CALCINED MATERIALS AS COMPONENTS OF SOILLESS ROOT MEDIA: PHOSPHATE

SORPTION CHARACTERISTICS AND EFFECTS ON PHOSPHATE AND WATER USE IN

GREENHOUSE PRODUCTION OF *IMPATIENS WALLERANA*

by

ROSE ATIENO OGUTU

B.S., University of Eastern Africa, Baraton, 1994
M.S., Cornell University, 2004

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture, Forestry, and Recreation resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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Abstract

The use of calcined clays contributes properties of nutrient and water retention to soilless root media, which varies greatly depending on the parent clay and calcining treatment. This research characterized phosphate (PO_4) sorption of various calcined clay products, including low volatile and regular volatile material (LVM and RVM) 2:1 Attasorb clays (Engelhard Corp.), 2:1 Terra Green LVM clays (Oil-Dri Co.), and Turface (Profile Products LLC) at various particle sizes; 1:1 kaolin clays (Thiele Kaolin Co.) in powder form, and diatomaceous earth (Diatomite, Eagle Picher Minerals, Inc.). Three of the calcined materials, Terra Green montmorillonite and Attasorb attapulgite (which had high PO_4-sorption based on isotherms), and diatomaceous earth (which had negligible PO_4-sorption) were evaluated as components of soilless root media in two separate greenhouse experiments. The effect of the calcined materials, rate of incorporation (0%, 5%, 10% and 20% by volume in a mix with peat and perlite), and PO_4-P application rate (0, 5, 15, 45 mg$^.$L^{-1} PO_4-P) on plant growth, effluent P content and water use were determined during production and post-production of *Impatiens wallerana* Hook f. 'Tempo Rose'. The calcined materials varied in their ability to adsorb PO_4-P and generally yielded L-type isotherms. Laboratory results indicated potential for substantive P retention by several of the calcined materials when used in container production. For most materials, PO_4-P sorption did not show pronounced pH dependence. During production and post-production, the test materials not only improved PO_4-P retention but also water retention and water use efficiency while still maintaining optimal physical properties at incorporation rates of 5 to 10%. Diatomaceous earth resulted in PO_4-P retention not significantly different from the calcined clays.

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Dedication

To my late father whose encouragement made me come this far, and to my mother whose

love and patience endures much

CHAPTER 1 - Laboratory Studies to Characterize Phosphate Sorption of Calcined Materials Used as Components of Soilless Root Media

Abstract. The use of calcined materials may contribute enhanced nutrient retention to soilless root media; properties of nutrient retention vary greatly depending on the parent clay and calcining treatment. This research characterized phosphate sorption of various calcined clay products, including low and regular volatile material (LVM and RVM) 2:1 attapulgite, montmorillonite, and illite clays (Attasorb, Engelhard Corp.; Terra Green, Oil-Dri Co.; and Turface, Profile Products LLC) at various particle sizes; 1:1 kaolin clays (Thiele Kaolin Co.) in powder form, and diatomaceous earth (Diatomite, Eagle Picher Minerals, Inc.). Extractable PO_4-P, initial pH, PO_4-P sorption isotherms, amount of P sorbed as a function of solution pH at a fixed total concentration and degree of phosphorus saturation (DPS) were determined. Initial pH of the clays ranged from 3.7 to 8.7. Sorption isotherms were conducted with initial adsorbate concentrations ranging from 0 to 200 $mg \cdot L^{-1}$ PO_4-P from KH_2PO_4. The calcined materials varied in their ability to sorb PO_4-P and generally yielded L-type isotherms, indicating that the adsorbate had relatively high affinity for the calcined material sample surface at low surface coverage. Some 2:1 calcined clays exhibited substantial phosphate retention, but 1:1 calcined clays and diatomaceous earth did not. Clays with less moisture (LVM) resulted in greater PO_4-P sorption than those calcined at lower temperatures (RVM). Terra Green montmorillonites had higher PO_4-P adsorption than Terra Green attapulgites. In summary, laboratory results indicated potential for substantive P retention by several of the calcined clay materials when used in container production. For most materials, PO_4-P sorption did not show pronounced pH

dependence, which suggests that PO_4-P retention is not influenced by pH-dependent charge within the pH range of container production.

Introduction and Literature Review

Small volumes (2 to 20%) of a variety of calcined clay-type products are being used as components of soilless root media because of their potential to increase nutrient retention, air space, water retention and bulk density of mixes used for container production. Properties imparted by these materials are inherited from the parent clay or source, particle size distribution, and calcining process. High calcining temperatures result in expansion of the crushed clay to form a porous fused structure that is physically and chemically stable. The resulting granules provide aeration to the root medium and hold water internally within their pore structure.

Traditionally, the soil component of root media used for crop production in containers imparted significant PO_4-P retention to the mix. Marconi and Nelson (1984) showed that over 33% of the total P applied was leached from a soilless root medium containing 1:1 peat moss: vermiculite, but less than 5% was leached from a 1:1:1 sand: soil: peat moss mix in a simulated plant watering scheme. This difference, they concluded, was related to differences in P fixation by the various medium components. Use of soil in container mixes has fallen out of favor with commercial producers because it is relatively expensive compared to other components, variable from source to source, and must be pasteurized before use (Nelson, 2005).

Many types of calcined clay amendments may enhance PO_4-P and water retention of soilless root media. Incorporation of 13% (by volume) of a calcined clay has been shown to reduce the amount of PO_4-P leached from pine bark-based container media by 73% in production of *Loropelatum chinensis* var. rubrum 'Blush' over a 16 week period (Ruter, 2003). Reduction in fertilizer and water use in poinsettia (*Euphorbia pulcherrima*) with incorporation of calcined

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clays has been shown (Catanzaro et al., 2004; Catanzaro and Bhatti, 2005). Owen et al. (2003) found that amending a pine bark root medium with 8% (by volume) calcined clay led to increased nutrient retention and water buffering capacity in production of container-grown *Cotoneaster dammeri* 'Skogholm'. A root medium of 30 peat: 50 compost: 20 Turface (calcined arcillite clay) (v/v) reduced PO_4-P leaching by 70% compared to a control of 30 peat: 50 compost: 20 sand in production of black-eyed susan, *Rudbekia hirta* L. (Bugbee and Elliot, 1998).

