

Root Medium Chemical Properties

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SUMMARY. Maintaining medium pH and nutrient concentrations at levels acceptable for growth are important for producing vigorous transplants in the shortest time. Medium chemical properties, such as cation-exchange capacity, aeration, liming materials, preplant fertilizer, irrigation-water sources, water-soluble fertilizers, and plant species, interact to affect medium pH and nutrient management. However, these chemical properties do not affect medium pH or the nutrient supply simultaneously or with equal intensity. The objective of this review is to consider key chemical properties of container media and their affects on pH and nutrient management initially and over time.

A Plug or small containerized transplant is the primary method of producing ornamental and vegetable transplants in the United States. Styer and Koranski (1997) estimated that ~25 billion ornamental and vegetable plug transplants were produced in the United States in 1996. The advantage of growing plug transplants include greater transplant uniformity, a reduction in labor when transplanting, and increased production per unit area of bench space in the greenhouse (Nelson, 1991; Styer and Koranski, 1997).

In plug production, the most common component of a plug medium is sphagnum peat (Adams, 1992; Fonteno et al., 1996; Koranski and Kessler, 1991; Styer and Koranski, 1997). In peat-based media, a number of factors interact to affect the nutrient supply in container root media throughout crop production. These factors can include cation-exchange capacity (CEC), lime, preplant fertilizers, irrigation water sources (IWS), and water-soluble fertilizer (WSF) (Argo, 1996). Nutritional management in container root media also is affected by pH management because of the direct effects that many nutrient sources (lime, IWS, WSF)

have on media pH and the indirect effects that pH has on nutrient solubility (Lindsay, 1979) and plant availability (Lucas and Davis, 1961; Peterson, 1981). Finally, plant growth may directly affect medium pH as well as nutrient uptake (Argo, 1996, Argo et al., 1997b; Bailey et al., 1996). However, the nutrient supply is not affected by all factors simultaneously or with equal intensity. The objective of this review is to consider the key chemical properties that affect pH and nutrient management of plants grown in peat-based root media.

Medium pH, nutrient availability, and plant uptake

The pH of the soil solution affects nutrient solubility (Lindsay, 1979) and plant availability (Fig. 1) (Lucas and Davis, 1961; Peterson, 1981). However, mineral soils are affected differently than organic soils and soilless root media. For example, in mineral soils fertilized with P, dicalcium phosphate initially control PO₄-P solubility at high pH (>7.0) and Al and Fe phosphates control PO₄-P solubility at lower pH (<7.0) (Lindsay and Moreno, 1960). Recommendations to lime soils to a pH of 7.0 are based the fact that

maximum P solubility occurs at ~7.0 (Lindsay and Moreno, 1960; Lucas and Davis, 1961). In organic soils and soilless root media, which tend to contain naturally low amounts of Al and Fe, P does not precipitate at low pH but does at high pH (Lucas and Davis, 1961; Peterson, 1981; Yeager and Barrett, 1985). Lucas and Davis (1961) and Peterson (1981) concluded that the optimal pH for PO₄-P nutrition was 5.5 in media without soil, because above this pH, water-soluble PO₄-P concentrations began to decrease. In mineral soils, Ca availability also is reduced at low pH because of the presence of Fe and Al. Soluble Fe and Al readily replace Ca on the soil colloid and on the root surface, both of which reduces Ca uptake (Marschner, 1986). In peat-based media, Peterson (1981) and Styer and Koranski (1997) indicate a reduction in Ca availability at low pH (Fig. 1). Lucas and Davis (1961) in organic soils and Argo and Biernbaum (1996a) in peat-based root media both concluded that low PH did not reduce Ca availability. Instead, the low PH was an indication of a lack of Ca sources applied to the soil or media.

Decreasing nutrient solubility does not necessarily affect plant uptake. For example, Peterson (1981) concludes

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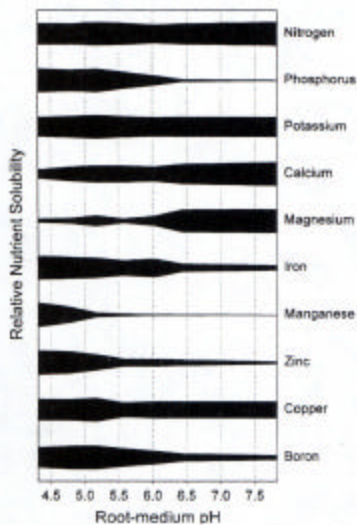


Fig. 1. Relative solubility of nutrients at different pH levels in one peat-based media (Peterson, 1981). The solubility of sulfur and molybdenum were not measured.

that P availability decreases rapidly at a media pH > 5.5 (Fig. 1). However, Adams et al. (1978) found that the tissue P concentration measured in lettuce (*Lactuca sativa* L.) leaves was unaffected by medium pH up to 6.5, even though the concentration of water-soluble $\text{PO}_4\text{-P}$ measured in the medium was 38% of that measured at pH 5.5. Argo and Biernbaum (1996a) found that the tissue P concentration measured in hybrid impatiens (*Impatiens wallerana* Hook F.) was minimally affected by medium pH < 7.6. However, at medium pH > 7.6, tissue P concentrations decreased rapidly.

Medium PH can affect assimilation because of changes in the form of the nutrient in the soil solution. Between a pH of 4.5 to 8.5, there are two forms of P in the soil solution (H_2PO_4^- and HPO_4^{2-}) with an equilibrium constant of 7.2. The H_2PO_4^- form of water-soluble P is 10 times more available to the plant than the HPO_4^{2-} form (Bunt, 1988). Argo and Biernbaum (1996a) concluded that while the concentration of water-soluble $\text{PO}_4\text{-P}$ in the root medium decreased with increasing pH, the effect on tissue P was minimal until the form of the water-soluble $\text{PO}_4\text{-P}$ changed to a less-available form. Nitrogen uptake can be influenced by the N form (Barker and Mills, 1980; Marschner, 1986), which in turn is affected by nitrification rate.

The critical pH for the inhibition of nitrification in soilless media was found to be in a range from 5.4 to 5.7 (Argo and Biernbaum, 1997a; Lang and Elliott, 1991; Niemiera and Wright, 1986). Argo and Biernbaum (1997a) and Niemiera and Wright (1986) found that above this critical pH range, minimal $\text{NH}_4\text{-N}$ concentrations were measured in the medium, even when applying up to a 100% $\text{NH}_4\text{-N}$ WSF, while below the critical pH range, $\text{NH}_4\text{-N}$ began to accumulate in the medium with a corresponding decrease in the $\text{NO}_2\text{-N}$ concentration. Argo and Biernbaum (1997a) found an increase in shoot-tissue N concentrations of hybrid impatiens with decreasing medium pH, but concluded that medium pH in itself did not affect N uptake, but rather medium pH affected the nitrification rate.

