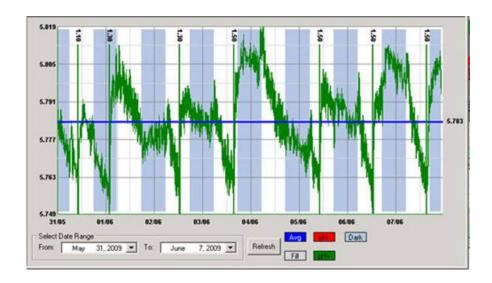
Five dos and don'ts for automated pH control in hydroponics

The pH is one of the most important variables to control in hydroponic culture as it plays a key role in the availability of different ions and their absorption dynamics. Although most growers control pH manually it is often desirable to implement automatic pH control so that you can ensure that your solution always stays within an optimum range. This is especially true in recirculating systems where correcting the pH of the solution after it goes through the plants' roots is necessary. Today I want to share with you five dos and don'ts when implementing automated pH control in hydroponic culture.

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Do test your pH meter frequently with a buffer solution. In hydroponics pH meters can lose calibration rather quickly as a consequence of being immersed in a nutrient solution that is at a lower ionic concentration than what's ideal for most glass electrodes. This means that testing your pH meter with a buffer solution often — every week is ideal — is necessary in

order to ensure that you are getting accurate readings. If the reading is not accurate you can then recalibrate the meter.

Do recondition your pH meter every month. In line with the above and in other to increase the life of a pH meter and each calibration it's necessary to immerse the pH electrodes in a pH 4 or 7 buffer solution every month — for at least 2-3 hours — to ensure that the ionic content of the electrode is restored and the glass membrane's responsiveness remains accurate. If you do this your electrode will be happier and you will need to calibrate less frequently. If an electrode is covered in biofilm the putting it in a hot bleach solution for half an hour before the buffer immersion is also necessary.

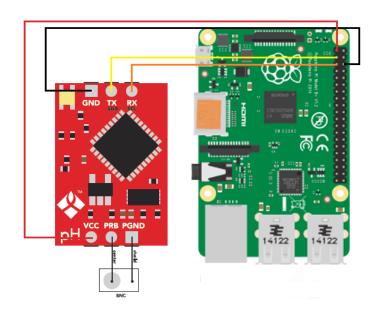
Do use electrodes designed for constant immersion. Regular pH electrodes — including those sold with some automated pH controllers — are not meant to be immersed the whole time and therefore get damaged and lose calibration much more quickly when used in this manner. To get best results use pH electrodes that are fabricated with long term immersion in mind. I wrote a blog post about these electrodes and why they are different than traditional pH electrodes.

Do place your electrode as far as possible from your pH changing inputs. When using a pH controller you should place the pH probe as far away as possible from the place where your pH up/down solutions will enter the hydroponic system. This is so that your pH electrode can get a slow change in pH as the pH up/down is mixed with the entire reservoir. Placing the probe close to the inputs will cause very erratic changes in the pH that do not really reflect the effect of the addition across the entire reservoir.

Do have addition limits in your controllers. Allowing a pH controller to add as much substance as needed to correct the pH can be a very bad thing to do. This is because several things can go wrong — pH probe losing calibration, controller getting damaged, electrical noise etc- that can cause

unnecessary levels of addition that can kill an entire crop. Always have controllers where maximum additions per unit of time can be specified so that the possibility of this happening is minimized.

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Don't rely on a single pH probe. Although single probe controllers are the most common they can also be the most dangerous. A pH probe can get damaged, it can lose calibration or it can give erratic readings due to other reasons (for example electrical interference from other things in the reservoir). Therefore it's always best to use two-probe controllers where readings are always verified across the two probes to ensure that the reading the controller is getting is accurate. If you have a commercial enterprise then this is a must, you wouldn't want to lose an entire crop due to a bad pH probe adding a ton of acid/base to your solution.

Don't aim for a specific pH value. A pH controller should not aim for a specific value of pH but to maintain pH within an adequate range. Usually the best way for a controller to act is to have a range with high/low thresholds where the controller will act to take the pH to the middle of the range

when these thresholds are exceeded. For example a controller can be told to maintain pH in the 5.6-6.4 region and then it will act whenever the pH reaches 5.6 or 6.4 to take it back to 6 when any one of these two thresholds is breached. However if the pH is at 6.4 and the controller drops it to 5.8 it will not try to then bring the pH up (because it's above the lower threshold).

Don't place your pH probes near pumps or other electrical equipment in reservoirs. A pH probe takes an electrical measurement and is therefore prone to electrical interference. Having a pH probe close to other electrical equipment — especially those that draw significant current — can cause those wires to induce currents in the pH probe wires and generate all sorts of issues with pH readings. Always place pH probes away from pumps and ensure the pH probe and pump wires are never tangled together.

Don't use very concentrated acid/base input solutions. A pH controller will be doing very fine control over a small pH range so it won't need a very large amount of acid/base to do this job. Using very concentrated acid/base can cause the pH controller to completely overshoot its targets and cause it to either cause the system to get into an undesirable state — for example a very low pH if the controller can only add acid — or enter a loop where acid additions are followed by base additions in an endless cycle. Usually you want your acid/base mixtures to be concentrated enough to shift the pH over their addition volume but not much more than that. Strong acids/bases in the 10-20% concentration range are usually more than enough for this job.

Don't ignore your controller's data. A pH controller will do its job — control pH within a range — but it will not tell you whether your system is doing ok or not from a plant-health perspective. How often your pH controller has to add acid/base and how much acid/base it's using to perform its job are important pieces of information that you need to take into

account in order to ensure that your system is working properly. Remember that pH controlling substances often also contribute nutrients — like phosphorous or potassium — so it's important to keep all these additions in check.

Of course pH control is no simple task and different pH controllers will have different advantages and disadvantages. However doing what you can to ensure proper maintenance — cleaning, conditioning electrodes, having proper placement, etc — can go a long way in ensuring that your setup behaves as ideally as possible. If you can then I would advice you build your own controllers using things like arduinos, raspberry pi computers and robust immersion pH probes so that you can have an optimum setup that can deliver all the advantages of pH control with as few disadvantages as possible. I'll write about building your own pH controller in a future post.

Using triacontanol to increase yields in hydroponics

Usually additives used in hydroponics need to be added in rather large quantities to obtain palpable results. Molecules like salicylic acid — which we have <u>discussed before</u>

— need to be used in concentrations in the order of 10^{-4} to 10^{-2} M to obtain a significant effect. This means that you need to use quantities in the order of $20-150 \mathrm{ppm}$ of most additives in order to see a significant result. However there is a molecule called 1-triacontanol that can generate very significant

results with only a fraction of that concentration. Today we will talk about this substance, what it does, how to use it and why it's such a desirable tool in your hydroponic additive arsenal. Many of the things I will talk about in this article are derived from this 2011 review on triacontanol (make sure you read that for a deeper insight into why this molecule works).