Total and permanent charges of 2:1 clays differ from 1:1 clays. Clay surfaces bear electrical charge that is a function of permanent charge, variable charge, and inner and outer surface charge. The resultant particle charge is either created through isomorphic substitution, protonation and deprotonation reactions, or partial charge as expressed through the polarity of atoms at the clay surface (Essington, 2004). The silicate minerals present in clays develop pH-dependent charge at the broken edges of the layer structure. The pH-dependent edge charge is a phenomenon that occurs in both 1:1 and 2:1 clay soils (Havlin et al., 2003).

Adsorption of phosphate by clay minerals has been attributed to pH-dependent reaction of phosphate with Ca, Fe and Al in the clay (Havlin et al., 2003). Exchange reactions involving polynuclear ligands such as HPO_4^{2-} and $H_2PO_4^{-}$ result in monodentate-mononuclear or bidentate-binuclear surface complexes (Essington, 2004). Much of the P-adsorption by soils can be attributed to chemisorptions involved in ligand exchange between PO_4-P and hydroxyl ions at Fe and Al oxyhydroxides (Parfitt, 1978). The PO_4-P sorption process, therefore, takes place through different mechanisms that could involve adsorption, partitioning and precipitation (Essington, 2004). Phosphate sorption by calcined clays has not been systematically investigated and it is not clear how the process of calcining changes the PO_4-P sorption characteristics of clays.

The commercial calcining process results in low volatile material (LVM) or regular volatile material (RVM) moisture contents, depending on calcining temperatures. Calcining, generally, reduces the amount of water trapped between the clay's silicate sheets and also produces a very hard granule that, even when fully saturated with water, does not break apart easily. The first stage of calcining, known as fluid bed drying, reduces the clay moisture level from 40% to 45% down to 6% to 9% using temperatures of about 120 to 176 oC, resulting in RVM clays. The LVM clays have even lower moisture content of 0 to 3%, which is achieved by secondary calcining at temperatures in the range of 460 to 800 oC (Moll and Goss, 1997). Heating the clays causes aggregation of particles that optimizes sorbtivity by creating a stable porous internal structure. Calcining reduces the exchange capacity of the clays, but surface binding and internal pores maintain some nutrient retention capacity. X-ray diffraction studies on a 2:1 Ca-montmorillonite clay showed that heat treatment of 200 to 400oC completely collapsed the interlayer, incorporating interlayer cations into the tetrahedral or unoccupied octahedral sheets (Bray et al., 1998). Hülya et al. (2006) evaluated the specific surface area (S), specific micro-mesopore volume (V), total surface acidity (nm) and adsorption equilibrium constant (K) of original and heated samples of a bentonite clay from Turkey. The S, V and nm stayed constant as temperature increased to 450 oC and then decreased. Total surface acidity, in general, declined with increasing temperatures. The most acidic sites, however, increased with heating and especially at temperatures of dehydration (100 to 550 oC) and dehydroxylation (550 to 700 oC). Calcining temperatures for maximizing sorbtivity, generally, do not exceed the dehydration interval. Hülya et al. (2006) concluded that the decomposition of the 2:1 layers of the clay and collapsing of micro and mesopores by intra- and inter-particle sintering caused rapid decrease in S and V values as the temperature increased.

Diatomaceous earth (DE) is not derived from clay, but consists of granules mined from sedimentary rock deposits resulting from accumulation of amorphous silica comprising the cell walls of dead, single-celled aquatic organisms called diatoms (Handreck and Black, 2002). The usual commercial function of DE is as an absorbent. Although this material is being used by some commercial growers as a root medium component, it is not expected to sorb PO_4-P because it lacks charged sorption sites.

Phosphate retention properties of clays after calcining are generally unknown, and the role of pH-dependent edge charge in the PO_4-P retention of calcined materials is untested. In addition, the calcined materials themselves may provide PO_4-P and other nutrients as fertilizer if native levels are high. Therefore, this research characterizes several calcined clay materials and diatomaceous earth as a basis to evaluate their potential to reduce PO_4-P leached during container production when used as components of soilless root media. Specifically, we 1) determined inherent PO_4-P via extraction and total P present in the mineral; 2) determined initial pH of unaltered samples; 3) characterized PO_4-P sorption at natural pH; 4) developed PO_4-P adsorption envelopes under variable pH conditions to establish the role of pH-dependent edge charge on PO_4-P retention; and 5) determined initial degree of phosphorus saturation of calcined materials.

Materials and Methods

The tested calcined materials are commercially available (Table 1.1). The test materials included: 2:1 clays of attapulgite (Attasorb; Engelhard Corp., Quincy, Fla.) calcined at two temperatures, RVM and LVM; LVM montmorillonite mined in Miss. and LVM attapulgite mined in Ga. (Terra Green; Oil-Dri Prod. Co., Ripley, Miss.) and montmorillonite + illite

(Turface; Profile Products LLC, Buffalo Grove, Ill.) at various particle sizes; calcined 1:1 clays (Thiele Kaolin Co., Sandersville, Ga.) in powder form; and diatomaceous earth (Diatomite Eagle-Picher Minerals, Inc., Reno, Nev.). For ease of reference, the test materials were coded using trade name, temperature treatment and particle size as mesh size designated by the manufacturer (Table1.1).

Particle size distribution. Particle size distribution was determined by dry sieving. The sieving process was carried out using woven analytical precision sieves (USA standard testing sieves, A.S.T.M.E specification, Fisher Scientific Co., Columbia, Md.). Dry test materials were weighed to 1,000 g and passed through a stack of eight sieves ranging from 5 mesh (4.0 mm nominal sieve opening) to 80 mesh (180 μm sieve opening) that were arranged in order of size with the smallest sieve at the bottom of the stack. Samples were uniformly shaken on a circular motion shaker set at 33 r•s^{-1} (2000 rpm) for 5 min. Sample recovered in each sieve was weighed and the proportions calculated as a percentage of the whole test sample (Table 1.2), averaged across three replications.

pH measurements. The pH was measured on a slurry consisting of 5 cm^3 test material to 10 ml deionized water. Mixtures were thoroughly stirred and allowed to settle for 10 min. prior to reading pH (Oyster pH meter, Extech Instr. Waltham, Mass.) at 27 $^{\circ}$C. The data were analyzed using PROC GLM in SAS ver. 9.1 (SAS Institute, 2002) with three replicates per material.

