PLANT NUTRITION TESTING PROCEDURES: GREENHOUSE SAT'S?

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A test: many of us tense up upon hearing that word from previous experiences during our school careers. Actually, the types of tests growers should be conducting are more closely related to the true origin of the word "test" than the meaning most often implied today in classrooms. An etymologist will tell you that a test is nothing more than a pot or clay vessel used in procedures for examining metals; a means of monitoring the purity of an ore.

Growers should establish routine monitoring procedures too. Testing is crucial to avoid nutritional disorders and to insure the subsurface environment is properly created during plant production. These tests fall into three categories: ❶ general operations, ❷ preplant, and ❸ post-plant tests.

General operations testing includes examining irrigation water quality and conducting injector calibrations. Preplant tests are measuring substrate moisture content, pH, and soluble salts prior to flat filling and planting. Post-plant tests involve checking fertilizer delivery (rechecking injectors); and monitoring nutrients, pH, alkalinity, and soluble salts during the crop. All of these tests should be simple, and performed frequently to be useful to the grower.

General Operations Testing

Every greenhouse should be submitting water samples for complete chemical analysis at least annually as part of their general operations testing (Table 1). If your greenhouse has a history of alkalinity problems in the irrigation water, you should have an on-site test kit and should be testing your water source at regular intervals (we will discuss alkalinity testing in more detail later). Chemical analysis of your irrigation water is critical information for formulation of a fertilization program. For example, some waters in North Carolina already contain ample calcium for plant production while others would supply very little calcium. These two locations should be using a different fertilization program to assure proper nutrition for their crops.

Fertilizer and acid injectors should be *calibrated monthly*; more often when you suspect a problem. Remember, these devices are only as accurate as their last calibration, so frequent calibration is essential.

Preplant Testing

Preplant testing of substrate solution pH and soluble salts should be done prior to pot or flat filling. You're about to place a crop into this mix; wouldn't it be nice to know what it's chemical properties are before you plant?

The substrate solution pH will affect nutrient availability to plants, so it is crucial to assure it is in an acceptable range. Limestone may take two days to two weeks to fully adjust the pH. If you make your mix just before you fill, the pH will be different than if you mix the substrate a few days ahead and moisten the mix. You should know the rate of reaction time necessary for your mix to reach its final pH. The best way to do this is to establish a *liming curve* for your mix. The rate of reaction will change with changes in peat source and quality / type / particle size of the limestone used.

Soluble salts should be measured to assure that salt levels are below levels that could cause plant damage (Table 2). Note that acceptable salt levels depend on the sampling method used as well as the crop being grown (more on how to

Table 1. Recommended upper limits of nutrient and chemical capacity factors for water used for greenhouse crop production.

Capacity factor	Upper limit for greenhouse use
Substrate pH Factors	
pH[A]	5.4 to 6.8 is acceptable
Alkalinity[B]	100 ppm $CaCO_3$ (2 meq/L)
Total Carbonates (TC)	100 ppm $CaCO_3$ (2 meq/L)
Bicarbonate (HCO_3^-)	122 ppm (2 meq/L)
Hardness[C] (Ca + Mg)	150 ppm $CaCO_3$ (3 meq/L)
Salinity Factors	
Electrical conductivity (EC)	
for plug production	0.75 mmho/cm
for general production	2.0 mmho/cm
Total Dissolved Salts[D] (TDS)	
for plug production	480 ppm
for general production	1,280 ppm
Sodium absorption ratio (SAR)	4
Sodium (Na)	69 ppm (3 meq/L)
Chloride (Cl^-)	71 ppm (2 meq/L)
Macro Elements	
Nitrogen[E] (N)	10 ppm (0.72 meq/L)
Nitrate[E] (NO_3^-)	10 ppm (0.16 meq/L)
Ammonium[E] (NH_4^+)	10 ppm (0.56 meq/L)
Phosphorus[F] (P)	1 ppm (0.3 meq/L)
Phosphate[F] ($H_2PO_4^-$)	1 ppm (0.01 meq/L)
Potassium[F] (K)	10 ppm (0.26 meq/L)
Calcium[G] (Ca)	0 to 120 ppm (0 to 6 meq/L) is normal range
Magnesium[G] (Mg)	0 to 24 ppm (0 to 2 meq/L) is normal range
Sulfur[H] (S)	20 to 30 ppm (0.63 to 0.94 meq/L) is optimum for most plants
Sulfate[H] (SO_4^{--})	30 to 45 ppm (0.63 to 0.94 meq/L) is optimum for most plants