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Triacontanol is a very long fatty alcohol. Each molecule has 30 carbon atoms linked in a linear structure which makes this molecule extremely hydrophobic and hence very hard to dissolve in something like water. Using triacontanol therefore involves dissolving this molecule in something other than water — for example Tween 20, chloroform, methanol — before adding water in order to prepare an emulsion for use in either root applications or foliar feeding. Most research using triacontanol has used foliar feeding as this is the easiest way to control the application of the molecule and also how it seems to have the largest effect.

The effects of this molecule are not short of miraculous. Triacontanol is usually applied in concentrations on the order of 10^{-7} to 10^{-9} M, which means it is used from around 0.01 to 1

ppm. This means that we use about 1000 times less triacontanol than other additives in order to obtain a meaningful result. The table below shows some of the effects that triacontanol has showed in peer reviewed studies, with plant height, weight and yields increasing across a variety of different species, from tomatoes to japanese mint. Papers on other plants besides those on the chart have also been published, for example triacontanol has showed to significantly increase yields in lettuce crops (here). Some studies have also found that the effect of triacontanol can also be enhanced through the use of magnesium or in conjunction with other hormones (here).

Name of plant	Botanical name	Family name	Growth attributes	Yield attributes	Biochemical attributes	Quality attributes	Reference citation	
Opium poppy	Papaver somniferum L.	Papaveraceae	Plant height, dry weight and number of branches	Number of capsules, seed yield per plant, and crude opium yield per plant	Chl a, Chl b, and total content	Morphine content and morphine yield per plant	Khan et al. (2007)	
Γomato	Solanum lycopersicum L.	Solanaceae	Height per plant, number of leaves and plant fresh and dry weights	Number of fruits per plant, weight per fruit and fruit yield per plant	Total chl and carotenoids content, leaf-N, -P, and -K contents	Fruit ascorbic acid and lycopene contents	Khan et al. (2009)	
Hyacinth bean	Lablab purpureus L.	Fabaceae	Weights and dry weights, leaf-area per plant, number and dry weights of nodules weight and seed-yield per plant Number of pods per plant, number of seeds weight and seed-yield per plant Photosynthetic rate (P _N), stomatal conductance (gs) and transpiration rate, total per plant NR and CA activities, leaf-N P, -K, and -Ca content, nodule-N and leghemoglobin contents		Seed-protein content, total carbohydrate content, and tyrosinase activity	(2005), Naeem et		
artemisia	Artemisia annua L.	Asteraceae	Shoot and root lengths, plant fresh and dry weights	Artemisinin yield	P _N , gs and transpiration rate, total chl and carotenoid content, NR and CA activities, leaf-N, -P, and -K content	Essential oil content, artemisinin content	Aftab et al. (2010)	
Coriander	Coriandrum sativum L.	Umbelliferae	Shoot and root lengths, plant fresh and dry weights		Total chl and carotenoids content, NR and CA activities, leaf-N, -P, and -K content	Essential oil content	Idrees et al. (2010)	
Coffee senna	Senna occidentalis L.	Fabaceae	Plant fresh and dry weights	Number of pods per plant, number of seeds per pod, 100-seed weight and seed yield per plant	P _N , gs and transpiration rate, total chl and carotenoid content, NR and CA activities, leaf-N, -P, -K, and -Ca content	Total anthraquinone and sennoside contents, and seed-protein content	Naeem et al. (2010)	
weet basil	Ocimum basilicum L.	Labiatae	Shoot and root lengths, number of spikes per plant, total leaf area, plant fresh and dry weights	Essential oil yield	Chl a, Chl b, total Chl, and carotenoid contents, activities of NR and CA, leaf-N, -P, and -K contents	Leaf-protein and carbohydrate contents, essential oil content, linalool, methyl eugenol, and eugenol contents	Hashmi et al. (2011)	
apanese mint	Mentha arvensis L.	Lamiaceae	Plant height, leaf-area, leaf-yield, and plant fresh and dry weights	Herbage yield, essential oil yield	Total chl and carotenoid contents, activities of NR and CA, leaf-N, -P, and -K contents, total phenol	Essential oil content, menthol, L-menthone, isomenthone, and menthyl aceteate contents	Naeem et al. (2011)	

Abbreviation: Chl, Chlorophyll; NR, Nitrate reductase; CA, Carbonic anhydrase.

With such an impressive array of effects and such a low expected toxicity - due to its very low solubility - it's definitely one of the best additives to use to get production gains in hydroponic crops. This also makes it one of the most

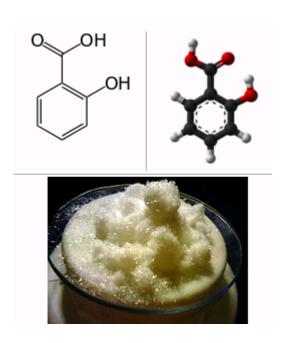
commonly used substances in commercially available grow enhancers. Nonetheless since it's used in such a small quantity it's very easy for someone to buy a small amount of triacontanol and use it for years before running out. You can buy small amounts of triacontanol as a powder (there are several reputable sellers on ebay) and you can then prepare your own concentrated triacontanol solution in Tween 20 — not water — that will last you for ages. A liter of 2000ppm solution of triacontanol will last you for 1000-2000 liters of foliar spray. You cannot get more economical than that.

The optimum application rate and frequency for triacontanol varies across different species but if you want to take an initial guess use a foliar application of a 0.5 ppm solution every week. There is usually a sweet spot for concentration — after that you start to see a decrease in results compared to the highest point — so you want to start below a 1 ppm application rate. For some crops repeated applications might be unnecessary — with just one or two applications giving most of the effect through the entire crop cycle — while for others you do want to apply every week. How you initially dissolve the triacontanol to make your concentrated solution is also important with Tween 20 being the most ecologically friendly — although not the easiest — option.

Salicylic acid and its positive effect in hydroponics

When looking for ways to increase crop yields we usually want something that is safe for the environment, safe for us and able to give us a substantial bang for our buck. From the multitude of additives that have been researched during the past 30 years one simple organic molecule seems to fit all the requirements very well: salicylic acid. Today we are going to talk about why this additive is so interesting for use in hydroponic culture, the results it has shown in peer reviewed publications and how we can use it to increase our crop yields. For those of you interested in this molecule I would also recommend reading this 2010 review which contains a much more detailed look into the scientific literature surrounding salicylic acid research in higher plants.

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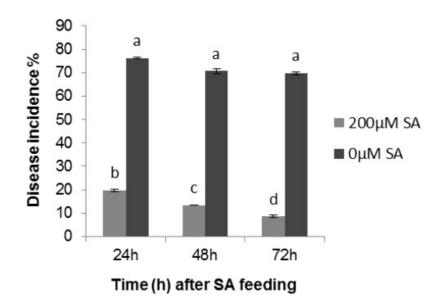
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Salicylic acid is a simple organic molecule with the structure showed above. We have known for a long time that plants produce it and we knew almost right from the start that it played a key role in plants' response to diseases and stress (see here for some early insights from Tobacco cultivation). Salicylic acid is used as a signaling molecule in plants (a.k.a hormone), moving from stressed organs to non-stressed ones as the plant is attacked. However its role is much more complex, having functions related with chloroplast creation,

inhibition of fruit ripening and many other important processes.