P extraction. Naturally occurring P present in the calcined materials was evaluated with three methods: dilute acid extraction, Mehlich III (M3) extraction, and salicylic-sulfuric digestion. For dilute acid extraction, the weight of 5 cm^3 of each test material was determined and measured into 50 ml Erlenmeyer flasks. Thirty ml of acid extractant consisting of 0.5 N HCl and 0.2 N H$_2$SO$_4$ was added. The flasks were placed on a circular motion shaker at 3 r•s^{-1} (175

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rpm) at 26.5 $^{\circ}$C, and after 10 h the supernatant was transferred into 50 ml centrifuge tubes and centrifuged at 33 r·s^{-1} (2000 rpm)for 5 min. Solution pH was adjusted by drop-wise addition of 5 M NaOH, using p-nitrophenol as the indicator, until the color of the sample just changed from colorless to yellow (Bender and Wood, 2000). Phosphate in the supernatant was then analyzed using the colorimetric method of Murphy and Riley (1962) on a UV/VIS spectrophotometer (Perkin-Elmer, Norwalk, Conn). The experimental design was completely random (CRD) and each treatment was replicated three times. The data were analyzed using PROC GLM in SAS ver. 9.1 (SAS Institute, 2002).

Mehlich III (M3) extraction solution contained 0.2 N acetic acid, 0.25 N NH$_4$NO$_3$, 0.015N NH$_4$F, 0.013N HNO$_3$ and 0.001N EDTA (Sen Tran and Simard, 1993). Mehlich III extractable P (1:5 test material: solution ratio) was analyzed with a Lachat-FIA system (Lachat FIA 800 series, Loveland, Colo.) The M3 procedure uses a strong acid extractant and estimates available P in soils. Two replications of each test material were run.

Finally, total P of the test materials was analyzed by colorimetric procedures after salicylic-sulfuric acid digestion (Bremner and Mulvaney, 1982). The extract was analyzed by colorimetric procedures using the Technicon Auto Analyzer II (Technicon Industrial Systems, Tarrytown, NY). Two replications of each test material were run.

PO$_4$-P sorption isotherms. To characterize and compare P-sorption of the calcined products, adsorption isotherms were created for each test material. An amount equal in weight to 5 cm^3 volume was measured into a 50 ml Erlenmeyer flask. Samples were equilibrated for 18 h with 30 ml of solution containing initial adsorbate concentrations of 0, 10, 25, 50, 100 and 200 mg·L^{-1} PO$_4$-P prepared from KH$_2$PO$_4$. Treatment structure was factorial with three replicates of each material for each P concentration and experimental design was completely random (CRD).

Flasks were placed on a circular motion shaker at 3 r·s^{-1} (175 rpm) for 10 h at 25 $^{\circ}$C and then

centrifuged at 33 r·s^{-1} (2000 rpm) for 5 min. Equilibrium P concentration and pH of the

supernatant were determined using colorimetric procedures and the pH meter described above.

The amount of P adsorbed by the clay sample was calculated as follows:

$$Q = v \ (C_i - C_f)/m$$

where Q is the amount of PO$_4$-P sorbed (mg P/kg calcined material), v is the liquid

sample volume (L), C_i is the initial concentration of PO$_4$-P in the solution containing adsorbate

(mg·L^{-1}), C_f is the final (equilibrium) concentration of PO$_4$-P in the supernatant solution (mg·L^{-1}), and m is the amount of the test material (kg, dry weight basis; Essington, 2004). Phosphate

sorbed, Q, was converted to g·m^{-3} for ease of application to greenhouse container production.

The Freundlich equation, although considered purely empirical in nature, has been

extensively used to describe ion adsorption by soils (Sposito, 1980; Aslam et al., 2000; Chaudhry

et al., 2003; Obaid-ur-Rehman et al., 2004). The sorption isotherms were examined by modified

Freundlich equations proposed by Le Mare (1982). The form of the modified Freundlich model

is as follows:

$$P = a \ C^{b/a}$$

where P is quantity of sorbate (g) per unit volume (m^3) of adsorbent, C is equilibrium

solution concentration (mg·L^{-1}) of the adsorbate, 'a' is the amount of PO$_4$-P sorbed (g·m^{-3}) when

the concentration C is 1 mg·L^{-1} and 'b' is the buffer power defined by the slope of the sorption

curve at the point where P/C = 1 L·m^{-3}.

The main advantage of this equation is that 'a' and 'b' are the amount of P sorbed and buffer capacities, respectively, at the same point on the curve where C= 1 mg·L^{-1}, and this point is the same for all the test materials. In our research, the parameters 'a' and 'b' were estimated by regression of the logarithmic form of the data obtained from adsorption isotherms. Therefore a plot of log P (y-axis variable) against log C (x-axis variable) yields a straight line with slope b/a and y-intercept of Log a.

Log P=Log a + b/a Log C

From the Freundlich equation the parameter 'a' could be considered as a capacity factor and was referred to as P sorption capacity (PSC); this implies that a material having a larger 'a' value has a larger adsorption capacity than one with a smaller 'a' value. Therefore, 'a' value estimates were used to differentiate the P sorption capacities of calcined materials. The Freundlich equation does not predict or include a maximum adsorption capacity, but it is reliable with low solution P concentrations (Havlin et al., 2003). R-values were determined for each Freundlich equation.