Plant species differ in their ability to take up nutrients at a given pH. Nelson (1994) concludes that geraniums (*Pelargonium xhortorum* Bailey) and African marigolds (*Tagetes erecta* L.) are very efficient accumulators of Fe and Mn, and require a higher pH media (6.5) to prevent toxicity problems. Biernbaum et al. (1988) found that below a medium pH of 5.8, geraniums were susceptible to Fe and Mn toxicity, while at a pH > 5.8, Fe and Mn did not accumulate in the tissue. In comparison, Nelson (1994) concludes that pansies (*Viola xwittrockiana* Gams), petunias (*Petunia xhybrida* Vilm), snapdragons (*Antirrhinum majus* L.), and vinca [*Catharanthus roseus* (L.) G. Don] have difficulty taking up Fe, and require a lower pH media (5.5) to prevent deficiency problems.

Cation exchange capacity

It has been suggested that an adequate CEC is desired in soilless media to buffer it from sudden changes in pH and nutrient concentrations (Biernbaum, 1992; Bunt, 1988; Nelson, 1991; Styer and Koranski, 1997). The CEC of organic materials such as peat or bark often are associated with pH and nutrient buffering capacity. The CEC of organic materials are due to the pH-dependent exchange of cations with H^+ from organic acid functional

groups on the particles. Helling et al. (1964) found that the CEC of a sphagnum peat increased by 140 $\text{meq}\cdot\text{L}^{-1}$ as the pH increased from 3.5 to 8.0. The ratio of H^+ to cations bound to the peat also changes with increasing pH. For example, one type of acid sphagnum peat was 100%, 56%, 30%, or 0% H^+ saturated at a pH of 3.7, 4.5, 5.5, or 7.8, respectively (Lucas et al., 1982; Puustjarvi and Robertson, 1975). Bunt (1988) reported that the CEC of peat indicates the potential for divalent ions adsorption (primarily Ca and Mg), with most monovalent cations ($\text{NH}_4\text{-N}$, K, Na) remaining water-soluble.

The CEC of organic materials such as peat on a weight basis is much higher than that of mineral soils. For example, Lucas (1982) reported that the CEC of a sphagnum peat was 1000 $\text{meq}\cdot\text{kg}^{-1}$ while that of a loam mineral soil was 120 $\text{meq}\cdot\text{kg}^{-1}$. However, because of the low bulk density of the sphagnum peat, the effective CEC measured on a volume basis was 40% less than that of the mineral soil (80 for the peat vs. 140 $\text{meq}\cdot\text{kg}^{-1}$ for the mineral soil). Puustjarvi (1982) reported a linear increase in the CEC of sphagnum peat from 45 to 130 $\text{meq}\cdot\text{kg}^{-1}$ as the degree of decomposition increased from H1 to H5 as measured with the von Post scale (Puustjarvi and Robertson, 1975). The overall increase in CEC was associated with both a higher CEC of the more degraded peat itself (H1 peat was 1000 $\text{meq}\cdot\text{kg}^{-1}$, H5 peat was 1240 $\text{meq}\cdot\text{kg}^{-1}$) and an increase in the bulk density with greater decomposition (H1 peat was 45 $\text{kg}\cdot\text{m}^{-3}$, H5 peat was 105 $\text{kg}\cdot\text{m}^{-3}$).

Other materials such as perlite, polystyrene, or rockwool (RW) have minimal CEC and are included in container media to increase aeration or water-holding capacity (Argo and Biernbaum, 1994; Nelson, 1991). Bark, calcined clay, coconut coir, and expanded vermiculite are added to soilless media for aeration and water-holding capacity, but each also has significant CEC (Argo and Biernbaum, 1997b; Bunt, 1988; Nelson, 1991).

Root medium aeration

Root-medium aeration is important when plants are produced in containers (Bunt, 1988; Deboodt and Verdonck, 1971; Fonteno, 1996; Milks et al., 1989). From a chemical property standpoint, O_2 partial pressure is important because it affects the redox potential of the medium, which directly affects nitrification and denitrification rates and the solubility and availability of micronutrients (Lindsay, 1979; Marschner, 1986). Hanan (1964) measured O_2 partial pressures (PP) in cut flower beds ranging in depths from 8 to 60 cm. and containing media with various percentages of leaf mold, loam, peat, perlite, sand, and silt. At the 5 to 7 cm depth within the beds, O_2 partial pressure ranged from 9.8 to 21 kPa (ambient O_2 partial pressures are \sim 21 kPa), with the highest O_2 partial pressure (21 kPa) measured in the beds containing a soilless root media (1 peat : 1 perlite [v:v]). Paul and Lee (1976) found that the oxygen diffusion rate correlated well with the growth of chrysanthemums (*Dendranthema grandiflora* Ramat.) in 13 root media. Fifteen percent air-filled porosity at container capacity was suggested for optimum oxygen diffusion rates and plant growth in 12-cm-tall pots. Argo et al. (1996) found that the O_2 partial pressure in three soilless medium in 12-cm-tall pots with chrysanthemum was 21 kPa. Irrigating the pots using either drip irrigation or subirrigation had minimal effect on O_2 partial pressure measured at three levels in the pot.

Medium CO_2 partial pressure also is important because of its effect on solution pH and nutrient solubility. Lindsay (1979) reported that for soils at equilibrium with $CaCO_3$ (calcareous), the measured pH varied from 7.3 to 8.5, depending on the CO_2 partial pressure. Soil pH values of 8.5 in calcareous soils can be obtained only when the partial pressure of CO_2 in the soil is similar to that measured in the ambient atmosphere (30 to 40 Pa). Because of factors such as root respiration, microbial activity, and organic matter degradation, average CO_2 partial pressure in the soil atmosphere are commonly reported at 300 Pa, or 10

times higher than that measured in the air (Lindsay, 1979).

In container-grown plants, root respiration is thought to be higher than that of plants grown in mineral soils because of faster plant growth rates (Paul and Lee, 1976) and higher microbial respiration because of the high organic matter content of most soilless container media (Bunt, 1988). Argo et al. (1996) found that the CO_2 partial pressure of three soilless medium in 12-cm-tall pots with chrysanthemum was 63 Pa (ambient CO_2 partial pressure was 46 Pa). Irrigating the pots with water containing alkalinity at 320 mg $CaCO_3/L$ caused an increase in medium CO_2 partial pressure up to 1600 Pa. The high medium CO_2 partial pressure measured after the irrigation was not persistent, and within 180 min, returned to levels averaging 45% higher (100 Pa) than that measured before the irrigation. In comparison, when reverse osmosis purified water (alkalinity of <20 mg $CaCO_3/L$) was used instead of well water, the large increase in medium CO_2 did not occur. This indicated that the alkalinity in the irrigation water was the source of the CO_2 .