After learning that this was an interesting molecule it wasn't long before people started studying whether exogenous applications provided any benefit. We have learned that it enhances dry mass and leaf area in corn and soybean (here), that it can enhance germination in wheat (here), the oil content in basil (here), the carbohydrate content in maize, etc. There are also several studies pointing to improvement in root development — even from foliar applications (here) — suggesting that this hormone is able to increase plant productivity through several different mechanisms. The incidence of diseases can also be reduced dramatically by salicylic acid applications (here).

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We also know this molecule has important effects on the flowering process. It can induce earlier flowering in plants and can often cause larger fruit settings in some plants (like papaya (here)). Most importantly foliar spraying of tomato and cucumber plants with salicylic acid has showed important increases in yields (here). It is therefore clear that

exogenous applications of salicylic acid can have many important benefits in crop production and this is therefore an important candidate to consider for enhancing crop production.

But how do we apply it? Most commonly this molecule is applied in foliar feeding regimes, although in some cases it is also applied directly in hydroponic solutions. Most commonly concentrations in the order of 10^{-5} -10^{-4} M are used since it has been showed across a few studies that negative effects start to show up when the concentration level reaches 1mM. This means that regular doses will be around 1-100 ppm with the lowest spectrum of dosage being preferred if the effect on the particular plant is unknown. The solubility of salicylic acid is 2.48g/L at 25°C so concentrated solutions of up to around 20-30x can be prepared without issues to make it easier to apply on plants. The preparation of more concentrated solutions requires some tricks but it certainly can be done.

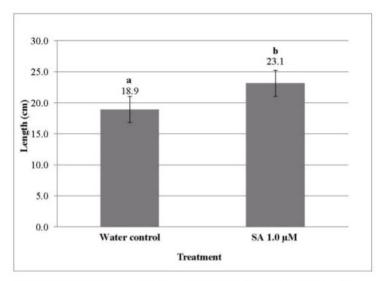


Figure 2. Effect of the spray application of $1\mu M$ of Salicylic Acid on the length of Brosimum alicastrum seedling stems. The average of 6 repetitions \pm standard error is shown. Similar letters indicate no significant difference (Fisher, $p \le 0.05$).

Salicylic acid also has the advantage of being a very safe molecule so it can be applied without a lot of worry in order to experiment with its effects. For testing on new plants foliar applications of 20-30ppm would be most common, with applications usually carried out once every 5-10 days. The frequency of application as well as the best concentration to use will of course depend on the particular plant you're growing. There are also several other molecules that can be used with salicylic acid to enhance its effect on some plants, but this will be the focus of a future post.

Finally it is also worth noting that salicylic acid is not aspirin (aspirin is acetylsalicylic acid, a related yet different molecule) so if you want to experiment with this additive you should buy salicylic acid instead of just "dumping some aspirin" into your foliar or hydroponic nutrient solution.

Using titanium to increase crop yields

There are many additives that can be used to enhance the yield of flowering crops. Some have been covered in this blog — like silicon — while others haven't been mentioned here. Today we are going to talk about a rarely discussed additive that is infrequently used in plant culture these days: Titanium. I want to talk about this additive in light of a Literature review that came up recently (April 2017) about the use of Titanium in crop production. The magazine where this review came from (Frontiers in Plant Science) is a magazine that often has good content in the field of innovative crop enhancing techniques.

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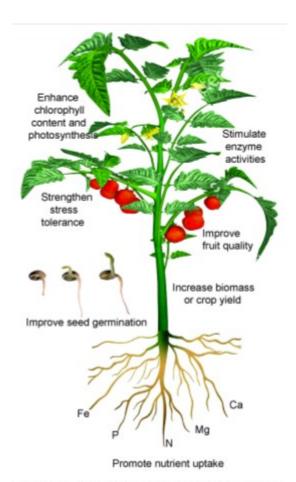


FIGURE 1 | A schematic illustration of Ti effects on crop performance. Ti applied via roots or leaves at appropriately low concentrations has been shown to promote seed germination, enhance root uptake of other nutrient elements, stimulate the activity of some enzymes, increase chlorophyll biosynthesis and photosynthesis, strengthen stress tolerance, and improve crop quality and yield.

Titanium use in plant culture is not new. From the early 1980s people started to experiment with titanium as techniques were developed in order to produce titanium chelates that could be used in foliar applications. Basically all reports of yield increases — that show wonderful increases up to even 95.3% in yields — come from a paper on the biological importance of titanium by Dr. István Pais in 1983 and then another publication in 1991 by the same person (here). Other authors have also showed increased yields (here and here) although in some cases in conjunction with other additives (like Si) with results often much less dramatic than the initial 1983 papers. Titanium nanoparticles have also been tested and their effect has mostly been negative with decreases in plant growth and often DNA damage. For this reason when using titanium you want

to go with a soluble chelate and not nanoparticle sources.

Creating aqueous stable Ti is not a cake walk. There is currently only one product that carries water soluble Ti (called Tytanit) and as far as I can tell no other commercial products for the application of Ti exist at this moment. This tytanit product is most probably titanium ascorbate — the most popular chelate used — but other organic chelates, like Ti citrate, might be usable as well. Preparing Ti ascorbate is not so easy to get as well — you cannot just buy it on ebay/alibaba as it's not stable as a solid — so you need to prepare it from scratch. Titanium chemistry in solution is sadly very complicated.

However there is probably a route to the easy preparation of such complexes using a simple method involving titanium dioxide and ascorbic acid. We know from dissolution studies of titanium dioxide that it can be dissolved significantly by ascorbic acid but the final concentration of these solutions is not very high with a final concentration of around 0.025M of Ti possible in solution using this method, with a surrounding concentration of 0.15M of ascorbic acid. More acid does not help dissolve more titanium dioxide as this seems to be the solubility limit of the titanium complex. This gives you around 1.2g/L of Ti which you need to dissolve 500-1000x to arrive at the recommended application rate of 1-2 ppm. This will give a final ascorbic acid concentration of 26ppm which is acceptable as an additive as well.

Obviously there are some further formulation steps necessary to get the above to work correctly but this outlines the basics to develop a concentrated titanium ascorbate product that can be used for the creation of a Titanium supplement. Industrally this can be achieved much more efficiently with the use of titanyl sulfate which is a readily soluble and easy to get industrially — but hard to get for your home — form of titanium. You can see this patent for examples of how a fertilizer using titanyl sulfate can be prepared.

Evidence about titanium — applied as titanium ascorbate in a foliar spray — being positive for crops is significant. Various positive effects have been shown across a significant variety of plants across several different plant types — tomatoes, beans, peppers — by different authors. The effect on yields is not so clear — probably in reality not as large as shown in the original studies, but probably significant enough to warrant further studying. The development of low-cost processes for the manufacturing of titanium fertilizers will further enhance their use and increase our knowledge about their true capabilities. More studies with ascorbic/ascorbate controls will also show us clear evidence of whether we are seeing effects related with the ascorbate or the actual Ti chelate.

