc2: 4.69*10^(-11.0), co2: 1.32*10^-5];
log10(x) := log(x)/log(10) ;
pH(x) := float(-log10(x));

float(solve([h*oh=kw, h = 2*co3+hco3+oh, kh=h2co3/co2, kc1=(hco3*h)/h2co3, kc2=(co3*h)/hco3],[oh, co3, hco3, h2co3,
```

h]));

This is the solution obtained for the molar concentrations (rounded for clarity):

oh = 4.21*10^-*9*
co3 = *4.68*10^-11
hco3 = 2.36**10^-6*
h2co3 = *2.24*10^-8
h = 2.37*10^-6

After executing this code you will get several different possible solutions, but the only one that interests us is the one where the H_3O^+ (h) concentration is a positive number (this solution is showed above). We can then use the pH function to calculate the value of pH for this H_30+ concentration, which gives us a value of 5.62, this matches the real measurement of a distilled water solution at 25C under a 387ppm carbon dioxide atmosphere. Note that the amount of none dissociated acid in solution is very small. Taken to mass, the concentration of carbonic acid is 0.00138 ppm. However the concentration of bicarbonate is significantly greater, at 3.6 times the concentration of undissociated carbonic acid. This explains why the pH drops so much, since a significant amount of the generated carbonic acid ends up dissociating and contributing H_3O^+ ions to the solution. This also shows you how little acid is needed to drop the pH of an unbuffered solution.

To create the buffer with the biggest possible strength we would need to add enough strong base to shift the pH to the point where the pH equals the pKa (which is just -Log(equilibrium constant)) of the joint reactions created from the reaction of carbon dioxide with water to create carbonic acid and the subsequent dissociation of this acid into bicarbonate and H_3O^+. This point is at 6.3 under atmospheric

conditions at 25C. This can be achieved with the code below:

[kw : 10^(-14.0), kh: 1.7*10^(-3.0), kc1: 2.5*10^(-4.0), kc2: 4.69*10^(-11.0), co2: 1.32*10^-5, h:10^(-6.3)];
float(solve([h*oh=kw, base+h = 2*co3+hco3+oh, kh=h2co3/co2, kc1=(hco3*h)/h2co3, kc2=(co3*h)/hco3],[oh, co3, hco3, h2co3,base]));

This is the solution obtained for the molar concentrations(rounded for clarity):

oh = 1.99*10^-8
co3 = 1.04*10^-9
hco3 = 1.11*10^-5
h2co3 = 2.24*10^-8
base = 1.07*10^-5

The pH here is set to 6.3 and we can see that to get there we would need to add a base at a concentration of $1.07*10^{-5.0}$. If this base was KOH this would imply adding it at a rate of 0.6 ppm. We can see how the pH changes as a function of adding base or acid from this point. If at this point we decided to double the addition of strong base we would get to 6.57, tripling it would take us to 6.73 and adding 10 times more base would take us to 7.25. The buffer is indeed resisting the increase in pH by basically drawing CO_2 from the air to react with the incoming base as base is added to the solution. *However you might notice that under equilibrium conditions the buffering capacity of this system is very low*. Just 6 ppm of a KOH equivalent strong base addition can strongly affect the pH – taking it from 5.6 to 7.25 – so how can the carbonic acid/bicarbonate buffer be effective at all in hydroponics?

The answer is in the first image in this post. The equilibrium reaction between carbonic acid and water plus carbon dioxide in water (k23/k32) is fundamentally slow. We can take advantage of this by generating larger amounts of carbonate species in solution through the use of exogenous carbonate or bicarbonate additions and then setting the pH at a lower value

to generate more carbonic acid, this acid will then take some significant time to reach equilibrium. This is the reason why using tap water with a significantly high alkalinity can provide a surprisingly stronger buffer than what would be expected at equilibrium and it also has some interesting consequences in the use of nutrient solutions.