[A]Water with high pH should be analyzed for alkalinity and can be safely used if alkalinity is neutralized.
[B]Water with high levels of alkalinity can be used safely if it is treated with acid to neutralize the bicarbonates and other ions contributing to alkalinity. A limit of 1.5 meq/L alkalinity is suggested for plug production. Labs differ in how they report alkalinity. “Alkalinity”, “TC”, and “bicarbonates” are the three methods used.
[C]Hardness is a measure of Ca and Mg content, but it can be used as an indicator of alkalinity. Hard water should be checked for high alkalinity and can be safely used if alkalinity is neutralized.
[D]A conversion factor of 1 mmho/cm EC = 640 ppm TDS is assumed for TDS readings.
[E]Nitrate and ammonium provide nitrogen to plants and should not cause damage at moderate levels. Nitrate and ammonium levels higher than listed indicate that the water source may be contaminated with fertilizer or some other contaminant.
[F]Phosphorus and potassium normally occur in very low concentrations in irrigation water. If your water contains more the the listed levels, it may be contaminated with fertilizer, detergent, or some other contaminant.
[G]The numbers reported here indicate the range of both elements usually found in North Carolina waters. Calcium and magnesium content of water should be taken into account during fertilization programming.
[H]Sulfur is usually found at low concentrations. The numbers listed here indicate the suggested optimum range of sulfur for most greenhouse crops.

Table 1, continued.

Capacity factor	Upper limit for greenhouse use
Micro Elements	
Aluminum (Al)	5 ppm
Boron (B)	0.5 ppm
Copper (Cu)	0.2 ppm
Fluoride[I] (F^-)	1 ppm
Iron[J] (Fe)	0.2 to 4 ppm
Manganese (Mn)	1 ppm
Molybdenum (Mo)	---
Zinc (Zn)	0.3 ppm
Organisms to Test For	
Iron fixing bacteria	
Plant pathogens	

[I]Safe for most crops but toxic for many members of the lily family.
[J]Although 4 ppm is maximum for plants, even as little as 0.3 ppm can lead to iron rust stains on foliage if water is used for overhead irrigation.

take a substrate sample for salts and pH later). Some growers prefer to analyze substrates for nutrient content prior to use. This is a good habit and definitely should be practiced if soluble salt readings are high and / or if you suspect a problem in the substrate blending.

Post-Plant Testing

A complete post-plant testing program should include visual monitoring of the crop's appearance; routine substrate monitoring checking for pH, soluble salts, and substrate nutrient concentrations; fertilizer solution analysis including pH and soluble salts; irrigation water analysis including pH, soluble salts, and alkalinity; and plant tissue analysis.

The frequency of monitoring depends on the crop being grown. During plug production, weekly substrate and tissue analysis should be conducted. For finishing flats and pot crops, every two weeks may be sufficient. In the ideal world, separate substrate and tissue tests should be conducted for different plant species, as individual species differ in pH and fertility requirements. Fertilizer delivery should be checked daily, or at least at every fertilization if done every second or third irrigation. This can be accomplished by simply capturing some of the fertilizer water in a glass, jar, or beaker and measuring the EC.

Frequency of water analysis depends on the alkalinity content and stability of the water quality. If your water quality (especially alkalinity) changes frequently, then weekly testing of these parameters may be needed, especially for plug production. The alkalinity of a water source can change drastically with weather conditions and pumping fluctuations. We have measured alkalinity ranging from 2.8 meq/L to 5.4 meq/L in well water drawn from the same well in North Carolina during the course of one year! Municipal water in many locations is derived from different sources. Although municipalities try to maintain consistent output from water plants, it is possible to encounter alkalinity fluctuations from a municipal water source also.

Regular monitoring of alkalinity is essential if your water quality changes over time. For a plug producer, *weekly measurements* may be needed due to the rapid effects alkalinity can have on a plug substrate system, because of the small volume of substrate in each plug. Alkalinity effects on larger sized containers (larger substrate volumes) occur more slowly, and monthly testing may be sufficient to allow growers to adjust for alkalinity fluctuations in the water source.