Adsorption envelopes. Adsorption envelopes were created to determine the amount of P adsorbed as a function of solution pH at the fixed total P concentration of 600 mg·L^{-1}. An amount equal in weight to 5 cm^3 volume of eight test materials, A-LVM-8/16, A-RVM-24/28, T-A-24/48, T-M-24/28, T-M-5/20, K-LSA-P, Turface and Diatomite (Table 1.1) were equilibrated for 10 h at 25 ^{o}C with 25 ml KNO$_3$. A 2.5 ml aliquot of 600 P mg$^-$L^{-1} from KH$_2$PO$_4$ was added and pH adjusted to ranges of 2 to10 at intervals of one unit using additions of 0.1 M HNO$_3$ or 0.1 M KOH. Samples were centrifuged, decanted, filtered, and analyzed for PO$_4$-P concentration as

described above. The experimental design was completely random (CRD) with three replications of each treatment. Eight test materials were subjected to 9 pH levels.

Degree of phosphorus saturation. Degree of P saturation (DPS) estimates how close the test material is to being saturated with PO_4-P (Sharpley, 1995). The DPS of the calcined materials was determined to compare the level of initial saturation with PO_4-P of each material's exchange sites. A DPS index (Pote et al., 1999) was created from soil test phosphorus (STP) determined by M3 extraction and a phosphorus sorption index (PSI) calculated from a single point isotherm, as follows (Bache and Williams, 1971; Sims et. al., 2002). To establish the PSI, 30 ml of a 500 mg·L^{-1} PO_4-P sorbate solution from KH_2PO_4 was added to 5 cm^3 of test material, equilibrated on a shaker for 18 h and centrifuged. Phosphate was determined as described previously (Murphy and Riley, 1962). The PSI was calculated using the equation:

$$PSI = q \, (\log C)^{-1}$$

where q is the amount of P sorbed (mg·kg^{-1}) and C is the equilibrium solution P concentration (mg·L^{-1}). The second step involved estimating DPS $_{STP}$ using the ratio of STP to (PSI + STP) and multiplying by 100: DPS $_{STP}$ (%) = {STP (mg·kg^{-1})/[PSI + STP (mg·kg^{-1})]} X 100

Results and Discussion

Particle size distribution, pH, and bulk weights. Characterization of particle size distribution of the test materials is summarized in Table 1.2. Results follow U.S. standard mesh sizes.

Attasorb materials were alkaline with pH ranging from 8.2 to 8.7 (Table 1.3). Terra Green montmorillonites were acidic with pH ranging from 3.8 to 4.3, while Terra Green

attapulgites were less acidic with pH ranging from 5.6 to 6.2. Turface and diatomite had pH

values of 6.1 and 5.1, respectively (Table 1.3). The various calcined materials exhibited a wide

range of pH. It is important for a grower to beware of the pH levels and buffering capacity that

root medium components contribute to a mix because they may influence nutrient retention and

management during production.

Calcined materials have lower bulk weight (< 1.0 g·cm^3) compared to most mineral soils

which have bulk weights between 1.0 and 2.0 g·cm^3 (Hillel, 2004). Variation in bulk weights is

attributable to the relative proportion and specific gravity of solid particles (which decreases with

calcining) and to the porosity of the test material. Compared to Attasorb and Terra Green

materials, DE exhibited greater porosity (Table 1.3). Compared to clay soils, the granular test

materials have the advantage of adding stable pore space to soilless mixes, which contributes to

beneficial physical properties in container production.

Phosphorus content of calcined materials. Total native P present in the materials was

relatively high in the Attasorb and Terra Green attapulgites (700 to 2800 mg·kg^{-1}, Table 1.3).

This significant amount of PO_4-P may provide some P fertilizer during production and/or remain

in the container after the production cycle concludes. Kaolin test materials contained between

580 to 670 mg·kg^{-1} P while diatomite and Terra Green montmorillonite had the least native P at

between 250 and 370 mg·kg^{-1} P (Table 1.3).

Phosphorous was extracted from the test materials using two procedures, an acid

extraction and the M3 test which was developed in North Carolina for routine analysis of P, K,

Ca, Mg, Na and micronutrients in acid soils. The two extraction methods yielded substantially

different P contents (Table 1.3). Different chemical extractants are designed for soils depending

on their chemical characteristics. Attapulgite test materials, which have pH ranging from 5.6 to

8.7, resulted in greater P extracted by 0.5 N HCl + 0.2 N H_2SO_4 than the M3 procedure, but the opposite was true for kaolinite test materials, which have pH of 4.5 to 5.3. The evolution of carbon dioxide during acid extraction of the Attasorbs indicated a possible presence of free $CaCO_3$, which in combination with the higher pH, suggests that the M3 test is not ideal for these calcareous clays. Results of the M3 test showed the influence of particle size on available PO_4-P with smaller sizes of the same material yielding more PO_4-P. Kaolinite materials KLSA and K-P yielded the most PO_4-P, 460 and 116 mg·kg^{-1} PO_4-P, respectively, from the M3 procedure. Attasorb RVMs yielded more available PO_4-P compared to LVMs (45 to 92 mg·kg^{-1} P and 6 to 14 mg·kg^{-1} P, respectively).

PO_4-P isotherms. The isotherms, which are L-type according to classification of adsorption isotherms by shape, indicate monomolecular adsorption of PO_4-P (Figs. 1 through 4).

Using the parameter 'a' from the Freundlich equation as a capacity factor, Terra Green montmorillonites had the highest PO_4-P sorption (425 to 700 g·m^{-3}). Terra Green attapulgites had lower PO_4-P sorption (210 to 250 g·m^{-3}) as shown in Table 1.4 and Fig.1.1A. Information obtained from the manufacturer of the Terra Green calcined materials indicated differences in the clays mined in Ga. versus Miss. The montmorillonites from Miss. contained more Fe, while the product mined in Ga. had higher Mg and Ca content, which are capable of forming surface or solution precipitates with oxyanions. Differences in surface area may have influenced PO_4-P sorption; however, the specific surface area provided by the suppliers ranged from 98 m^2·g^{-1} for Attasorb materials and 102 to 122 m^2·g^{-1} for Terra Green materials based on the standard Brunauer, Emmett and Teller (BET) procedure (Brunauer, et al., 1938), which does not appear to be different enough to explain difference in PO_4-P sorption.