In general, soilless container root media maintain high air-filled porosities in pots (Deboodt and Verdonck, 1971; Fonteno, 1996; Milks et al., 1989). This high porosity after the irrigation allows for rapid CO_2 dispersion and reestablishment of O_2 partial pressures to near pre-irrigation levels. In small containers such as plugs, air-filled porosity is less than in pots (Fonteno, 1996; Milks et al., 1989). However, small containers tend to dry out quickly, which would also lead to a high air-filled porosity and O_2 and CO_2 partial pressures similar to that of ambient levels.

Liming materials

Liming materials ($CaCO_3$, $MgCO_3$, $Ca(OH)_2$, and $Mg(OH)_2$) are added to a soilless root medium to neutralize acidity, increase pH to a level acceptable for plant growth, and provide a source of Ca (and Mg if dolomitic lime). Incorporating sufficient lime into a soilless root medium

to obtain an initial pH range of 5.5 to 6.4 is recommended (Nelson, 1991; Peterson, 1981; Warncke and Krauskopf, 1983). The amount of liming material required to obtain an equilibrium pH of \sim 6 in the root medium depends not only on the components used to produce the medium, but also on the liming material's reactivity and particle size (Argo and Biernbaum, 1996b; Chapin, 1980; Gibaly and Axley, 1955; Schollenberger and Salter, 1943; Sheldrake, 1980; Williams et al., 1988) as well as the surface area of the liming material (Parfitt and Ellis, 1966).

Argo and Biernbaum (1996b) found that the lime that reacted initially to increase the medium's pH had minimal effect on root-medium Ca (or Mg if dolomitic lime) concentrations measured with the saturated media extract (Warncke, 1986). Water-soluble Ca and Mg concentrations remained below levels considered acceptable for plant growth (Warncke and Krauskopf, 1983) even though the pH of the peat increased, indicating that the lime was still reacting. Argo and Biernbaum (1996a) proposed that not all the liming material incorporated into a soilless root medium may have reacted once an equilibrium pH is reached. Instead, it was found that a portion of the liming material remained unreacted in the medium after the equilibrium pH was reached. The residual lime fraction was found to have an important role in pH, Ca, and Mg buffering under acidic conditions (Argo and Biernbaum, 1996a, 1997b). It can be speculated that the ratio of reacted : residual lime contained in the medium depends on the reactivity of the liming material.

Preplant fertilizers

In general, unamended acidic peat-based root media do not contain sufficient nutrients for sustained plant growth (Bunt, 1988; Nelson, 1991). Current recommendations for the incorporation of fertilizer materials other than liming materials into a soilless root media before planting include sources of N, NPO_4-P , K, Ca, Mg, SO_4-S , and trace elements (Table 1). These

Table 1. Recommended types and incorporation rates for lime and preplant fertilizers. The nutrient content of the individual fertilizer salts was estimated from Hawkes et al. (1985) and Young and Johnson (1982).

	Cornell Peat-lite A and B ^z	Cornell Foliage Media ^z	Pennsylvania State Media ^y	Nelson Potting Media ^x	GCRI-1 Potting Media ^w	GCRI-2 Potting Media ^w
All incorporation rates in kg·m ⁻³ of root media						
	0.9 KNO ₃	0.9 KNO ₃	0.6 KNO ₃	0.6 KNO ₃ ^t	0.8 KNO ₃	0.8 KNO ₃
	0.6 0-8.6-0 ^v	0.6 0-8.6-0 ^v	1.2 0-8.6-0 ^v	0.6 Ca(NO ₃) ₂	0.4 NH ₄ NO ₃	0.9 urea-formaldehyde
Preplant Fertilizers		1.6 10-4-8 ^u	0.6 20-8-15 ^u	0.3 MgSO ₄ ^t	1.5 0-8.6-0 ^v	1.5 0-8.6-0 ^v
				2.7 0-8.6-0		
				Or		
				1.3 0-19.8-0		
				0.9 gypsum		
Lime rate (kg·m ⁻³)	3.0 ground limestone	4.9 dolomitic limestone	3.0 dolomitic limestone	6.0 dolomitic limestone	2.25 each ground and dolomitic limestone	2.25 each ground and dolomitic limestone
Total N	0.12	0.28	0.2	0.18	0.25	0.45
PO ₄ -P	0.05	0.12	0.15	0.23	0.13	0.13
K	0.33	0.46	0.31	0.22	0.29	0.29
Ca	0.12	0.12	0.23	0.64	0.29	0.29
Mg	0.00	0.00	0.00	0.03	0.00	0.00
SO ₄ -S	0.07	0.07	0.14	0.35	0.18	0.18

^zBoodley and Shedrake, 1972^yWhite, 1974^xNelson, 1991^wGlasshouse Crops Research Institute (Bunt, 1988).^vN-P-K content of single superphosphate (3Ca(H₂PO₄)₂·H₂O+7CaSO₄·2H₂O+2HF).^uN-P-K content of blended fertilizer. The exact formulation of this fertilizer is unknown and is not included in the nutrient calculation for Ca, Mg, or SO₄-S.^tThe incorporation of these materials is optional (Nelson, 1991) but is included in the nutrient content calculations.^sN-P-K content of triple superphosphate (10Ca(H₂PO₄)₂·H₂O+2HF).^rThe lime recommendation is not included in the nutrient content calculation.

guidelines come from the early soilless container media recommendations, including the Cornell peat-lite media (Boodley and Sheldrake, 1972), the Pennsylvania State University media (White, 1974), Glasshouse Crops Research Institute media (Bunt, 1988), and floriculture textbooks (Nelson, 1991). The most commonly recommended macronutrient preplant fertilizers include Ca(NO₃)₂, KNO₃, super phosphate or triple superphosphate, and gypsum (Bunt, 1988; Nelson, 1991; Warncke and Krauskopf, 1983).

The N and K content of preplant fertilizers is small compared to the total amount applied to a crop. For example, Yelanich (1991) found that a minimum of 1.0 to 1.5 g mineral N/pot was required to produce a poinsettia in a 15- x 12-cm-wide (1.3-L) pot in 16 weeks. An initial incorporation of 0.17 kg mineral N/m³ would supply 0.22 g mineral N to the 1.3-L pot, or 15% to 22% of the total N requirement. In comparison, Ca, Mg, PO₄-P and SO₄-S content of the preplant fertilizers may

represent a large percentage, in some cases up to 100%, of the total amount applied to the crop.

A number of studies have tested the persistence of preplant fertilizer in peat-based root media. Yeager and Barrett (1985) found that soilless media have a limited ability to retain PO₄-P against leaching. Biernbaum et al. (1995) demonstrated that all macronutrients (N, P, K, Ca, Mg, S) supplied from one blended preplant fertilizer leached very quickly from peat-based medium when placed in pots under mist irrigation. The rate of nutrient loss could be predicted by quantifying the volume of water leached from the pot. While there were minor differences in rate of loss between the individual nutrients, The concentration of all nutrients were below acceptable levels for plant growth by the time two container capacities were leached from the pot. Argo and Biernbaum (1996a, 1996b) concluded that the nutrients from preplant fertilizer (such as gyp-

sum and 0-46-0) were soluble and easily leachable.