Phosphorous toxicity and concentration in higher plants

If you search the web for symptoms of nutrient toxicities you will often find clear pictures and descriptions for most elements. Feed a plant too much nitrogen and it will grow leggy and weak, with dark leaves and long stems, feed it too much boron and you will see yellowing and tissue necrosis. However you will struggle to find descriptions for toxicity symptoms for potassium (K) or phosphorous (P). Is there really no P or K toxicity? Why are they no pictures or clear ideas of how these problems look? Today I am going to talk a bit about P toxicity and why it's so difficult to reach levels where plants react very negatively to ions from the phosphate family. Images posted were taken from articles cited within

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Table 1. Yield % (v/w) of the Essential Oils of Leaves and Bracts of Cultivated *Origanum dictamnus*

phosphorus concentration		
mg/L	leaves	bracts
5	3.1	3.8
30	2.7	4.0
60	2.8	4.3

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You will often find websites that talk about P toxicity as saying that it is rare or that what it causes is mainly problems with other elements. In general increases in P concentration can cause problems with other elements particularly because the solubility of dihydrogen phosphate salts (H₂PO₄⁻), salts that form with the ionic form of phosphate that's mainly present around the pH values used in hydroponics (5.5-6.5) can be very insoluble. You will struggle to find solubility values for heavy metal dihydrogen phosphates, but Fe, Zn and Cu dihydrogen phosphates can be reasonably presumed to be poorly soluble. However calcium dihydrogen phosphate has a solubility of 20g/L at 25°C and is therefore very soluble, problems with Ca S 0 due to having а lot phosphorous (this salt is also known as mono calcium phosphate).

The solubility of Ca dihydrogen phosphate is in fact very important because rock phosphate — tricalcium phosphate — is one of the main sources of phosphorous in soil and it dissolves to form protonated phosphate species at the pH usually created around plant roots. This means that many plants evolved with very large occasional concentrations of dihydrogen phosphate around them and therefore they generated mechanisms to down-regulate the uptake of phosphorous from really high concentrations.

 Table 7

 Effect of nutrient solution PO₄-P level on the sesquiterpene lactone (SL) concentration of hydroponically grown lettuce plants

Phosphorus level (mg L ⁻¹)	SL concentration ^a	(μg g ⁻¹ dwt)		Total SL content (µg plant ⁻¹)	
	Lactucin	8-Deoxylactucin	Lactucopicrin	Total	
8 16 48 Significance	3.4 ± 0.3 c ^b 6.2 ± 0.2 b 13.6 ± 1.1 a	5.4 ± 0.3 b 4.2 ± 0.4 b 9.0 ± 0.8 a	20.4 ± 1.4 b 20.8 ± 1.0 b 35.7 ± 1.0 a	29.2 ± 1.3 b 31.2 ± 0.8 b 58.4 ± 0.3 a	141.2 ± 6.3 c 215.0 ± 5.6 b 295.3 ± 1.7 a

A Values are expressed as mean ± S.E.M. (n = 3).

Significant at P < 0.01.

There is strong evidence about the above. In fact plants that evolved in phosphorous-poor soils did not evolve mechanisms for down-regulation and do exhibit P toxicity even at moderate concentrations of this element. A few plants native to Australia exhibit this behavior, you can read more about this here. Due to this fact many plants can be cultured in media that is amended with fertilizers that generate large local concentrations of phosphorous when watered without showing any strongly negative effects. Note however that plants will eliminate these down-regulation mechanisms significantly if they are in a P deficient media and if you feed them P rapidly you can cause P toxicity just because the plant couldn't react fast enough to the large increase in P concentration. See for example this study using P deficient Barley which accumulated toxic levels of P upon supplementation although this did not happen when the plants were constantly exposed to high P levels.

In hydroponics we do see excess of P manifest itself as deficiencies of other elements because of the solubility issues for heavy metal acid phosphates mentioned above. Several studies show the strong link between P concentration and the availability of some micro-elements. For example this paper shows the relationship between P and Zn and how the relationship corresponds with Zn phosphate precipitation in the roots. However if heavy metals are properly chelated we in fact don't see these problems. I have made experiments with plants — basil and mint — cultivated in 600 ppm of P where I

Mean separation within columns by Duncan's multiple range test at P = 0.05.

have failed to see any significant problems although I have failed to find any papers that describe experiments under such extreme P concentrations.

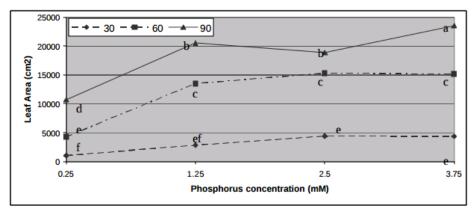


Figure 3.1 Effect of phosphorus concentration on leaf area of tabasco pepper plants grown in hydroponic greenhouse culture at 30, 60, and 90 DAT. Observations with the same letter are not significantly different, means separation by Tukey Kramer method (P<0.05).

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Is more P always better then? Studies in tomatoes show better responses to salinity at higher P concentrations (for example <u>here</u>). Although the highest concentration tested here is 61 ppm (2mM) which is higher than but still close to what is generally used in hydroponic culture of tomato plants (30-50 ppm). Tabasco pepper has also been found to grow better under higher P concentrations (see here). A study varying P concentration in hob marjoram found lower essential oil concentrations at higher P levels, although these levels are around 60 ppm as well. Lettuce on the other hand shows increases of sesquiterpene lactones at high P levels (see here). There are a few publications about P toxicity in higher plants - notably this one about tomatoes - where problems caused by P are generally associated with the previously mentioned micronutrient issues and P concentrations in leaf tissue above 1%.

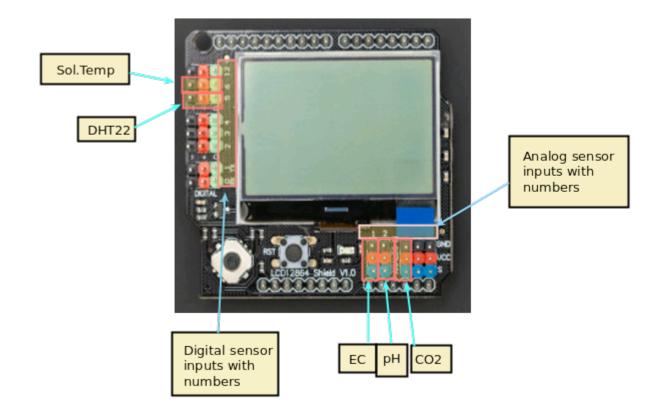
In summary P toxicity depends heavily on plant type and its ability to regulate P uptake, it is also most likely heavily

dependent on micronutrient concentration and the strength and stability of the chelating agents used to prevent the precipitation of heavy metal phosphates. There are no studies I could find with P under very high concentrations (>=20mM) using chelated heavy metal sources so this is an interesting topic for research for anyone interested in exploring the limits of P uptake.

A simple Arduino based sensor monitoring platform for Hydroponics

Last time I posted about automation I talked about how I use an Arduino to automate the monitoring and management of my home hydroponic system. Today I want to talk about how you can build an Arduino based station to monitor the most important variables of your hydroponic crop without having to solder anything, use complicated bread board setups or learn to how to do any coding. I will walk you through some of the steps to build the system, talk about the parts you need and show you the code you need to run to have this setup work.