High levels of native P in the calcined materials might be expected to reduce PO_4-P sorption capacity.

Phosphate adsorption levels of Terra Green materials increased with increasing initial pH. The T-M-16/30 and T-M-5/20 had the highest adsorption with the batch solution pH range of 4.0 to 4.5, while T-A-16/30, T-A-24/28, and T-A- 5/20 had comparatively lower PO_4-P sorption with pH ranging from 6.0 to 7.0 (Fig. 1.1A, Fig. 1.1B). The high PO_4-P sorption under lower pH could have involved the dissolution of Al in the clay lattice in the formation of $AlPO_4$ crystals. In acidic solutions, the mineral surface has a net (+) charge, although both (+) and (-) sites exist. The predominance of (+) charges readily attracts $H_2PO_4^{2-}$ (Havlin et al., 2003).

The Attasorb LVM materials had higher PO_4-P sorption ('a'= 320 to 495 g·m^{-3}) than Attasorb RVM materials ('a'= 220 to 230 g·m^{-3}) as shown in Table 1.4. Particle size played a part in enhancing PO_4-P sorption in Attasorb LVMs with the smallest particle size having higher sorption than larger particle sizes. It was observed that RVM materials had a tendency to disintegrate into smaller particles when in solution compared to the LVM materials; therefore, the difference between the eventual surface area of RVM clay particles was not as great, which explains the lack of effect of particle size on PO_4-P sorption. The LVM materials demonstrated better aggregate stability than RVM materials and would be preferred for use as soilless root medium components. Owen et al. (2006) compared the use of two temperature treatments (RVM and LVM) of a Georgian palygorskite-bentonite calcined clay at 8% by volume of a bark-based root medium; the mix with LVM-clay leached 35% less PO_4-P than the mix containing RVM-clay.

The Terra Green attapulgites that originated from Georgia, T-A-5/20, T-A-16/40, and T-A-24/48, resulted in 'a' as 250, 240 and 210 g·m^{-3}, respectively, showing no influence across

these particle sizes on amount of PO_4-P sorbed. Ruter (2003) investigated the influence of three particle sizes of a calcined clay (Sud-chemie, Meigs, Ga.) on PO_4-P retention. He concluded that particle size had limited influence on amount of PO_4-P sorbed when particle sizes were > 3.36 mm and < 1.00mm (24/48 US mesh), and within the range of 1.00 to 3.36 mm (5/20 and 16/30 US mesh); 61%, 76% and 74% reduction of PO_4 leached occurred, respectively.

The slopes of the isotherms are indicators of buffer capacity, with steeper slopes indicating higher buffering capacity (Ozone and Shaw, 1968). Such plots can be used to estimate the quantity of P needed to be applied to maintain the soil solution concentration at the desired level (Fox and Kamprath, 1970). Material with high PO_4-P sorption like Terra Green montmorillonites continued to sorb PO_4-P at even the highest levels of added PO_4-P (200 mg·L^{-1}, Fig. 1.2A). The higher PO_4-P buffer capacity of these materials would necessitate greater P addition to achieve 0.2 mg·L^{-1} soluble PO_4-P, which is considered optimum for most plants (Beckwith, 1965), but ensures that the level of soluble PO_4-P is maintained for a longer period. As PO_4-P is removed from solution by the plant, there would be a less dramatic change in intensity (root medium solution PO_4-P concentration) in the more highly buffered media.

The buffer index from the slope of the Freundlich equation indicated that the kaolinite materials had very low buffer capacity (25 to 53 L·m^{-3}); they also had the lowest bulk weight (Table 1.3). The kaolins are processed to achieve a low permeability, a property that would curtail sorption capability. Among the kaolin samples, K-HAS-P had the highest bulk weight (0.26 g·cm^{-3}) and the highest PO_4-P sorption (Tables 1.3 and 1.4).

The relatively low PO_4-P sorption exhibited by Turface (1.4A) could be as a result of high calcining temperatures of over 550 ^{o}C leading to the collapse of micro and mesopores. Calcining temperatures play an important role in determining the sorptivity of the test materials.

Diatomaceous earth resulted in the lowest PO_4-P sorption. If diatomaceous earth increased PO_4-P retention after incorporation into soilless root media, the mechanism would not appear to be of chemical nature.

pH. The pH of the test materials remained fairly stable above the equilibrium concentration of 0.5 mg$^.$L^{-1} PO_4-P (Figs. 1B, 2B, 3B and 4B). Between 0 and 0.5 mg$^.$L^{-1} PO_4-P equilibrium concentration, the Attasorb materials significantly changed pH (1.2B) and PO_4-P sorption increased (1.2A); thereafter, a stable pH occurred. The initial pH reduction at very low (< 0.5 mg$^.$L^{-1}) equilibrium concentrations occurred in all test materials except in the kaolinites which resulted in slight increase in pH (Figs. 1 to 4).

This is an indication that the calcined clays could stabilize pH of soilless root media, which often contribute to problems of pH drift because of their poor buffer capacity. In peat-based soilless root media, lack of cation exchange capacity (CEC) and base saturation (BS) of peat moss have been implicated as causes (Rippy et al., 2005). However, calcined clays would need to comprise a significant volume of the total mix to stabilize problems with pH drift during production.

The adsorption of PO_4-P and pH of the equilibrium batch solution were correlated. The Attasorb materials, which were highly alkaline, showed a slight pH reduction with increase in PO_4 sorption. The pH of samples ranged from 7.4 to 7.8, and the samples at the lowest pH had most adsorption (Fig 2a and 2b). The trend was most pronounced with the Terra Green montmorillonites, which had a lower equilibrium solution pH (< 5.5) and exhibited a higher PO_4 sorption than the Terra Green attapulgites (pH > 6.0), as shown in Fig 1a and 1b. This trend is the result of the protonation and deprotonation of metal oxides or orthophosphoric acid.