Let’s consider a case where there is no decomposition of carbonic acid – let’s suppose it’s extremely slow – and say we add 100 ppm of potassium carbonate into a solution and then set the pH back to 5.8 using phosphoric acid. In this case the predominant reactions in solution would be the dissociation of dihydrogen phosphate to hydrogen phosphate and H_3O+ and the carbonic acid dissociation discussed before. In order to properly consider this case we must also introduce two additional equations, mainly the mass balance equations for the phosphate and carbonate species, since this time we are assuming no carbon dioxide is ever lost to the atmosphere. Note that I have changed the equilibrium constant for the carbonic acid reaction here to $10^{-6.3}$ where carbonic acid is now “apparent carbonic acid”. You can see the equation system and solution below:

[kw : 10^(-14.0), kh: 1.7*10^(-3.0), kc1: 10^-6.3, co2: 1.32*10^-5, kp:10^-7.2, total_p: 1.7*7.2310^-4, total_c: 7.23*10^-4];

float(solve([h*oh=kw, total_c=hco3+h2co3, total_p=h2po4+hpo4, 2*total_c+h = hco3+oh+h2po4+2*hpo4, kc1=(h*co3h)/h2co3, kp=(hpo4*h)/h2po4],[hco3, h2co3, h2po4, hpo4, h, oh]));

This is the solution obtained for the molar concentrations(rounded for clarity):

hco3 = 1.72*10^-4
h2co3 = 5.50*10^-4
h2po4 = 0.00118
hpo4 = 4.64*10^-5
h = 1.60*10^-6

The final pH of this solution is very close to 5.8 and the concentration of P is 47.9 ppm with K at 38.10 ppm. Notice however that apparent carbonic acid has a concentration of $5.50*10^{-4}$ M, which implies that the system is not at equilibrium since this amount is significantly larger than what we would expect from Henry's law. If we reduce the concentration of carbonic acid to half then the pH will increase to 6.01, as we would expect from extracting an acid from the solution. The implication is that – with time – the pH of this solution is going to slowly increase, as carbonic acid decomposes and the solution reaches an equilibrium with the atmospheric carbon dioxide level. This is also why nutrient solutions that are prepared with tap water high in carbonates and then aerated will tend to show a rapid increase in pH – even if the solution is not fed to plants – as the reaching of equilibrium is accelerated by the agitation of the solution and the contact with air (that allows CO_2 in solution to escape).

As soon as the above solution is prepared it offers a substantially superior buffering capacity when compared with a solution containing only phosphates. This is why water with high alkalinity tends to provide better pH stability in drain to waste type systems when compared with solutions prepared with RO water. This water contains a significant amount of carbonates that are turned into carbonic acid and bicarbonate as soon as the pH is lowered to the pH range used in hydroponics. As long as the solution is used quicker than the carbonic acid decomposes, there will be a substantial increase in pH stability.

If you are using RO water or water with low alkalinity to prepare your solutions you can obtain a similar effect by adding 100-200 ppm of potassium carbonate before you start preparing the nutrient solution, you can similarly use bicarbonate but I would recommend using potassium carbonate, as it is cheaper. It would also be advisable to use the

solution as fast as possible, since time will cause the solution to reach equilibrium and the pH to increase. This effect will take much longer if the CO_2 concentration is higher – which is true for setups that use enriched CO_2 – or if the temperature is lower, which increases the solubility of CO_2.

Hydroponics nutrients and microgreens

One of the most important goals in microgreens is to maximize the amount of weight gained by shoots from seed to harvest. Since the entire upper body of the plant is harvested and plants are sold by weight, maximizing the weight gain is vital in order to obtain the highest possible margins in a crop cycle. Hydroponically cultured microgreens offer the grower an unprecedented control over the microgreens' nutrition, with the ability to tightly control nutritional parameters in order to maximize this weight. In this article we are going to take a look into the scientific literature surrounding microgreens and what we know about maximizing their yield and quality using nutrient solutions. I will use the table below to reference different articles in the literature.

Number	Species	Studied	Link
1	Broccoli	FlograGro, sterile, compost	https://www.frontiersin.org/articles/10.3389/fnut.2017.00007/full
2	Purple Cabbage	Nutrient sol conc	https://www.scielo.br/scielo.php?pid=S1983-21252019000400976&script=sci_arttext&tlng=en
3	Table Beet	Calcium Nitrate	https://www.tandfonline.com/doi/abs/10.1080/19315261003648241
4	Radish	Calcium Chloride	https://bearworks.missouristate.edu/theses/3328/
5	Basil	Sodium Selenate	https://onlinelibrary.wiley.com/doi/abs/10.1002/jsfa.9826

Published articles talking about hydroponic nutrients and

microgreen yield or quality

Despite the overwhelming growth in the microgreen industry during the past 10 years, the amount of research looking into microgreen nutrition has been surprisingly limited, with only a handful of papers looking at the relationship between nutrition and yields or quality. Paper one contains a comparison between microgreens grown in either compost, sterile water or a solution using a 0.4% FloraGro Advanced Nutrient solution (4mL/L). The results show clear weight benefits from using hydroponic nutrients, with the weight being markedly higher (mean of 24.64g vs 21.01g) between the sterile and hydroponic treatments. However the concentration of different minerals was actually lowest in the plants using a hydroponic nutrient.

Table 3: Shoot fresh weight per plant and per population of 'Early Wonder Tall Crop' table beet at 15 days after planting in response to seed ball and fertilizer treatments.

Seed treatment (ST)	Fertilization treatment (FT)[a]	Shoot fresh weight ($g \cdot m^{-2}$)	Shoot fresh weight (mg/shoot)
Nontreated	Check	2705h	166e[b]
	CN	4207f	268d
	SF	4676e	268d
	0.5 CN + 0.5 SF	4676e	284cd
	CN + SF	5469cd	299cd
Pregerminated[c]	Check	3391g	298cd
	CN	5087de	362b
	SF	5649c	306c
	0.5 CN + 0.5 SF	6294b	362b
	CN + SF	6937a	415a
Interaction $LSD_{0.05}$		444	36
Significance			
ST		***	***
FT		***	***
ST × FT		*	**

*,**, ***Significant at $P = 0.05$, $P = 0.01$, or $P = 0.001$, respectively.