Fertilizer salt stratification within the pot also affects the availability of nutrients from preplant fertilizers. Fertilizer salt stratification within the pot is thought to be caused by evaporation from the root-medium surface (Argo and Biernbaum, 1994, 1995) or a water front moving into the root medium with each irrigation (Yelanich, 1995) and occurs with all methods of irrigation. Argo and Biernbaum (1994, 1995 1996a, 1996b) found that preplant fertilizer moved rapidly from the root zone (lower 2/3 of media in the pot) and into the top layer (top 2-cm of media in the pot) within a few days after planting. With flood subirrigation, the nutrients in the top layer were unavailable to the plant, and the salt concentration in the top layer continued to increase even when the nutrient levels in the root zone were below levels considered acceptable for growth (Argo and Biernbaum, 1994, 1995 1996a, 1996b). With top

watering, the fertilizer salts contained in the top layer were found to gradually moved down into the root zone, buffering the medium from

sudden changes in nutrient concentrations when application of WSF were stopped (Argo and Biernbaum, 1995). Fertilizer salt stratifica-

tion also has been demonstrated in 406 plug trays (Argo and Biernbaum, unpublished data).

Table 2. Suggested minimum (Min) and maximum (Max) acceptable pH, electrical conductivity (EC), alk alinity, nutrient concentration and sodium adsorption ratio (SAR) for irrigation water used for greenhouse plant production. Units of measure are EC, $\text{dS}\cdot\text{m}^{-1}$; alkalinity, mg CaCO_3/L ; Ca, Mg, $\text{SO}_4\text{-S}$, Na, Cl, B and F, $\text{mg}\cdot\text{L}^{-1}$.

	Biernbaum (1994) ^z		Fafard (1996) ^y		Gabriels (1978)		Nelson (1991) ^x		Rose et al. (1995)		Scotts (1996) ^w		Sungro (1996) ^v	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
PH	5.5	7.0	5.0	7.0	NA	NA	NA	NA	5.0	7.0	NA	NA	5.0	7.5
EC	0.2	0.8	0	1.0	0	0.85	0	0.75	0	1.5	0.2	1.3	0	1.0
Alkalinity	40	160 ^u	0	100	NA	200	0	40	0	100	40	150 ^t	75	150 ^s
Ca	25	75	40	120	0	120	NA	NA	40	120	25	100	40	80
Mg	10	30	6	24	0	25	NA	NA	6	24	15	50	20	40
$\text{SO}_4\text{-S}$	0	40	NA	NA	NA	NA	NA	NA	0	80	NA	NA	30	60
Na	0	20	0	50	NA	NA	0	70	8	50	0	50	0	80
Cl	0	20	0	20	0	70	0	100	0	140	0	70	0	80
B	0	0.1	0	0.5 ^f	0	0.75	0	1.0 ^f	0.2	0.8	0	0.5 ^f	0	0.5
F	0	0.1	0	0.75 ^f	0	1.0	0	0.5 ^f	0	1.0	0	1.0 ^f	0	1.0
SAR	NA	NA	0	4	NA	NA	NA	NA	0	4	NA	NA	NA	NA

^{NA}Not Available

^zSuggested target values from water analysis. A broader range of acceptable values was also presented.

^yFafard Analytical Services, Athens, Ga

^xSuggested concentrations at which no nutritional problem should occur.

^wScotts Analytical Services, Allentown, Pa.

^vSun Gro Analytical Services, Warwick, N.Y.

^uAverage suggested alkalinity concentration. The actual acceptable suggested alkalinity concentrations are dependent on the container size. With plugs (in mg CaCO_3/L), 40 to 80; while with 15-cm pots, 120 to 180

^tAverage suggested alkalinity concentration. The actual acceptable suggested alkalinity concentrations are dependent on the container size. With plugs (in mg CaCO_3/L) 40 to 120; bedding flats, 40 to 140; 10- to 12-cm pots and large bedding flats, 40 to 160; and 15-cm pots or larger, 60 to 200.

^sIf plugs are grown, alkalinity values on the lower end to the range are suggested.

^fThe concentration that can cause toxicity in certain crops may be much lower.

Irrigation-water sources

The IWS is often considered one of the most important factors in container plant production (Bailey, 1997; Biernbaum, 1994; Bunt, 1988; Lang, 1996; Nelson, 1991; Reed, 1997; Styer, 1996; Styer and Koranski, 1997). Recommendations for acceptable levels of pH, alkalinity, electrical conductivity (EC), and nutrients concentrations exist (Table 2). In general, factors used to characterize an IWS are alkalinity, Ca, Mg, $\text{SO}_4\text{-S}$, Na, Cl, B, and F concentrations and sodium adsorption ratio (SAR) (Argo et al., 1997a).

Several studies have been conducted to quantify the nutrient content of different sources of irrigation water in the United States. Based on 4300 samples, Argo et al. (1997a) found that the overall median water source in the United States had a pH of 7.1; an EC at $0.4 \text{ dS}\cdot\text{m}^{-1}$; an alkalinity of 130 mg CaCO_3/L ; (in $\text{mg}\cdot\text{L}^{-1}$) 40 Ca, 11 Mg, 8 $\text{SO}_4\text{-S}$, 13 Na, 14 Cl, 0.02 B, and <0.01 F; a Ca : Mg ratio of 3.2 and a SAR of

0.7. These values were also quantified for the 10 leading states in floriculture production. More limited studies that quantified IWS were conducted by Ludwig and Peterson (1984) (all nutrients) and Reddy et al. (1994) (only $\text{SO}_4\text{-S}$)

Different IWS require different types of management in order to maintain an acceptable pH in the root medium (Bunt, 1988; Nelson, 1991; Styer and Koranski, 1997; Vetanovetz and Hulme, 1991). The suggest range for IWS pH and alkalinity is 5 to 7 and 40 to 100 mg CaCO_3/L , respectively. Argo et al. (1997a) suggest that IWS having pH and alkalinity levels outside these ranges are not detrimental to plant growth as long as the pH of the medium is maintained within an acceptable range. Argo and Biernbaum (1996a) demonstrated that IWS alkalinity, not pH, is the primary factor influencing medium pH management. Irrigation water containing large amounts of alkalinity (>250 mg CaCO_3/L) commonly are treated by adding strong mineral acid (HNO_3 ,

H_2SO_4 , or H_2PO_4). Researchers recommend adding sufficient acid to reduce the alkalinity to 40 to 120 mg CaCO_3/L (depending on the crop) or reduce the solution pH to 6.0 to 6.5 (Bunt, 1988; Nelson, 1991; Spurway and Wildon, 1938; Whipker et al., 1996). Alternative sources such as rainwater or reverse osmosis (RO) purified water are gaining popularity because of their low alkalinity (Biernbaum, 1992). However, rainwater and RO water contain minimal nutrients.