Adsorption envelopes. The Attasorb RVM material sorbed more PO_4-P with increasing

pH, with 0% sorbed at pH 2 to 3 and up to about 90% sorbed at pH 10; about 40 to 60% was

sorbed at pH range of 5 to 8 (Fig 5b). The Attasorb LVM, material, on the other hand, had 60 to

80% adsorption over the pH range of 2 to 10, and the fraction generally increased as pH

increased (Fig 5b). The LVM materials (A-LVM-8/16, T-A-24/28) compared to an RVM

material (A-RVM-24/28) showed yet another desirable characteristic of pH stability: sorption

increased with increasing pH up to 6, and no significant change in PO_4-P adsorption was

observed from pH 6 to 9. Three possible mechanisms are proposed to explain the increasing PO_4-

P sorption with increasing pH exhibited by Attasorb: precipitation of Ca-phosphates, Ca-induced

P sorption, or co-adsorption of Ca and $H_2PO_4^-$ or HPO_4^{2-} as ion pairs or complexes (Essington,

2004).

Terra Green montmorillonite of 5/20 mesh had a stable, high PO_4-P sorption of 98%

over the entire pH range, while the smaller particle size of this material, 24/28 mesh, had a high

sorption fraction of 85 to 90% between pH 2 to 8 with a sharp decrease in adsorption after pH 8

to about only 20% PO_4-P adsorption at pH 10.

Turface had a stable PO_4-P sorption of about 60% over the pH range 2 to 10.

Diatomaceous earth had a small fraction of PO_4-P sorbed (15 to 30%) which decreased with

increase in pH. Low surface area metakaolin (K-LSA-P) had a high PO_4-P sorption of 98% at pH

2 and 3 which decreased with increasing pH to 40% PO_4-P adsorbed at pH 10 (Fig 5a).

The adsorption envelopes indicate that pH-dependent charge of the calcined materials is

not a critical mechanism of PO_4-P sorption in greenhouse production. Laboratory results from

various calcined clays demonstrate that the mechanism by which PO_4-P attaches to the surface of

a calcined material is generally not pH-dependent within the pH ranges of 5.0 to 7.0 maintained during container production.

Degree of phosphorus saturation. The DPS was calculated using the ratio of M3 PO_4-P to the experimentally determined phosphorus sorption index (PSI; Bache and Williams, 1971; Pote et al., 1999; Sims et. al., 2002; Table 1.3). The DPS of the calcined materials generally suggested that they possess significant capacity to sorb PO_4-P with DPS < 7.7% for all materials except two of the 1:1 kaolinites (Table 1.3). The low STP and high PSI values associated with several of the calcined materials, namely Attasorb LVM and Terra Green attapulgites and montmorillonites, suggest that a large quantity of vacant sites exist for PO_4-P sorption.

Several of the calcined materials that we characterized could be used as a component of soilless media to decrease PO_4-P leaching. Results of isotherm and DPS calculations indicated that the most promising materials were Terra Green montmorillonites and attapulgites and Attasorb LVM attapulgites. The least promising materials were diatomaceous earth and kaolinites. The PO_4-P adsorption envelopes indicated that PO_4-P sorption was not strongly pH-dependent within the pH range of commercial production, indicating that pH-dependent change is not a critical means of PO_4-P retention during greenhouse production. Calcining temperature affects optimal PO_4-P sorption: LVM attapulgites had better sorption than the RVM attapulgites that were calcined at lower temperatures, but Turface, which is also a 2:1 clay and calcined at a very high temperature, did not match the PO_4-P sorption potential of LVM Attasorb and LVM Terra Green attapulgites. Finally, the high level of native total P in some of the materials may even provide PO_4-P as fertilizer for crops.

Benefits of using calcined materials beyond PO_4-P retention may include increased water retention because the calcined products have significant moisture sorption properties, which is

related to their primary commercial use as absorbents. The temperatures of calcining are crucial in determining the extent to which the hardened aggregates maintain internal porosity.

Limitations of using calcined products as soilless root medium components include the high cost of purchase and shipping, especially if used at high enough percentages in soilless mixes to impart adequate benefit, such as buffering against pH drift. Because the materials are mined, natural variability occurs at different mines and even mining depths within the same mine; this would contribute to lack of uniform and consistent quality attributes in the materials. Finally, if calcined materials with very high PO_4-P sorption capacity are used, the materials themselves may remove PO_4-P from root medium solution when used in tandem with very low rates of PO_4-P fertilization.

Future research should investigate optimal percentages of incorporation of calcined products into soilless media, and especially under conditions of greenhouse production. The mechanism of PO_4-P sorption by the calcined materials is ambiguous and further research could elucidate these mechanisms. Phosphate desorption of the materials should be further evaluated. Finally, the economic benefits of reduced PO_4-P run-off in greenhouse effluent and reduced water use during production should be evaluated to help growers make decisions about using calcined materials.