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A basic sensor monitoring application for hydroponics should be able to get the most critical information needed to grow a crop successfully. The basic variables you would want to monitor to achieve this goal would be: temperature, humidity, carbon dioxide concentration, pH and electrical conductivity. An Arduino micro-controller can help you achieve all these goals at a reduced cost when compared with commercially available monitoring solutions of the same quality.

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- <u>Arduino UNO R3</u> 23.90 USD
- LCD 12864 screen shield 24.05 USD
- DHT22 temperature and humidity sensor 9.50 USD
- Gravity pH sensor 56.95 USD
- Gravity EC sensor 69.90 USD
- Gravity CO2 sensor 58.00 USD

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The list above contains all the pieces you need to get this to

work. This includes the Arduino plus an LCD display that we will use to be able to read the information we obtain from the sensors. I have included links to the pieces at the dfrobot site (one of my favorite sources for DIY electronics) but you can definitely get them elsewhere if you prefer. The pH sensor included here is of industrial quality while the EC sensor has a lower quality level. However I have been able to use both for extended periods of time without anything else than a calibration around once every 2 months. If you want you can also purchase an industrial quality EC probe if you find the prove from the included Gravity kit to be insufficient for your needs.

The cool thing about this setup is that the LCD screen already contains all the connections we need for the sensors. The bottom part contains numbered analog inputs while the left part contains numbered digital inputs. In this setup we have two digital sensors — the DHT22 humidity/temperature sensor and the solution temperature sensor that comes with the EC sensor — and three analog sensors, which are pH, EC and CO_2 . I have put some text on the image to show you exactly where you should connect the sensors according to the code, make sure the orders of the colors on the wires match the colors on the connector in the LCD screen. The Arduino code contains some defines with the pins for each sensor so you can just change those numbers if you want to connect the sensors in different places.

//Libraries
#include <DHT.h>;
#include <U8glib.h>
#include <stdio.h>
#include <OneWire.h>
#include <Wire.h>
#include <Arduino.h>
#include <Adafruit_Sensor.h>

```
//PINS
                                // DHT pin
#define DHT PIN
                      5
#define DHTTYPE
                     DHT22
                                // DHT 22 (AM2302)
#define PH PIN
                      2
                                //pH meter pin
#define CO2 PIN
                     3
                                //ORP meter pin
#define EC PIN
                      1
                                //EC meter pin
#define DS18B20 PIN
                                   //EC solution temperature
                    6
pin
// AVERAGING VALUES
#define MEDIAN SAMPLE 8
#define MEASUREMENTS TAKEN 100
// EC - solution temperature variables
#define StartConvert 0
#define ReadTemperature 1
// EC values // CHANGE THESE PARAMETERS FOR EC PROBE
CALIBRATION
#define EC PARAM A 0.00754256
//pH values // CHANGE THESE PARAMETERS FOR PH PROBE
CALIBRATION
#define PH PARAM A 1.0
#define PH_PARAM_B 0.0
#define XCOL SET 55
#define XCOL SET2 65
#define XCOL SET UNITS 85
//-----
DHT dht(DHT PIN, DHTTYPE);
U8GLIB NHD C12864 u8g(13, 11, 10, 9, 8);
unsigned long int avgValue;
float b, phValue;
int buf[MEASUREMENTS TAKEN], tmp;
int chk:
float hum;
float temp;
unsigned int AnalogAverage = 0,averageVoltage=0;
```

```
float solution temp, ECcurrent;
unsigned int levelAverage;
float co2;
OneWire ds(DS18B20 PIN);
//-----
void draw() {
  u8g.setFont(u8g font 04b 03);
  u8g.drawStr( 0,11,"Temp:");
  u8g.setPrintPos(XCOL SET,11);
  u8g.print(temp);
  u8g.drawStr( XCOL SET UNITS, 11,"C" );
  u8g.drawStr(0,21, "Humidity:");
  u8g.setPrintPos(XCOL SET,21);
  u8q.print(hum);
  u8g.drawStr( XCOL_SET_UNITS,21,"%" );
  u8g.drawStr(0,31,"pH:");
  u8g.setPrintPos(XCOL SET,31);
  u8g.print(phValue);
  u8g.drawStr(0,41,"EC:");
  u8g.setPrintPos(XCOL SET,41);
  u8g.print(ECcurrent);
  u8g.drawStr( XCOL SET UNITS,41, "mS/cm" );
  u8g.drawStr(0,51, "Sol.Temp:");
  u8g.setPrintPos(XCOL SET,51);
  u8q.print(solution temp);
  u8g.drawStr( XCOL SET UNITS,51,"C" );
  u8g.drawStr(0,61, "C02:");
  u8g.setPrintPos(XCOL SET,61);
  u8g.print(co2);
  u8g.drawStr( XCOL SET UNITS,61,"ppm" );
}
float TempProcess(bool ch)
{
  static byte data[12];
  static byte addr[8];
  static float TemperatureSum;
  if(!ch){
          if ( !ds.search(addr)) {
```

```
ds.reset_search();
               return 0;
          }
          if ( OneWire::crc8( addr, 7) != addr[7]) {
               return 0;
          }
          if ( addr[0] != 0x10 \&\& addr[0] != 0x28) {
               return 0;
           }
          ds.reset();
          ds.select(addr);
          ds.write(0x44,1);
  }
  else{
          byte present = ds.reset();
          ds.select(addr);
          ds.write(0xBE);
          for (int i = 0; i < 9; i++) {
             data[i] = ds.read();
          }
          ds.reset search();
          byte MSB = data[1];
          byte LSB = data[0];
          float tempRead = ((MSB << 8) | LSB);
          TemperatureSum = tempRead / 16;
    }
          return TemperatureSum;
}
void calculateAnalogAverage(int pin){
 AnalogAverage = 0;
  for(int i=0;i<MEASUREMENTS TAKEN;i++)</pre>
  {
    buf[i]=analogRead(pin);
    delay(10);
  }
  for(int i=0;i<MEASUREMENTS_TAKEN-1;i++)</pre>
  {
    for(int j=i+1;j<MEASUREMENTS TAKEN;j++)</pre>
      if(buf[i]>buf[j])
```

```
{
        tmp=buf[i];
        buf[i]=buf[j];
        buf[j]=tmp;
     }
    }
  avgValue=0;
               for(int
                                i = (MEASUREMENTS TAKEN/2) -
(MEDIAN SAMPLE/2);i<(MEASUREMENTS TAKEN/2)+(MEDIAN SAMPLE/2);i
++){
    avgValue+=buf[i];
  AnalogAverage = avgValue/MEDIAN SAMPLE ;
}
void read pH(){
  calculateAnalogAverage(PH PIN);
  phValue=(float)AnalogAverage*5.0/1024;
  phValue=PH PARAM A*phValue+PH PARAM B;
}
void read EC(){
  calculateAnalogAverage(EC PIN);
  solution_temp = TempProcess(ReadTemperature);
  TempProcess(StartConvert);
  averageVoltage=AnalogAverage*(float)5000/1024;
  float TempCoefficient=1.0+0.0185*(solution temp-25.0);
                                                          float
CoefficientVolatge=(float)averageVoltage*TempCoefficient;
  ECcurrent=EC PARAM A*CoefficientVolatge;
}
void read CO2(){
  float voltage;
  float voltage difference;
  calculateAnalogAverage(CO2 PIN);
  voltage = AnalogAverage*(5000/1024.0);
  if(voltage == 0)
  {
    co2 = -100.0;
```

```
}
  else if(voltage < 400)
  {
    co2=0.0;
  }
  else
  {
    voltage difference=voltage-400;
    co2=voltage difference*50.0/16.0;
  }
}
void setup()
{
    pinMode(13,0UTPUT);
    Serial.begin(9600);
    dht.begin();
    u8g.setContrast(0);
    u8g.setRot180();
    TempProcess(StartConvert);
}
void loop()
{
  digitalWrite(13, HIGH);
  delay(800);
  digitalWrite(13, LOW);
  hum = dht.readHumidity();
  temp= dht.readTemperature();
  read pH();
  read EC();
  read C02();
  u8g.firstPage();
        {
    do
      draw();
    }
      while( u8g.nextPage() );
}
```