[a]Check = no additional fertilizer added to the peat-lite; CN = preplant addition of solid $Ca(NO_3)_2$ at 2000 $mg \cdot L^{-1}$ of N (150 $mL \cdot L^{-1}$ of peat-lite); SF = daily application of 150 $mg \cdot L^{-1}$ of N solution fertilizer from 21-5-20; 0.5 = one-half rate.
[b]Means within a column followed by the same letter are not significantly different by $LSD_{0.05}$.
[c]Pregerminated = seed ball incubation in fine (grade 5) vermiculite with 150% water for 5 days at 20°C.

Table taken from article number three

Papers three and four look at different forms of Ca nutrition – either Ca chloride or Ca nitrate – and different ways to apply this treatment to see if it makes a difference in microgreen production. Paper three, shows a statistically significant gain in weight when using calcium nitrate, either applied into the media pre-cultivation or applied within a nutrient solution. The best results were found when both treatments were carried out and represented an increase of

more than double in terms of weight over the control. The fact that paper four fails to show a consistent increase in yields using Ca chloride, suggests that this has to do mainly with the nutritional contribution of the nitrate and not the calcium ions.

Paper two is rather interesting, as it looks into different nutrient solution strengths (either 0, 50 or 100%) using a solution published for hydroponic forage. The results – in the table below – clearly show that there is a strong weight gain as the nutrient solution concentration increases, again showing that at a full strength solution there is an expected increase of more than 2x in the final weight. However this comes – in agreement with paper one – at the potential expense of nutritional value. The paper shows a significant decrease in carotenoid concentration when nutrient solution strength increases, which the paper hypothesis is caused by high nutrient concentrations slowing down plant metabolism. This hypothesis is however hard to reconcile with the larger and heavier plants.

Table 2 Effect of cultivation substrate and nutrient solution concentration on shoot fresh matter yield (SFMY) and shoot dry matter yield (SDMY), shoot height at harvest (SHH), and total soluble solids (TSS) content of purple cabbage microgreens (*Brassica oleracea* var. *capitata f. rubra*) in a recirculating system. Porto Alegre, Brazil, 2018.

Factors	Tratamentos	SFMY	SDMY	SHH (cm)	TSS (°brix)
		(g m^{-2})			
Substratos	S1 (CSC® Vermiculite)	1829.52^{ns}	74.01^{ns}	6.86^{ns}	3.62^{ns}
	S2 (Beifiur®S10)	1761.30	79.21	6.89	3.64
	S3 (Carolina Soil® seedling)	1795.73	75.70	6.83	3.73
	S4 (Carolina Soil® organic)	1793.57	81.10	7.19	3.82
Concentration Nutritive Solution**	C1 (0%)	1111.31 c*	64.34 c	5.00 c	5.03 a
	C2 (50%)	1933.16 b	78.62 b	7.36 b	3.37 b
	C3 (100%)	2340.62 a	89.59 a	8.48 a	2.72 c
	Mean	1795.03	77.52	6.94	3.70
	CV (%)	16.34	11.29	6.83	14.45

^{ns}not significant by the Tukey's test at 5% probability;

*means followed by the same letter in the columns are not different by the Tukey's test at 5% probability.

**initial electrical conductivity (ECi) established for the three evaluated nutrient concentrations (0%, 50%, and 100%) in the nutritive solution: C1 = 0.0; C2 = 1.20, and C3 = 2.0 dS m^{-1}, respectively.

Table taken from article number two

Article five is also an interesting example of the use of microgreens to carry out antioxidant supplementation. Sodium selenate was used to prepare a solution to treat basil seeds

and the resulting microgreens were found to be fortified with selenium. This might be an interesting way to incorporate mineral micro nutrients into microgreens and therefore increase their presence within our diet. However there is also the potential to hyperaccumulate these nutrients, so experiments of this kind should not be done with adequate care and lab analysis to ensure proper doses of these micro nutrients.

From all of the above it seems quite clear that the research of hydroponic nutrients in microgreen production is in its very early infancy. So far only a handful of research papers have been published on the subject and the conclusions so far seem to be that hydroponic nutrient solutions – in a couple of different forms – tend to significantly increase microgreen production weights. However it is also clear that there is a strong interaction with the nutritional value of the microgreens and using nutrients can in fact lead to decreases in the nutritional value, despite the significant weight gain from the process.

The echoes of the above can be seen in a wide variety of anecdotal experiences on youtube channels and forums. Growers running side by side experiments seem to have found the same phenomena (see this video for an example), where adding nutrients increases yields significantly but at the expense of some of the flavor – and potentially nutritional – characteristics of the microgreens. Some growers have therefore chosen to avoid nutrients – to preserve flavor qualities – while others have chosen to use nutrients because of the increases in marketable appearance and yield.

There is a lot of research to be done on the subject. It would certainly be interesting to find out if we could somehow have the best of both worlds.