Water-soluble fertilizers

The type of WSF applied to a root medium affects pH and nutrient concentrations two ways: directly, by nutrients applied to the root medium, and indirectly, by acidification of the rhizosphere pH. Fertilization with $\text{NH}_4\text{-N}$ causes the medium pH to decrease because of H^+ secretion during root uptake and nitrification of the $\text{NH}_4\text{-N}$ to the $\text{NO}_3\text{-N}$ form, which also releases H^+ . In comparison, fertilization with $\text{NO}_3\text{-N}$ causes the medium pH to increase because of OH^- or HCO_3^- secre-

tion associated with balancing ion uptake (Barker and Mills, 1980; Bunt, 1988; Hawkes et al., 1985; Marschner, 1986; Nelson, 1991; Vetanovetz and Hulme, 1991).

Table 3 contains the analysis from several commercially available WSF. Many commercially available WSF contain a high percentage of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ but little Mg and no Ca [examples: 21-7-7 Acid Special, 100% $\text{NH}_4\text{-N}$, 0.05% Mg, 0% Ca; 20-20-20 General Purpose, 72% $\text{NH}_4\text{-N}$, 0.05% Mg, 0% Ca; 20-10-20 Peatfite Special, 40% $\text{NH}_4\text{-N}$, 0.05% Mg, 0% Ca]. Because of the high $\text{NH}_4\text{-N}$ content, the reaction produced by these WSF are acidic [21-7-7 = 0.78 kg acidity/kg, 20-20-20 = 0.30 kg acidity/kg, 20-10-20 = 0.21 kg acidity/kg]. In comparison, WSF that produce neutral or basic reactions in the root medium are typically low in $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ but high in Ca and $\text{NO}_3\text{-N}$ and sometimes Mg (examples: 17-5-17, 20% $\text{NH}_4\text{-N}$, 3% Ca, 1% Mg, 0 kg acidity/kg; 15-5-15, 28% $\text{NH}_4\text{-N}$, 6% Ca, 3% Mg, 0.07 kg basicity/kg; 13-2-13 Plugcareplus, 5% $\text{NH}_4\text{-N}$, 6% Ca, 3% Mg, 0.19 kg basicity/kg; 15-0-15 Dark Weather Special, 13% $\text{NH}_4\text{-N}$, 11% Ca, 0.21 kg basicity/kg).

Nutrient solution (NS)

The NS is the combination of the IWS and WSF. The term NS should be used whenever discussing fertilization of any crop because whenever WSF is applied, it is in conjunction with an IWS, that also affects the pH and nutrient concentrations in the medium. For example, Argo and Biernbaum (1996a) found that the an acceptable medium pH of ~ 6.0 could be maintained in the medium with a 50% $\text{NH}_4\text{-N}$ WSF and a IWS alkalinity of 320 mg $\text{CaCO}_3\text{/L}$, a 25% $\text{NH}_4\text{-N}$ WSF and a IWS alkalinity of 120 mg $\text{CaCO}_3\text{/L}$, or a 3% $\text{NH}_4\text{-N}$ WSF and a IWS alkalinity of <20 mg $\text{CaCO}_3\text{/L}$. Thus the term acidic, neutral, or basic does not apply to the WSF because in each case, the overall reaction produced by the

NS was neutral. Low levels of nutrient in the IWS (particularly Ca, Mg and $\text{SO}_4\text{-S}$) are often supplemented with WSF containing those nutrients. Argo and Biernbaum (1996a, 1997a) found that the Ca, Mg, and $\text{SO}_4\text{-S}$ concentration measured in the root medium and shoot-tissue were better quantified by using the total concentration measured in the NS rather than discussing the concentration of those ions in the IWS or WSF separately.

Species effects

The plant may also affect pH management. With agronomic crops, some species are less susceptible to lime-induced iron chlorosis because of the plants ability to lower the rhizosphere pH through root exodation of H^+ and organic acid (citrate, malate) when grown in calcareous soils (pH > 7.8). In comparison, species that do not lower the rhizosphere pH are much more susceptible to lime-induced iron chlorosis (Marschner, 1986). Among cultivars of the same species, there may be considerable differences in the susceptibility of lime-induced iron chlorosis because of differences in the cultivars ability to lower the rhizosphere pH (Froehlich and Fehr, 1981; Saxena and Sheldrake, 1980). It was not determined if crops that lowered the rhizosphere pH in high pH soils were more susceptible to Fe or Mn toxicity in acid soils.

In vegetable and ornamental plug production, much less is known of species or cultivar effects on medium pH and the resulting differences in nutrient uptake. In laboratory experiments on germinating seedlings, Bailey et al. (1996) found that substrate pH varied from 4.5 with tomatoes (*Lycopersicon esculentum* Mill.) to 7.5 with zinnia (*Zinnia elegans* Jacq.) under the same conditions. In greenhouse experiments, Argo et al. (1997) found that the average root-medium pH of ten potted plant species given the same WSF (20N-4.3P-16.6K Peatlite Special [Scotts, Marysville, Ohio]) ranged

from 5.1 with African violets (*Saintpaulia ionantha* Wendl.) to 6.5 with gerbera (*Gerbera jamesonii* H. Bolus ex Hook.f.). Argo (1996) found up to a 1.7 pH unit difference in the media of seven bedding plant species given the same WSF. In general, geraniums had the lowest medium pH while pansies and petunias had the highest medium pH.

Interactive effects of multiple nutrient sources

The factors discussed in this review (CEC, liming materials, preplant fertilizer, NS, and plant species) interact to affect the nutrient supply initially and over time. However, these factors do not affect the nutrient supply simultaneously or with equal intensity. Argo (1996) proposed that the relative importance of the nutrient sources for pH buffering and calcium and magnesium nutrition in peat based media were: nutrient solution (IWS and WSF) > plant species > residual lime > preplant fertilizers > root media. This conclusion is based on a number of experiments testing the interactive effects of nutrient sources on pH and nutrient management in container grown crops.

With Ca nutrition as an example, Argo and Biernbaum (1996a, 1997a) demonstrated that there was a linear increase in the shoot-tissue Ca concentrations as the concentration of Ca in the nutrient solution (NS) (composed of both the IWS and WSF) increased from 20 to 210 mg L^{-1} with hybrid impatiens. Other ions contained in the NS (NH_4 , NO_3 , K, SO_4) did not appear to affect Ca. Argo (1996) found a linear increase in shoot-tissue Ca in eight other bedding plant species in addition to impatiens. However, there were differences in the shoot-tissue Ca concentrations of the nine species. Given the same NS, impatiens were found to contain the highest shoot tissue Ca, while Nonstop begonia (*Begonia stuberhybrida* Voss), pansies,

Table 3. macronutrient information on commercially available water-soluble fertilizers.