After you connect the sensors you can then upload the code above using the Arduino IDE to your Arduino via USB. You will need to install the following Arduino libraries to get it to compile and upload:

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- AdaFruit unified sensor driver
- AdaFruit DHT sensor library
- OneWire library
- <u>U8glib library</u>

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After you upload this to your Arduino it should start and show you a screen with the temperature, humidity, pH, EC and carbon dioxide readings. The carbon dioxide concentration might show as -100 in the beginning, which simply means that the sensor is heating up (it requires a few minutes before it can start giving readings).

It is also worth noting that you should calibrate your pH sensor. To do this you should read the pH of a 7.0 buffer (M7) - record the value you get - and then repeat the process with a pH 4.0 buffer (M4). You can then change the PH PARAM A and PH PARAM B values in the code (right at the beginning) to make the sensor match your measurements. The PH PARAM A parameter should be equal to 3/(M7-M4) while PH PARAM B should be 7-M7*PH PARAM A. If you ever need to recalibrate set PH PARAM A to 1 and PH PARAM B to 0 and repeat the process. For the EC sensor you should perform a calibration using the 1.412 mS/cm solution that comes with the sensor and then change EC PARAM A your sensor matches this reading (1.412/(MEC/0.00754256)).

With this new monitoring station you should now have a powerful tool to monitor your hydroponic system and make sure everything is where you want it. Of course making the arduino intereact with a computer to record these values and then

implementing control mechanisms using fans, peristaltic pumps, water pumps, humidifiers/dehumidifiers and other appliances is the next step in complexity.

What is the effect of amino acids in hydroponics?

It is very common for hydroponic nutrient manufacturers to add amino acids to their products. They often mention significant benefits that range from strengthening plants to greatly increasing yields or product quality but they rarely mention any peer reviewed evidence studying these effects. Today we are going to look at the use of amino acid applications in hydroponic culture and the effects that amino acids have been shown to have when used in a variety of different crop types. We will see some of the benefits and the problems that they have shown to cause as well and we'll discuss whether it is actually worth it to apply them in a hydroponic nutrient solution.



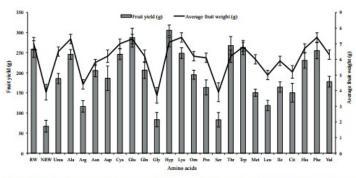


Fig. 3. Effect of twenty two amino acids on the yield of strawberry plants grown in non-renewed nutrient solution in closed hydroponic system. RW: renewed, NRW: non-renewed, amino acids are presented as their three letters abbreviation.

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Amino acids — which I am going to use here to refer to L-alpha amino acids — are basically organic molecules that are used as the basic block for protein construction in all life forms. Plants are able to synthesize all the amino acids they need internally while in the case of animals many of these amino acids need to come from other animal or vegetable sources. However since amino acids can be added to nutrient solutions and plants can absorb them (see here) it is interesting to wonder what the effects they might have.

There are two ways in which amino acids can affect a hydroponic crop. They may be absorbed and used directly by the plant or they may create a chelate with a metal ion and affect that metal's absorption. It is very difficult to separate both effects — except when specific metal absorption studies are carried out — so the effect on yields is generally a combination of these two. The specific amino acids used and their proportion are also critical to these effects as both plant absorption and the stability of metal chelates depend on the exact structure of the amino acids in solution.

There is significant evidence that amino acid applications reduce nitrate assimilation (see here and <a href=here) this is not surprising given that amino acids compete with nitrate in the nitrogen cycle and may be more readily assimilated by plants. This seems to be especially the case if nitrate concentrations are low and the plants are N deprived. The effect is most important for glutamine, not surprising as glutamate synthesis is basically the mechanism used for ammonium incorporation by plants.

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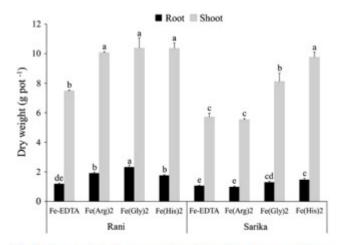
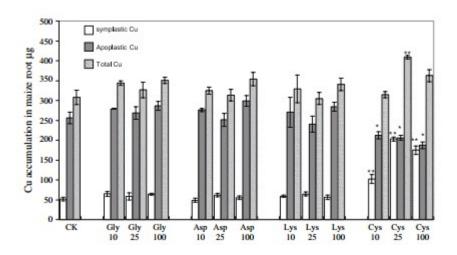


Fig. 1 Root and shoot dry matter weights of two tomato cultivars grown in nutrient solution containing Fe-EDTA, Fe-arginine $[Fe(Arg)_2]$, Fe-glycine $[Fe(Gly)_2]$, and Fe-histidine $[Fe(His)_2]$. Error bars represent standard error (n = 3). Bars having different letters in root or shoot are significantly different at the 5% level by LSD



There is also evidence that amino acids can help plants under stress conditions. For example strawberries in autotoxic conditions — meaning that they have made a nutrient solution toxic after a lot of recirculation — benefited greatly from an amino acid cocktail application (here) and Canola plants have shown to have increased yields under saline conditions with proline applications (here). Plants under heavy metal stress can also benefit from the presence of amino acid, for example rice seedling have shown to benefit from amino acid applications under cadmium stress (here).

There are also limited studies in the use of amino acids as

metal chelates in hydroponics. A 2012 study (here) compared different Fe chelates with Fe EDTA and showed that some of these chelates work better than the traditional EDTA chelate in Fe absorption. Fe glycine showed the best absorption across roots and shoots plus the best yields in tomatoes (second image in this post). This shows that Fe glycine may be a good candidate for the replacement of Fe EDTA in hydroponic solutions. Another study (here) also compared different Cu containing amino acid chelates and found that cysteine may be effectively used for Cu fertilization and phytoremediation.