Testing Procedures

Every greenhouse range should have the capability to measure pH and electrical conductivity (EC). These parameters can change too rapidly to rely solely on lab test results, and the cost of the testing equipment is no longer prohibitory for growers.

When selecting a pH meter, look for an accuracy of ±0.1 pH unit and a range of 1 to 14. To be useful for fertilizer injector calibration as well as substrate and solution testing, EC meters should have a range of 0 to 1,990 mho $\times 10^{-5}$/cm and have an accuracy of ±10 mho $\times 10^{-5}$/cm. Many EC meters report EC in units of µS/cm (microSiemens per centimeter). The conversion between S/cm and mhos/cm is simple: 1 S/cm = 1 mhos/cm. Both pH and EC meters are available from many sources including the following: Cole-Parmer Instruments, 745 North Oak Park Ave., Chicago, IL 60648, (800)323-4340; Extech Instruments Corp., 150 Bear Hill Road, Waltham, MA 02154, (617) 890-7440; Myron L Co., 6231 C. Yarrow Drive, Carlsbad, CA 92009, (619) 438-2021.

Whether you are collecting a sample for in-house testing (of substrate pH and EC for example) or for laboratory analysis (of substrate nutrient concentrations or nutrient analysis of plant tissue), take a "representative sample". In problem free, routine sampling situations, a sample should consist of material from several locations. This will provide a sample of the entire crop / greenhouse. When the cause of a problem is being investigated, such as why plants look chlorotic, then a representative sample should consist only of the material from problem areas, plants, or water sources. For best results, a comparative sample from non-affected areas should be taken and submitted at the same time to serve as a comparison for problem samples.

To complete the many analyses of a single sample, laboratories require a prescribed amount of material, whether it is plant tissue for foliar analysis, a water sample, or a substrate sample. Submitting less than the amount required results in incomplete testing and / or a delay until additional material is sent. Always be aware of and send the requested sample size for laboratory analysis, and use sample containers provided by the laboratory you utilize, if provided.

Collecting a substrate sample for laboratory analysis. When collecting a substrate sample, always sample more than one container and collect the sample from all levels in the pot. Draw at least 10 cores of substrate, each from a different location within the crop such that many different benches and locations within a bench are included. When drawing a problem sample, make sure to only sample from affected areas. Exclude the top $^1/_2$ inch of substrate (top $^1/_8$ inch for plug samples), since it is not representative of where plant roots are located and could contain high salt levels, especially in a subirrigation delivery system. If the substrate contains a slow release fertilizer such as Osmocote®, it will be necessary to remove all the fertilizer particles prior to testing to avoid skewing nutrient readings. Samples should be refrigerated until sent to the lab or dried for 24 hours at 125 °F. Do not heat to greater than 125 °F as nutrient loss from the sample may occur. One cup (8 fl oz.) of substrate is usually sufficient for most laboratories; always send the volume requested by the laboratory.

Recently, affordable meters for NO_3-N and K (Cardy® meters) became available. These meters allow growers to conduct in-house measurements for both NO_3-N and K. However, for use with substrate solutions, this means that growers must conduct saturated paste extraction for meaningful interpretation of meter readings.

Preparing a substrate extract for in-house measurement of pH and EC. Routine on-site analysis of substrate pH and EC allows growers to catch fertilization errors early and to prevent major problems from developing. One of the major obstacles to successful testing is the lack of uniformity when many workers do substrate sampling and testing; from location to location within in greenhouse range and from different times. The best remedy is to assign the task of sampling and testing to one worker for consistency in testing.