Formula ^z	Elemental Analysis (%)								Reaction		Macronutrient Salts
	$\text{NH}_4\text{-N}$	$\text{NO}_3\text{-N}$	Urea	P	K	Ca	Mg	Slope ^y	Type	Strength	
21-7-7	9.1	-	12.0	3.1	5.8	-	0.1	179	A	0.78	KCl, MgSO_4 , $\text{NH}_4\text{H}_2\text{PO}_4$, $(\text{NH}_4)_2\text{SO}_4$,

											urea
25-10-10	1.8	2.7	20.6	4.4	8.3	-	0.1	625	A	0.52	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
30-10-10	2.2	3.2	24.7	4.4	8.3	-	0.1	714	A	0.52	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
9-45-15	9.0	-	-	19.7	12.4	-	0.1	83	A	0.47	KCl, NH ₄ H ₂ PO ₄
27-15-12	3.0	3.8	20.3	6.6	9.9	-	0.1	455	A	0.47	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
20-2-20	7.1	5.9	7.1	0.9	16.5	-	1.0	161	A	0.41	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , (NH ₄) ₂ SO ₄ , urea
15-30-15	5.8	4.5	4.8	13.1	12.4	-	0.1	161	A	0.34	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
20-19-18	3.8	5.2	11.1	8.3	14.9	-	0.2	250	A	0.32	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
25-5-20	1.2	6.0	17.9	2.2	16.5	-	0.1	385	A	0.29	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
20-20-20	3.9	6.2	9.9	8.7	16.5	-	0.1	250	A	0.29	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
10-30-20	4.4	5.7	-	13.1	16.5	-	0.6	104	A	0.21	KH ₂ PO ₄ , KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄
20-10-20	8.0	12.0	-	4.4	16.5	-	0.1	152	A	0.21	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , NH ₄ NO ₃
25-0-25	-	7.3	17.8	-	20.7	-	0.1	333	A	0.20	KN ₀₃ , urea
15-20-25	4.0	7.0	4.0	8.7	20.7	-	0.1	147	A	0.15	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
15-15-15	3.0	7.2	4.8	6.6	12.4	-	0.1	156	A	0.13	KN ₀₃ , MgSO ₄ , NaNO ₃ , NH ₄ H ₂ PO ₄ , urea
20-15-25	2.8	7.8	9.4	6.6	20.7	-	0.2	238	A	0.12	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
15-16-17	4.5	10.5	-	7.0	14.0	-	0.1	147	A	0.08	KN ₀₃ , MgSO ₄ , NaNO ₃ , NH ₄ H ₂ PO ₄ , NH ₄ NO ₃
20-5-30	1.0	8.8	10.2	2.2	24.8	-	0.1	227	A	0.08	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
15-11-29	2.2	8.6	4.3	4.8	24.0	-	0.1	147	A	0.05	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
15-5-25	4.2	10.8	-	2.2	20.7	-	1.3	114	A	0.04	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
15-10-30	2.2	9.1	3.7	4.4	24.8	-	0.1	143	A	0.04	KN ₀₃ , MgSO ₄ , NH ₄ H ₂ PO ₄ , urea
20-0-20	5.0	15.0	-	-	16.5	6.0	-	147	A	0.02	Ca(NO ₃) ₂ , KN ₀₃ , NH ₄ NO ₃
17-5-17	3.4	13.6	-	2.2	14.1	3.0	1.0	147	A	0.00	Ca(NO ₃) ₂ , KN ₀₃ , Mg(NO ₃) ₂ , NH ₄ H ₂ PO ₄
15-5-15	1.2	11.8	2.1	2.2	12.4	5.0	2.0	128	B	0.07	Ca(NO ₃) ₂ , KN ₀₃ , Mg(NO ₃) ₂ , NH ₄ H ₂ PO ₄
13-2-13	0.6	12.8	-	0.9	10.7	6.0	3.0	147	B	0.19	Ca(NO ₃) ₂ , KN ₀₃ , Mg(NO ₃) ₂ , Urea Phosp.
14-0-14	1.2	12.9	-	-	10.2	5.9	2.9	116	B	0.21	Ca(NO ₃) ₂ , KN ₀₃ , Mg(NO ₃) ₂
15-0-15	-	13.0	2.0	-	12.4	11.0	-	135	B	0.21	Ca(NO ₃) ₂ , KN ₀₃ , urea

^zN-P₂O₅-K₂O formula

^yUnits for EC slope are Mg?L⁻¹ N per 1 dS?m⁻¹.

^xThe potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per kg of fertilizer.

vinca, and wax begonias (*Begonia xsemperflorens-cultorum* Hort.) contained the lowest shoot-tissue Ca.

The lime that reacted initially to increase the medium's pH was found to have a minimal effect on root-medium Ca concentrations (Argo and Biernbaum, 1996b). However, the residual lime did influence long-term Ca management. Both root-medium and shoot tissue Ca concentrations were increased when given an acidic NS containing low Ca and Mg. Reducing the acidity of the NS by reducing the NH₄-N content and increasing the alkalinity concentration in the IWS negated the residual lime as a Ca source (Argo and Biernbaum, 1996a, 1997a).

Preplant fertilizer other than lime (gypsum, triple superphosphate, Ca(NO₃)₂) did increase the initial Ca concentration in the medium. However, the Ca supplied with the preplant

fertilizers was found to be very soluble and easily removed from the root zone because of leaching or salt stratification within the pot (Argo and Biernbaum, 1996b; Biernbaum et al., 1995). With subirrigation, the preplant fertilizers had no effect on root-zone nutrient concentrations for longer than one week (Argo and Biernbaum, 1996a, 1996b, 1997a). With top watering, nutrients contained in the top layer would probably buffer root-zone nutrient concentrations (Argo and Biernbaum, 1995). The duration of the buffering would depend on the amount of water leached from the pot.

Historically, root media has been the primary focus of nutrient management and buffering in container grown crops (Biernbaum, 1992; Bunt, 1988; Nelson, 1991; Styer and Koranski, 1997). Argo and Biernbaum (1997a) found that root media CEC had minimal influence on both short term and

long term Ca management. The Ca concentrations in the root medium and shoot tissue of plants grown in a 70% rockwool/30% perlite medium were similar to those of plants grown in a 70% highly degraded peat/30% perlite medium. However, root medium did influence lime incorporation rate which may affect the amount of residual lime remaining in a medium once the equilibrium pH was reached.

Conclusion

One key to successful plug transplant growing is pH and nutritional management (Styer and Koranski, 1997). Optimizing the pH and nutritional management of container grown crops such as plugs requires an understanding of how a variety of factors interact to affect nutrient supply and uptake initially and over time. Changing one factor of a nutritional program requires a reevaluation of all other fac-

tors. For example, a new water source may require a reduction in the $\text{NH}_4\text{-N}$, content of the WSF (which also may affect the Ca and Mg content).

The key to nutritional research is reproducibility. Because of the interactive effect of the various chemical properties, all aspects of nutritional management including media (components and percentages or manufacturer), lime (Ca and Mg content, grind size, incorporation rate, and manufacture), IWS (pH, alkalinity, and nutrient concentration), WSF (macro- and micronutrient content, $\text{NH}_4\text{-N}$ percentage, and nutrient salts) and plant species and cultivar should be included in the material and methods to allow for consistent and reproducible result.