Acknowledgements

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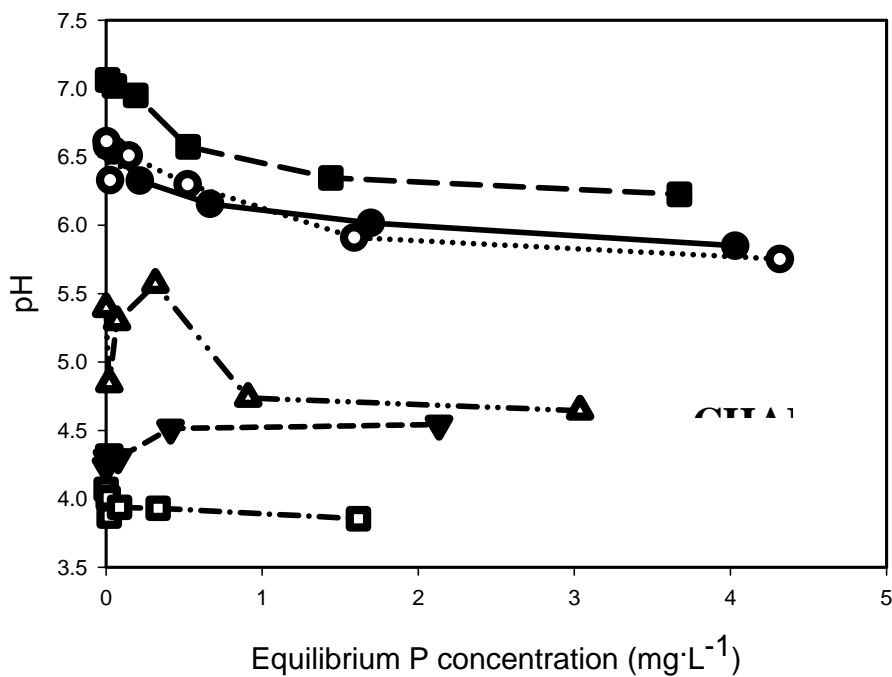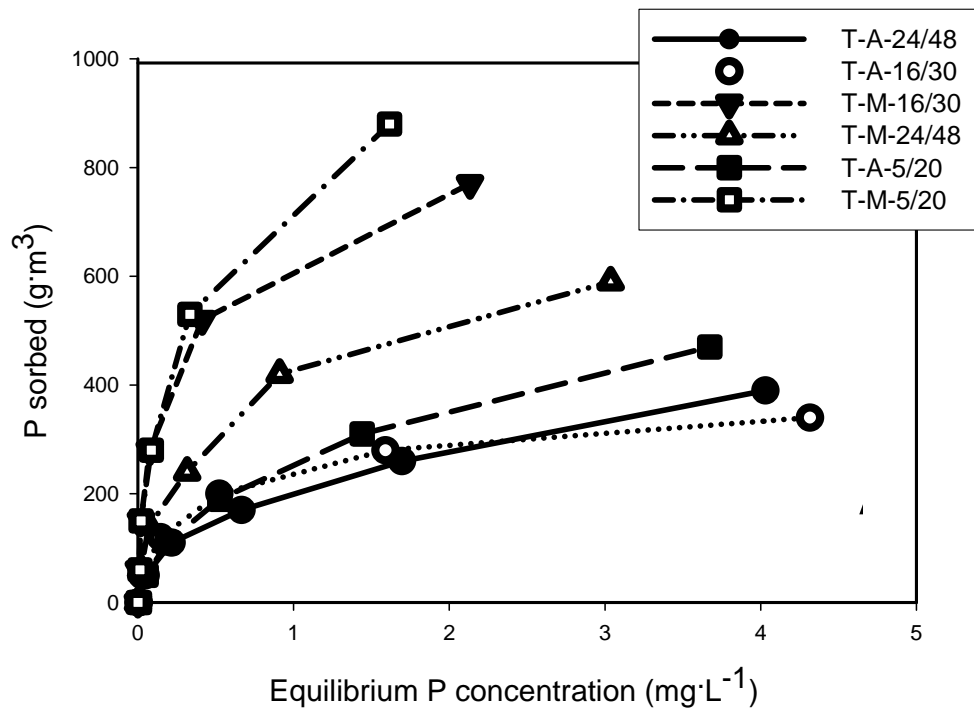
Figure 1.1 PO₄-P isotherms for Terra Green test materials (A) and pH of solution at various equilibrium P concentrations (B).
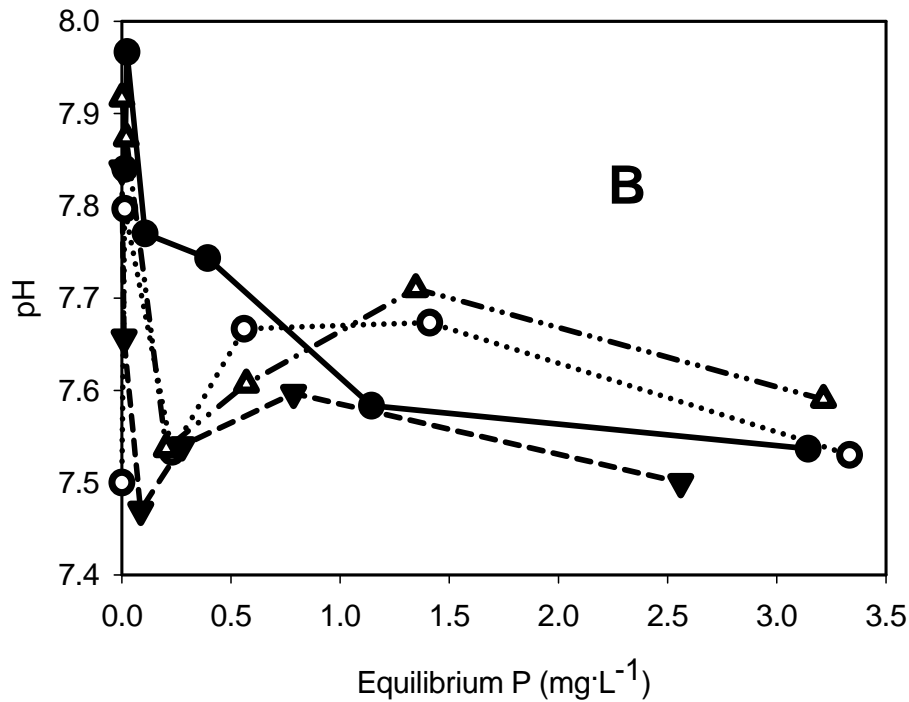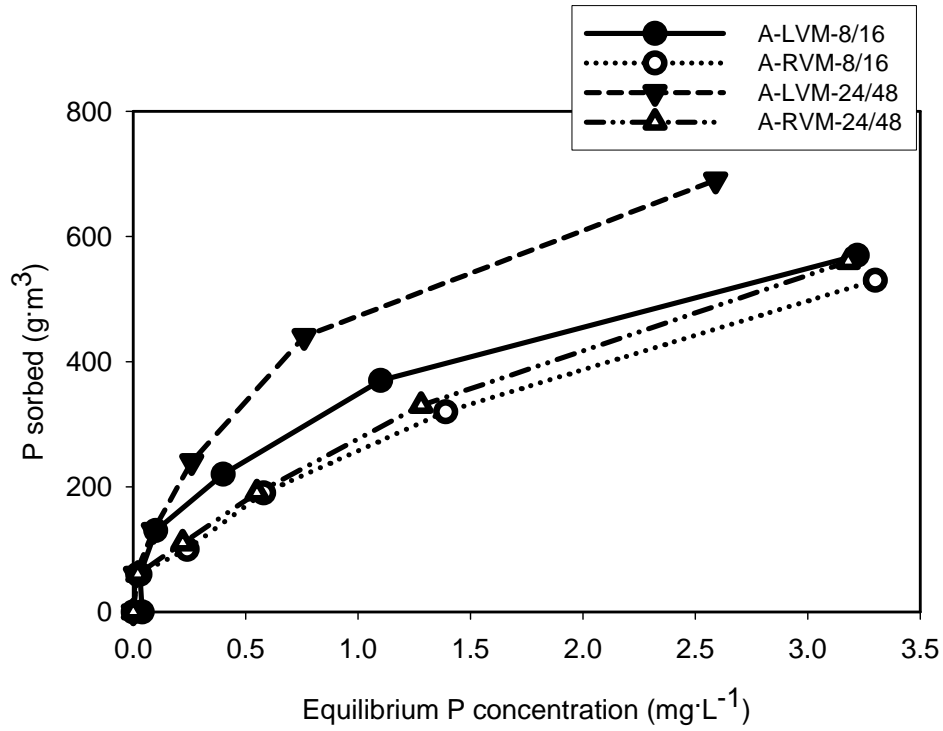