Probably the easiest method for growers to measure pH and EC of a substrate is a 2 water : 1 substrate mixture (volume : volume). When collecting a substrate sample for in-house testing, follow the collection procedures outlined

Table 2. Electrical conductivity guidelines from various laboratories using the saturated paste, 1 : 2, and pour through extraction techniques.*

Extraction method													
Saturated paste**						1 substrate : 2 water (v : v)**				Pour through exfiltrate**			
Soil-based		Soilless				Soil-based		Soilless		Soil-based	Soilless		
CU	NCSU	CU	MSU	FAS	NCSU	UC	NCSU	MSU	NCSU	CU	CU	VTU***	Interpretation
	≤0.75		≤0.74	≤0.75	≤0.75	<50	≤25	≤24	0 to ?				Insufficient nutrition
	0.75 to 2.0		0.75 to 2.0		0.75 to 2.0	50 to 70	26 to 50		? to 100			<0.5	Low fertility unless applied with every watering
2.5	2.0	3.5	1.99		2.0	100 to 120	100	75		0.6 to 1.0	1.5		Maximum for seedlings or newly rooted cuttings
<3.5	2 to 4		2.0 to 3.5	0.76 to 2.5 (no bark) OR 1.5 to 3.5 (with bark)	2 to 4	<150	51 to 125	75 to 125	100 to 175			0.75 to 1.5	Good for most crops
<3.5		<5.0	2.0 to 3.5			<200	126 to 175	125 to 175	176 to 225	1.0 to 2.0	≤2.0	2.0	Good for established crops
>3.5	4 to 8		5.0 to 6.0	>3.5	4.0 to 8.0	>200	176 to 200	175 to 225	225 to 350				Danger area
	>8.0		>6.0	>5.0	>8.0		>200	>225	>350				Usually injurious
	0.75 to 1.0				0.75 to 1.0		25 to 100		50 to 150				Range for Stage 1 & 2 plugs
	1.0 to 1.5				1.0 to 1.5		25 to 125		50 to 175				Range for Stage 3 plugs
	1.5 to 2.0				1.5 to 2.0								Range for Stage 4 plugs
	1.5 to 4.0				1.5 to 4.0		50 to 175		100 to 225				Range for finish flats of bedding plants

*Laboratory abbreviations are CU = Cornell University, NCSU = North Carolina State University, MSU = Michigan State University, FAS = Fafard Analytical Services, UC = University of Connecticut, and VTU = Virginia Tech University.

**Saturated paste and pour through exfiltrate ECs are given in mmho/cm (mho $\times 10^{-3}$/cm). The 1 substrate : 2 water ECs are given in mho $\times 10^{-5}$/cm.

***The Virginia Tech University (VTEM) pour through standards are for outdoor nursery production, not indoor greenhouse production. They are included as a comparison of greenhouse to outdoor culture recommendations.

Table 3. Interpretive values for essential macronutrients in the substrate solution of a soilless substrate using the saturated paste extraction method.

	Concentration in extract solution (ppm)				
Interpretation	Nitrates	Phosphorus	Potassium	Calcium	Magnesium
Michigan State University					
Low	0 to 39	0 to 2	0 to 59	0 to 79	0 to 29
Acceptable	40 to 99	3 to 5	60 to 149	80 to 199	30 to 69
Optimum	100 to 199	6 to 10	150 to 249	200+	70+
High	200 to 299	11 to 18	250 to 349	—-	—-
Very high	300+	19+	350+	—-	—-
The Ohio State University					
Extremely low	0 to 29	0 to 3.9	0 to 74	0 to 99	0 to 29
Very low	30 to 39	4.0 to 4.9	75 to 99	100 to 149	30 to 49
Low	40 to 59	5.0 to 5.9	100 to 149	150 to 199	50 to 69
Slightly low	60 to 99	6.0 to 7.9	150 to 174	200 to 249	70 to 79
Optimum	100 to 174	8.0 to 13.9	175 to 224	250 to 324	80 to 124
Slightly high	175 to 199	14.0 to 15.9	225 to 249	325 to 349	—-
High	200 to 249	16.0 to 19.9	250 to 299	350 to 399	125 to 134
Very high	250 to 274	20.0 to 40.0	300 to 349	400 to 499	135 to 174
Excessively high	275 to 299	40.0+	350+	500+	175+

previously taking care to collect a representative sample and removing any slow release fertilizer, if present. Collect an 8 fl oz. volume of substrate. To this volume of substrate, add twice the volume (16 fl oz.) of distilled or deionized water, readily available at most grocery stores. Stir the mixture, then allow it to stand for approximately 15 minutes prior to measuring pH and EC. During this time, calibrate both the pH and the EC meter against standard solutions to assure accuracy of sample measurements. Consult the instructions that came with your meters to know whether you must filter out particulate matter with a coffee filter or cheese cloth prior to reading the pH and EC. Use Tables 1 (pH) and 2 (EC) as guidelines for interpreting the readings of your samples. Out-of-range readings warrant submission of a substrate sample for laboratory analysis. Adjust your fertilization and / or pH control program to help bring salt levels and pH back into acceptable ranges.