Is it worth it to apply amino acids in hydroponics? This may depend on the exact conditions the plants are facing. While amino acids have proved beneficial for the assimilation of specific nutrients - like Fe and Cu - or the alleviation of some stress conditions (salinity, autotoxicity), there isn't any strong evidence suggesting wide range beneficial effects under normal plant growing conditions, especially if these are close to ideal. In normal hydroponic solutions introducing large amounts of amino acids may even have significant negative effects due to their effect on ion absorption and N Further evidence metabolism. is required general recommendations for exogenous amino acid applications can be made.

This doesn't mean that amino acids might not be beneficial under normal conditions, just that we have no evidence yet showing which amino acid profiles might work best for which plants and under what concentrations and we do know that there can be potentially harmful effects if these parameters are not studied carefully.

Probes for constant immersion in hydroponic nutrient solutions

If you have a hydroponic crop then you probably have to measure and monitor the pH and EC of your nutrient solutions. This means taking probes out of storage, ensuring they are calibrated and then carrying out measurements. This process can be very inconvenient, reason why growers might prefer to carry it out less often, even if this means they will have a lot less data. However there are several solutions that can enable constant monitoring of hydroponic nutrient solutions without the need to constantly take out, calibrate and then store away probes. Today we will talk about why regular probes are not suited for this and what types of probes are needed if you want to do this.



Usually low quality EC/pH pens cannot be kept within nutrient solutions because they are not built to withstand constant

contact with nutrient solutions. This is both due to the electrode composition — the actual glass or metal electrodes not being robust enough — and the actual junctions and other components not withstanding the nutrient solution as well. Although hydroponic nutrient solutions are not particularly harsh environments — with a slightly acidic pH and moderate ionic strengths — probes for constant monitoring of nutrient solutions must be designed with constant immersion in mind.

For constant monitoring of pH in nutrient solution tanks you want a proper submersible electrode assembly like this one. These electrodes are usually mounted on PVC fixtures and can be easily mounted on tanks to provide constant readings for the nutrient solution. The electrode comes with a standard BNC connector meaning that it is compatible with a wide variety of pH controllers. If you don't want to mount it on the tank but you just want the electrode to be like a normal probe but constantly submerged then you can use something like this industrial probe which comes with a pH controller as well that can be used with any other probes you purchased and interfaces with an arduino or raspberry pi to get and store readings. For probes like this last one I usually wrap the entire outside body of the probe in electrical tape to give further strength to the probe/cable junction.

For conductivity readings you will want to go with electrodeless EC probes (like these ones) which over PVC mountings as well with the advantage that they do not suffer from polarization issues — like normal EC pens use — so they lose calibration much more rarely and can give much more accurate readings across a wide range of different solution types and conductivity values.

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For the grower who wants it all there are also probes like the Mark I-A probe which is a tank-mounted probe assembly that does EC, pH and ORP readings, all in one single fixture. This is incredibly practical since it is able to implement all the readings you need in one single fixture. The problem of course is that calibration of any reading requires you to remove all three sensors so this can be a bit inconvenient when you want

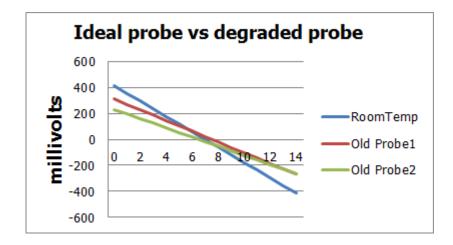
to ensure that any of the readings are indeed accurate.

Of course submersible robust probes are more expensive but they are much more convenient. They get damaged much less frequently, require much less maintenance, provide constant readings and need to be calibrated only a few times a year. For example the industrial EC and pH probes I use in my home hydroponic setup have only required calibration once a year, even then the loss in calibration was only around 0.2 units for the pH sensor and 0.3 mS/cm for the EC one so I probably could have continued using the probes without calibrating them for 2 years without having to face any dramatic consequences. If you spend 300-400 USD on high quality robust probes you will probably have them for much longer, with far more accurate results along the way.

Five things that will damage your pH probes

Since pH is one of the most important variables to control in hydroponic culture almost all hydroponic growers have and use pH probes. There are however several things that can go wrong with these probes due to the very nature of the sensor and the way in which other substances interact with it. Today we will learn about some of the worst things that you can do to your pH probes and how you can potentially avoid these issues.

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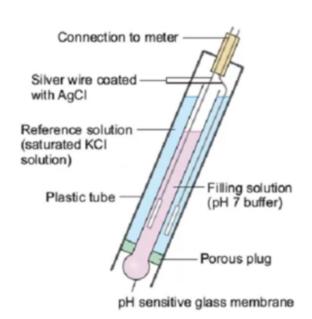
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1. Let them dry. These probes are made from glass and the readings depend on the potential difference between the inside and outside surfaces of the sensor. These are determined mainly by pH since hydronium (H30+) ions interact strongly with the glass surface. For measurements to be accurate the surface needs to be in equilibrium with the media that is being measured. If you let the electrode dry then the hydration of the surface will be lost and the equilibrium state will be much harder to achieve (a dry probe should be

placed in a KCl solution for at least 4 hours before being used). Any junctions within the probe might also dry which will require further stabilization before the probe can be used. Dry pH probes are therefore a big no no.

- 2. Keep them in water. Although keeping pH probes in water is better than letting them dry this has a similar effect in that it alters the composition of the glass with time. Since the solution around the probe is much more diluted, with time ions in the glass will have no problem migrating away from the probe, creating defects within the glass that will mess with your sensor's calibration. Ideally you will want to store your pH probes in a concentrated KCl solution (usually around 150-300g/L) which will prevent any of these migration effects and will ensure that your probe remains stable in the longer term. If you buy KCl you can use distilled water to prepare your own pH probe storage solution.
- **3. Measure very basic solutions.** Since pH probes are made of glass and glass is mainly made of silicates this means that basic solutions will tend to react with your pH probe. When the pH goes above 10 a pH probe will start to dissolve in solution, completely altering the surface and making the sensor lose calibration very quickly. In general avoid measuring the pH of any solution above 10 so that this effect can be kept to a minimum.
- 4. Measuring solutions with chemicals that react with glass. Besides basic solutions where hydroxide ions dissolve glass there are a variety of substances that can affect the performance of pH probes by reacting with the glass. This includes solutions containing silicate species and solutions containing fluoride ions. If the solution has ions that can react with glass then the pH probe's lifetime will be diminished and much more frequent calibration will be required. Try to avoid long term measurements of solutions containing large amounts of these ions and beware that weekly calibration might be necessary.

5. Not cleaning the probe. When measuring solutions such as hydroponic nutrient solutions the pH probe is usually subjected to an environment filled with potentially microorganism contaminants. If the probe is not properly cleaned then microbes can form a biofilm over the glass that will seriously affect the accuracy of pH readings. A probe can be cleaned with a bleach or hydrogen peroxide solution to remove these contaminants but the probe will then need to be recalibrated as the film will have effectively changed the glass surface to some extent.



Having pH probes that give accurate reading for a long time is not a difficult task if you take proper care of your sensors. Storing them adequately, ensuring they are not exposed to harmful conditions and cleaning them ensures that they will last for a much longer time. IF you keep track of your pH sensor calibrations you might notice changes in the calibration slope — as in the first image in this post — which indicates a loss of sensor sensibility (the slope becomes less pronounced). You can use a sensor until around 20% of the sensor's sensibility is lost, time after which you'll need to buy a new probe.