Further study is needed to determine the effects that other components, such as vermiculite or bark, have on the pH and nutrient buffering capacity of a soilless root medium. Better quantification of the effects that different plant species have on pH and nutrient management is needed. Finally, little research has been done to characterize the reactivity of different liming materials and their effects on residual lime content or to quantify the acidic-basic reactions of various WSF and their effects on medium pH management. Future experiments should be performed with consideration of the interactive effects that many factors have on medium pH and nutrient management.

Literature cited

- Adams, R. 1992. Make your own plug media. *GrowerTalks* 56(6):99-101.
- Adams, P., C.J. Graves, and G.W. Winsor. 1978. Some responses of lettuce, grown in beds of peat, to nitrogen, potassium, magnesium, and molybdenum. *J. Hort. Sci.* 53:275-281.
- Argo, W.R. 1996. Root-zone pH, calcium, and magnesium management in peat-based container media. PhD diss., Michigan State Univ., East Lansing.
- Argo, W.R. and J.A. Biernbaum. 1994. Irrigation requirements, root-medium pH, and nutrient concentrations of Easter lilies grown in five peat-based media with and without an evaporation barrier. *J. Amer. Soc. Hort. Sci.* 119:1151-1156.
- Argo, W.R. and J.A. Biernbaum. 1995. Root-medium nutrient levels and irrigation requirements of poinsettias grown in five root media. *HortScience* 30:535-538.
- Argo, W.R. and J.A. Biernbaum. 1996a. The effect of lime, irrigation-water source, and water-soluble fertilizer on root-zone pH, EC, and macronutrient management of container root media with impatiens. *J. Amer. Soc. Hort. Sci.* 121:442-452.
- Argo, W.R. and J.A. Biernbaum. 1996b. Availability and persistence of macronutrients from lime and preplant nutrient charge fertilizers in peat-based root media. *J. Amer. Soc. Hort. Sci.* 121:453-460.
- Argo, W.R. and J.A. Biernbaum. 1997a. Lime, water source, and fertilizer nitrogen form affect medium pH and nitrogen accumulation and uptake. *HortScience* 32(1):71-74.
- Argo, W.R. and J.A. Biernbaum. 1997b. The effect of root media on root-zone pH, calcium, and magnesium management in containers with impatiens. *J. Amer. Soc. Hort. Sci.* 122(2):275-284.
- Algo, W.R., J.A. Biernbaum, and W.C. Fonteno. 1996. Root-medium CO_2 partial pressures for container grown chrysanthemums. *HortScience* 31(3):381-384.
- Argo, W.R., J.A. Biernbaum, and D.D. Warncke. 1997a. Geographical characterization of greenhouse irrigation water. *HortTechnology* 7:49-55.
- Argo, W.R., B.J. Weesies, E.M. Bergman, M. Marshal, and J.A. Biernbaum. 1997b. Evaluation of rhizon soil solution samplers as a method for nutrient solution extraction and media analysis for container-grown crops. *HortTechnology* 7(4):404-408.
- Bailey, D.A., P.V. Nelson, W.C. Fonteno, J.W. Lee, J.S. Huang. 1996. Plug pH pandect. The systems approach to growing plugs: Water, substrate, and nutrition. NCSU plug research and information development center.
- Bailey, D.A. 1997. Alkalinity, pH, and acidification. In: D.W. Reed (ed.). Water, media, and nutrition for greenhouse crops. Ball Publishing, Batavia, Ill.
- Barker, A.V. and H.A. Mills. 1980. Ammonium and nitrate nutrition of horticultural crops. *Hort. Rev.* 2:395-423.
- Biernbaum, J.A. 1992. Root-zone management of greenhouse container-grown crops to control water and fertilizer use. *HortTechnology* 2:127-132.
- Biernbaum, J.A. 1994. Water quality. In: H. Tayama, T. Roll, and M. Gaston (eds.). Tips on growing bedding plants. 3rd ed. Ohio Florists' Assn., Columbus, Ohio.
- Biernbaum, J.A. and W.R. Argo. 1995. Effect of root-media pH on impatiens shoot micronutrient concentration. *HortScience* 30:858 (Abstr.).
- Biernbaum, J.A., W. Carlson, C. Shoemaker, and R. Heins. 1988. Low PH causes iron and manganese toxicity. *Greenhouse Grower* 6(3):92-97.
- Biernbaum, J.A., W.R. Argo, B. Weesies, A. Weesies, and K. Haack. 1995. Persistence and replacement of preplant nutrient charge fertilizers from highly leached peat-based root media. *HortScience* 30(4):763 (Abstr.).
- Boodley, J.W. and R. Sheldrake. 1972. Cornell peat-lite mixes for commercial plant growing. Cornell Ext. Bul. 43.
- Bunt, A.C. 1988. Media and mixes for container-grown plants. Unwin Hyman, London.
- Chapin, J.K. 1980. The effect of fineness in limestone on the PH of 50:50 peat-vermiculite mix. *Benchmarks* 1:7.