Alternative in-house substrate testing procedures include pour through exfiltrate (VTEM method) and the NCSU "squeeze" method (see GrowerTalks _____ for more info on the squeeze). The pour through exfiltrate method offers the advantage of nondestructive sample collection and the potential for submitting the sample to a lab for nutrient analysis after measuring pH and EC or using in-house meters (Cardy meters) for measuring NO_3-N and K. However, guidelines for interpreting the pour through exfiltrate results are not as complete as for saturated paste and 2 : 1 (Tables 2, 3, & 4). The squeeze method also allows the grower the option of in-house NO_3-N and K analysis or submitting the solution for nutrient analysis, but it is a destructive sampling method and some

Table 4. Recommended ranges for essential nutrients in the substrate solution of a soilless substrate using the saturated paste extraction or the pour through exfiltrate method.

	Extraction Method				
	Saturated paste			Pour through exfiltrate	
Element	Cornell University	Michigan State University	Fafard Analytical Services	Cornell University	Virginia Tech University*
NO_3-N	23 to 68	75 to 150	40 to 200	23	50 to 100
NH_4-N	<12	2 to 10	0 to 20	---	50
P	5 to 20	10 to 20	5 to 30	15	3 to 15
K	150 to 350	75 to 150	40 to 200	50	<100
Ca	200 to 400	125 to 175	40 to 200	15	40 to 200
Mg	70 to 200	40 to 60	28 to 80	15	10 to 50
S	---	75 to 125	---	---	75 to 125
Fe	---	1 to 2	0.3 to 3.0	---	0.3 to 3.0
Mn	---	1 to 2	0.1 to 3.0	---	0.02 to 3.0
Zn	---	1 to 2	0.1 to 0.3	---	0.3 to 3.0
Cu	---	0.1 to 0.5	0.01 to 0.3	---	0.01 to 0.5
B	---	0.1 to 0.5	0.05 to 0.5	---	0.5 to 3.0
Mo	---	0.1 to 0.5	0.01 to 0.1	---	0.0 to 1.0
Al	---	---	---	---	0.0 to 3.0
Fl	---	---	---	---	<1
Na	---	<25	---	---	<69
Cl	---	<25	---	---	<71

*The Virginia Tech University (VTEM) pour through standards are for outdoor nursery production, not indoor greenhouse production. They are included as a comparison of greenhouse to outdoor culture recommendations.

crop must be harvested during sampling. Also, as with the VTEM method, interpretive tables are still in the formulation stage of development.

Collecting a plant tissue sample for foliar analysis. Analysis of leaves is the most precise method of measuring micronutrient and macronutrient status of a crop. Routine sampling should be conducted in order to establish a "base line" of nutrition readings for reference in case of a future problem. For problem solving, remember to collect material only from problem areas, and to send a second sample representing a problem-free site concomitant with the problem sample for comparison.

Leaf samples should be collected in the morning (before noon), when plants are not under water stress. Collect the appropriate number of leaves / volume of leaves indicated on the instruction sheet included in the tissue analysis kit from the laboratory you utilize. Leaves that best represent the crop nutrient status are those that have most recently matured; collect new, fully expanded leaves. If no instructions are given for your crop species, collect at least one

cup (8 fl oz.) of leaves with the petioles attached. Collected leaves should be rinsed in distilled or deionized water. Do not use tap water, as the water nutrient content may contaminate the foliar sample. Allow leaves to dry prior to packing for shipment. Leaf samples often rot if enclosed in plastic bags; package in paper bags for best results. Keep samples refrigerated until shipping. Shipping via overnight or next day delivery is helpful in assuring that samples arrive at the lab in good shape.

The Cardy meters mentioned previous can be used for on site testing of plant NO_3-N and K concentrations, usually petiole sap concentrations. This technique has been used for many years to test the nitrogen status of tomato, pepper, and other food crops. In the future, standards for floricultural crops may allow for meaningful in-house testing of crop NO_3-N and K concentrations.