There are also several sensors that can be used for long term continuous measurements — which are made in a much more robust manner — we will talk about industrial quality and in-line sensors in a future post.

Vapor pressure deficit (VPD) in hydroponics

If you have read books or articles about greenhouse environmental control you have probably heard about Vapor Pressure Deficit, also known as VPD. This is an important variable to measure as it helps us understand the conditions our plants are facing, gauge their water use and even predict whether we will be getting better or worse yields. Today I am going to talk about vapor pressure deficit in hydroponics, what this variable means, what it takes to control it and why it is so important to understand and even change this value to obtain better results.

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Table 3. References VPD (kPa) for greenhouse production, recommended by Argus Ltd, (2009)														
TOCA	rH(%)													
T(°C)	35	40	45	50	55	60	65	70	75	80	85	90	95	100
15	1.11	1.02	0.94	0.85	0.77	0.68	0.60	0.51	0.43	0.34	0.26	0.17	0.09	0
16	1.18	1.09	1.00	0.91	0.82	0.73	0.64	0.55	0.45	0.36	0.27	0.18	0.09	0
17	1.26	1.16	1.06	0.97	0.87	0.77	0.68	0.58	0.48	0.39	0.29	0.19	0.10	0
18	1.34	1.24	1.13	1.03	0.93	0.83	0.72	0.62	0.52	0.41	0.31	0.21	0.10	0
19	1.43	1.32	1.21	1.10	0.99	0.88	0.77	0.66	0.55	0.44	0.33	0.22	0.11	0
20	1.52	1.40	1.29	1.17	1.05	0.93	0.82	0.70	0.58	0.47	0.35	0.23	0.12	0
21	1.62	1.49	1.37	1.24	1.12	0.99	0.87	0.75	0.62	0.50	0.37	0.25	0.12	0
22	1.72	1.59	1.45	1.32	1.19	1.06	0.92	0.79	0.66	0.53	0.40	0.26	0.13	0
23	1.82	1.68	1.54	1.40	1.26	1.12	0.98	0.84	0.70	0.56	0.42	0.28	0.14	0
24	1.94	1.79	1.64	1.49	1.34	1.19	1.04	0.89	0.75	0.60	0.45	0.30	0.15	0
25	2.06	1.90	1.74	1.58	1.42	1.27	1.11	0.95	0.79	0.63	0.47	0.32	0.16	0
26	2.18	2.02	1.85	1.68	1.51	1.34	1.18	1.01	0.84	0.67	0.50	0.34	0.17	0
27	2.32	2.14	1.96	1.78	1.60	1.43	1.25	1.07	0.89	0.71	0.53	0.36	0.18	0
28	2.46	2.27	2.08	1.89	1.70	1.51	1.32	1.13	0.94	0.76	0.57	0.38	0.19	0
29	2.60	2.40	2.20	2.00	1.80	1.60	1.40	1.20	1.00	0.80	0.60	0.40	0.20	0
30	2.76	2.54	2.33	2.12	1.91	1.70	1.48	1.27	1.06	0.85	0.64	0.42	0.21	0
31	2.92	2.69	2.47	2.24	2.02	1.80	1.57	1.35	1.12	0.90	0.67	0.45	0.22	0
32	3.09	2.85	2.61	2.38	2.14	1.90	1.66	1.43	1.19	0.95	0.71	0.48	0.24	0
33	3.27	3.02	2.76	2.51	2.26	2.01	1.76	1.51	1.26	1.01	0.75	0.50	0.25	0
34	3.46	3.19	2.92	2.66	2.39	2.13	1.86	1.59	1.33	1.06	0.80	0.53	0.27	0
35	3.65	3.37	3.09	2.81	2.53	2.25	1.97	1.69	1.40	1.12	0.84	0.56	0.28	0

Vapor pressure deficit — measured in kPa — basically measures how much water vapor pressure we would need to put into a room with a certain humidity and temperature to get it to the point where relative humidity would be 100%. The larger the VPD the more water you need to put into the air to get it to saturate while the lower the VPD the closer the air is to full saturation. Since air holds more water with increasing temperature this means that at a fixed relative humidity the VPD is directly proportional to the room's temperature. This simply means that the hotter the room, the higher the VPD and the colder the room, the smaller the VPD if humidity remains constant.

The problem with a very low VPD — room close to 100% humidity — is two fold. First, it's difficult for any organism to evaporate water and second, it's easy for water to condense on any surface it temperature drops just a bit. For humans this basically means having to wear a t-shirt soaked with your own sweat but for plants this means both an inability to cool their surfaces and an inability to transport nutrients to their leaves. A low VPD generates a lot of stress because it makes plants unable to properly transport water.

A high VPD is equally problematic as it means that the plants need to transpire a lot. If air can hold a lot of additional water vapor this means that plants will lose more water through their stomata and this permanent loss puts pressure on the roots to transport more and more water. If root mass is not large enough or water availability is not high enough then plants will face important problems and will simply tend to wilt as the air takes away more water than what the plant can effectively transport through its tissues. You can actually often create models using VPD to predict a crop's water usage (see image below).

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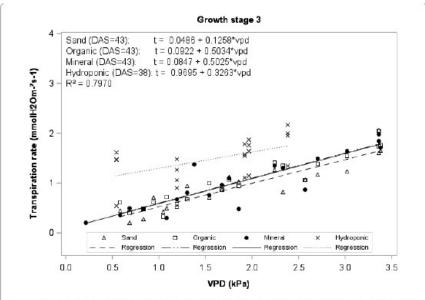


Figure 7: Transpiration rate in Panicum (*Panicum maximum* cv. *tanzania*) under VPD with different substrates in growth stage three.

The first graph in this post (which I took from this study on tomatoes) shows the optimum VPD — in green — as a function of humidity and temperature for greenhouse production of tomatoes. In general a range between 0.5 and 1.1 seems to work best but the window under which these conditions are possible becomes narrower as temperature increases. Ideally we would want to be somewhere around 20-25°C where we should sustain humidity values between 65-70%. This would give us a VPD value between 0.7-0.8 which is around what is commonly held to be most beneficial for greenhouse crops under normal conditions.

However optimal VPD can also change depending on lighting conditions and other sources of supplementation. For example the optimal VPD during the day is usually higher than the optimal VPD during the night. In general it's better to have a drop in VPD during the night relative to the VPD that is maintained during the day. Declines in canopy carbon dioxide exchange rates can be correlated with increases in the VPD during this time (see here for a study about this on soy bean). If you're supplementing carbon dioxide — which puts further transpiration stress on the plants — the optimal VPD is also likely to be lower than if you didn't use any

supplementation at all (you can see a practical application of this here).

Changing the VPD can be a challenge but under closed environments it is much easier to do. You can reduce the humidity using a dehumidifier to increase your VPD and you can use a humidifier to increase your VPD. Ideally you will want to use an AC unit to keep your temperature at exactly the value you want it to be and you can then use a humidifier/dehumidifier to control the exact point where you want your VPD to be by controlling the value of your relative humidity at the fixed temperature provided by the AC unit.