- DeBoodt, M. and O. Verdonck. 1971. Physical properties of peat and peat-moulds improved by perlite and foam-plastics in relation to ornamental plant-growth. *Acta Hort.* 18:9-27.
- Dufault, R.J. 1998. Transplant production and performance: Vegetable transplant nutrition. *HortTechnology* 8(4):515-523.
- Fonteno, W.C. 1996. Growing media: Types and physical/chemical properties. In: D.W. Reed (ed.). *Water, media, and nutrition for greenhouse crops.* Ball Publishing, Batavia, Ill.
- Fonteno, W.C., P.V. Nelson, and D.A. Bailey, 1996. Plug substrates: in search of the perfect mix. The systems approach to growing plugs: water, substrate, and nutrition. N.C. State Univ. plug research and information development center.
- Froehlich, D.M. and W.R. Fehr. 1981. Agronomic performance of soybeans with differing levels of iron deficiency chlorosis on calcareous soil. *Crop Sci.* 21:438-440.
- Gabriels, R. 1978. The effect of irrigation water quality on the growing medium. *Acta Hort.* 82:201-212.
- Gibaly, H.E. and J.H. Axley. 1955. A chemical method for the rating of agricultural limestones used as soil amendments. *Soil Sci. Soc. Amer. Proc.* 20:301-302.
- Hanan, J.J. 1964. Oxygen and carbon dioxide concentrations in greenhouse soil-air. *J. Amer. Soc. Hort. Sci. Proc.* 84:648-652.
- Hawkes, G.R., D.B. Campbell, A.E. Ludwick, R.M. Millaway, and R.M. Thorup (eds.). 1985. *Fertilizers: A source of plant nutrients*, p. 83-110. In: *Western fertilizer handbook*. 7th ed. Interstate, Danville, Ill.
- Helling, C.S., G. Chesters, and R.B. Corey. 1964. Contribution of organic matter and clay to soil cation-exchange capacity as affected by the PH of the saturating solution. *Soil Sci. Soc. Amer. Proc.* 28:517-520.
- Koranski, D. and R. Kessler. 1991. Plug medium. *GrowerTalks* 54(11):77.
- Lang, H. 1996. Insights into plug fertility. *Greenhouse Product News* 6(1):24-27.
- Lang, H.J. and G.C. Elliott. 1991. Influences of ammonium : nitrate ratio and nitrogen concentration on nitrification activity in soilless potting media. *J. Amer. Soc. Hort. Sci.* 116(4):642-645.
- Lindsay, W.L. 1979. *Chemical equilibria in soils.* Wiley, New York.
- Lindsay, W.L. and E.C. Moreno. 1960. Phosphate phase equilibria in soils. *Soil Sci. Soc. Amer. Proc.* 24:177-182.
- Lucas, R.E. 1982. Organic soils (Histosols). *Mich. Agr. Exp. Sta., East Lansing, Res. Rpt.* 435.
- Lucas, R.E. and J.F. Davis. 1961. Relationships between pH values of organic soils and availabilities of 12 plant nutrients. *Soil Sci.* 92:171-182.
- Lucas, R.E., P.E. Rieke, J.C. Shickluna, and A. Cole. 1975. Lime and fertilizer requirements for peats, p. 51-70. In: D.W. Robinson and J.G.D. Lamb (eds.). *Peat in horticulture.* Academic Press, London.
- Ludwig, L.S. and J.C. Peterson. 1984. An assessment of the chemical properties of water from floriculture industry firms throughout Ohio and the United States. *HortScience* 19(3):521 (Abstr.).
- Marschner, H. 1986. *Mineral nutrition of higher plants.* Academic Press, London.
- Milks, R.R., W.C. Fonteno, and R.A. Larson. 1989. Hydrology of horticultural substrates: II, Predicting physical properties of media in containers. *J. Amer. Soc. Hort. Sci.* 114:53-56.
- Nelson, P.V. 1991. *Greenhouse operations and management.* 4th ed. Prentice Hall, Englewood Cliffs, N.J.
- Nelson, P.V. 1994. Fertilization. In: E.J. Holcomb (ed.). *Bedding plants.* IV. Ball Publishing, Batavia, Ill.
- Niemiera, A.X. and R.D. Wright. 1986. The influence of nitrification on the medium solution and growth of holly, azalea, and juniper in a pine bark medium. *J. Amer. Soc. Hort. Sci.* 111:708-712.
- Parfitt, R.L. and B.G. Ellis. 1966. Studies on Michigan agricultural limestones. *Mich. Agr. Expt. Sta. Quarterly Bul.* 49:12-23.
- Paul, J.L. and C.I. Lee. 1976. Relation between growth of chrysanthemums and aeration of various container media. *J. Amer. Soc. Hort. Sci.* 101:500-503.
- Peterson, J. C. 1981. Modify your pH perspective. *Florist's Rev.* 169:34-35, 92-93.
- Puustjarvi, V. and R.A. Robertson. 1975. Physical and chemical properties, p. 23-38. In: D.W. Robinson and J.G.D. Lamb (eds.). *Peat in horticulture.* Academic Press, London.
- Puustjarvi, V. 1982. Nature of changes in peat properties during decomposition, p. 5-20. *Peat and Plant Yrbk.* (1981-82).
- Reed, D.W. 1997. Combating poor water quality with water purification systems. In: D.W. Reed (ed.). *Water, media, and nutrition for greenhouse crops.* Ball Publishing, Batavia, Ill.
- Reddy, S.K. M.A. Madore, and P.A. King. 1994. Survey of sulfur levels in greenhouse irrigation waters. *HortScience* 29(5):503 (Abstr.).
- Rose, M.A., J. Peterson, and L. Kramer. 1995. The Ohio State University water quality assessment program, p. 13-15. In: M.A. Rose and J.A. Chatfield (eds.). *Ornamental plants: A summary of research 1993-1994.* Ohio Agr. Res. Development Center, Wooster, Circ. 142.
- Saxenam, N. and A.R. Sheldrake. 1980. Iron chlorosis in chickpea (*Cicer arietinum* L.) grown on high pH

- calcareous vertisol. *Field Crops Res.* 3:211-214.
- Schollenberger, C.J. and R.M. Salter. 1943. A chart for evaluating agricultural lime stone. *J. Amer. Soc. Agron.* 35:955-966.
- Sheldrake, R. 1980. Lime source and quantity study on peat-vermiculite. *Benchmarks* 1:6-7.
- Styer, R.C. 1996. Key factors of water, media, and nutrition. *GrowerTalks* 60(8):24-26.
- Styer, R.C. and D. Koranski. 1997. Plug and transplant production. A grower's guide. Ball Publishing. Batavia, Ill.
- Spurway, C.H. and C.E. Wildon. 1938. Water conditioning for greenhouses. *Michigan Agr. Expt. Sta. Circular Bul.* 166:3-10.
- Vavrina, C.S. 1997. Transplant production and performance: Transplant age in vegetable crops. *HortTechnology* 8(4):550-555.
- Vetanovetz, R. and R. Hulme. 1991. Tested your water alkalinity lately? *Greenhouse Mgr.* 9(10):48-50.
- Warncke, D.D. 1986. Analyzing greenhouse growth media by the saturation extraction method. *HortScience* 21:223-225.
- Warncke, D. and D. Krauskopf. 1983. Greenhouse media: Testing and nutrition guidelines. *Michigan State Univ. Ext. Bul. E-1736.*
- Whipker, B., D.A. Bailey, P.V. Nelson, W.C. Fonteno, and P.A. Hammer. 1996. A novel approach to calculate acid additions for alkalinity control in greenhouse irrigation water. *Comm. Soil Sci. Plant Anal.* 27:959-976.
- White, J.W. 1974. Dillon Research Fund, progress report on research at Penn. State. *Penn. Flower Grower Bul.* 273:3-4.
- Williams, B.J., J.C. Peterson, and J.D. Utzinger. 1988. Liming reactions in sphagnum peat-based growing media. *J. Amer. Soc. Hort. Sci.* 113:210-214.
- Yeager, T.H. and J.E. Barrett. 1985. Phosphorous and sulphur leaching from an incubated superphosphate-amended container medium. *HortScience* 20:671-672.
- Yelanich, M.V. 1991. Fertilization of greenhouse poinsettia to minimize nitrogen runoff. MS thesis, Michigan State Univ., East Lansing.
- Yelanich, M.V. 1995. Modeling the concentration of nitrogen in the root zone of container-grown chrysanthemums. PhD diss., Michigan State Univ., East Lansing.
- Young, R. and F.J. Johnson. 1982. Fertilizer products, p.45-68. In: *The fertilizer handbook.* Fert. Inst., Washington, D.C.