Collecting a water or fertilizer solution sample for laboratory analysis. When collecting a solution sample, allow the water to run long enough to flush all piping prior to collecting the sample. Sample containers should be clean and must not be metallic or have an exposed metal cap; plastic bottles are ideal. A 16 fl oz. sample should be more than sufficient for solution analysis. Keep the sample refrigerated until it is submitted to the lab. Transfer samples to the laboratory as expediently as possible, and avoid prolonged exposure to air. Table 1 outlines irrigation water standards.

In-house analysis of water and fertilizer solution pH and EC. Both EC and pH can be measured in-house on a solution sample. However, accurate measurement of water pH is difficult and may require a longer measuring time than for a fertilizer solution or a substrate extract. This is due to the relatively low buffering capacity of tap water.

In-house analysis of water alkalinity. Water alkalinity is caused by the presence of carbonates, bicarbonates, hydroxides, and other dissolved salts. It is measured by titrating a water sample with an acid (usually dilute sulfuric acid) to an endpoint pH of about 4.6 (varies from 5.1 to 4.5 depending on the indicator dye used and the initial alkalinity). A pH indicator dye (usually bromcresol green plus methyl red) is added to a known volume of water (indicated in the test kit instructions; usually about 8 fl oz.), and acid is added until the solution changes color. With the bromocresol green plus methyl red dye system, the color will change from green to pink.

Most water sources acceptable for greenhouse use will have alkalinity of 0 to 8 meq/L (0 to 400 ppm alkalinity expressed as $CaCO_3$). When looking for a test kit, this is the range that is needed. The level of accuracy does vary from kit to kit; ± 0.4 meq/L (20 ppm alkalinity expressed as $CaCO_3$) is accurate enough for most situations, but more precise kits are available. We have used Hach alkalinity kits #24443-01 (about $30 for 100 tests) and #20637-00 (about $155 for 100 tests, but includes versatile digital titrator) and are satisfied by both (Hach Company, P.O. Box 389 Loveland, Co 80539; phone (800) 227-4224). Although the second model is more expensive, it does have twice the accuracy (± 0.2 meq/L) and also comes with a digital titrator that can be used to measure other solution parameters (using different titrants and indicators) such as water hardness, chlorine, iron, nitrite, and sulfite concentrations.

Interpretation of test results. Most commercial laboratories will send an interpretation along with sample results. However, since laboratories differ is procedures (say saturated paste extraction compared to a 1 : 2 extraction), it may not be possible to use interpretative guidelines from one lab for analyses conducted in another, especially with substrate samples. When interpreting results of substrate analyses, use the interpretations that correspond with the extraction method employed by the lab (Tables 2, 3, & 4).

One point of confusion for many growers is interpreting soluble salts (EC) readings. Interpretation of EC requires knowledge of the testing procedure employed. The two major extraction methods, saturated paste and the 1 : 2

(substrate : water) method are both reported in mho/cm, but at differing decimal places. Saturated paste EC is usually reported as mmho/cm, which is mho $\times$ 10^{-3}/cm, while 1 : 2 EC is usually reported as mho$\times 10^{-5}$/cm (Table 3). As previously mentioned, some EC meters read in µS/cm; remember that 1 µS/cm = 1 µmho/cm (1 mho $\times$ 10^{-6}/cm). Make sure to use the correct decimal placement when using interpretative tables. For example:

1.7 mmho (1.7 mho $\times$ 10^{-3}) = 170 mho $\times$ 10^{-5}

and

170 mho $\times$ 10^{-5} = 1,700 µmho (1,700 mho $\times$ 10^{-6})

Make sure to use the numbers and interpretations that correspond to the extraction method employed.

Foliar analysis interpretation varies from lab to lab and from crop to crop, especially for macronutrients. Consult the interpretation accompanying the sample analysis report for recommendations. Make changes to your fertilization program based on these interpretations.

Use Table 1 as a guide for interpreting water sample results along with laboratory interpretations. If micronutrient and / or sodium and chloride levels are out of range, then these ions could potentially lead to toxicity problems if the water source is used for irrigation. If alkalinity is too high, then you may need to acidify to neutralize the excess bicarbonates in the water for pH control.

All this testing seems like a full-time job. It should be, as prevention of problems is a much more efficient use of an employee's time than remedying problems after they arise.