Figure 1.2 PO$_4$-P isotherms for Attasorb test materials (A) and pH of solution at various equilibrium P concentrations (B).
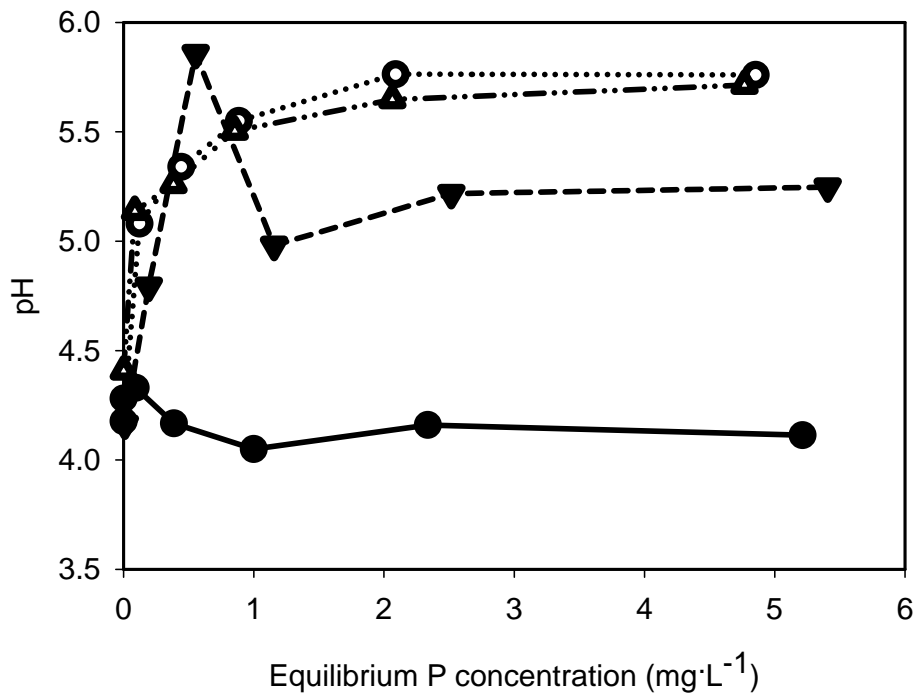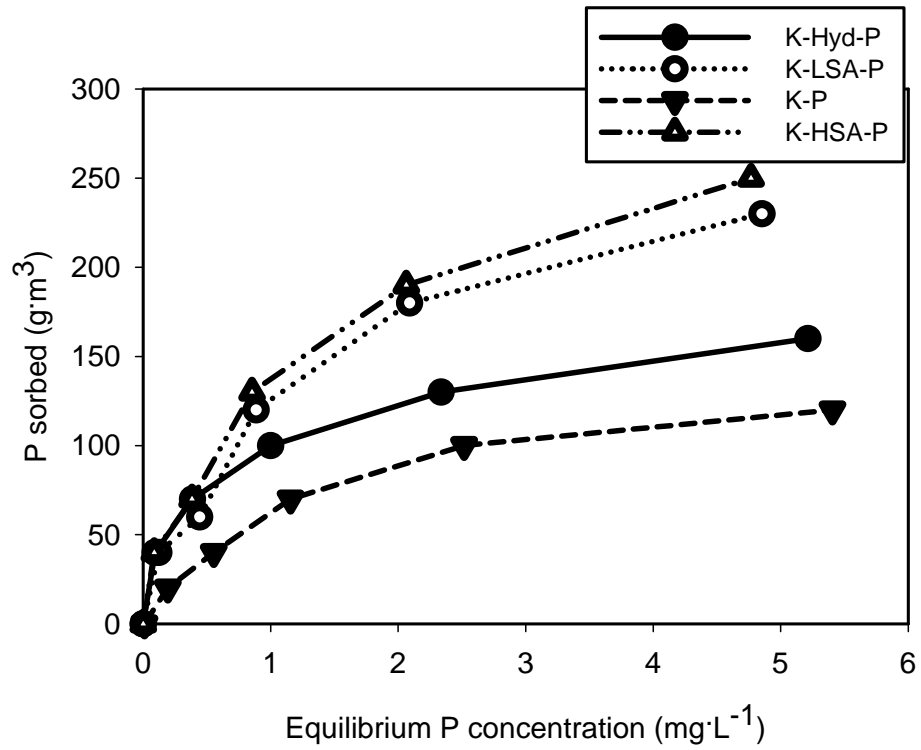
Figure 1.3 The PO$_4$-P isotherms for kaolin test materials (A) and pH of solution at various equilibrium P concentrations (B).
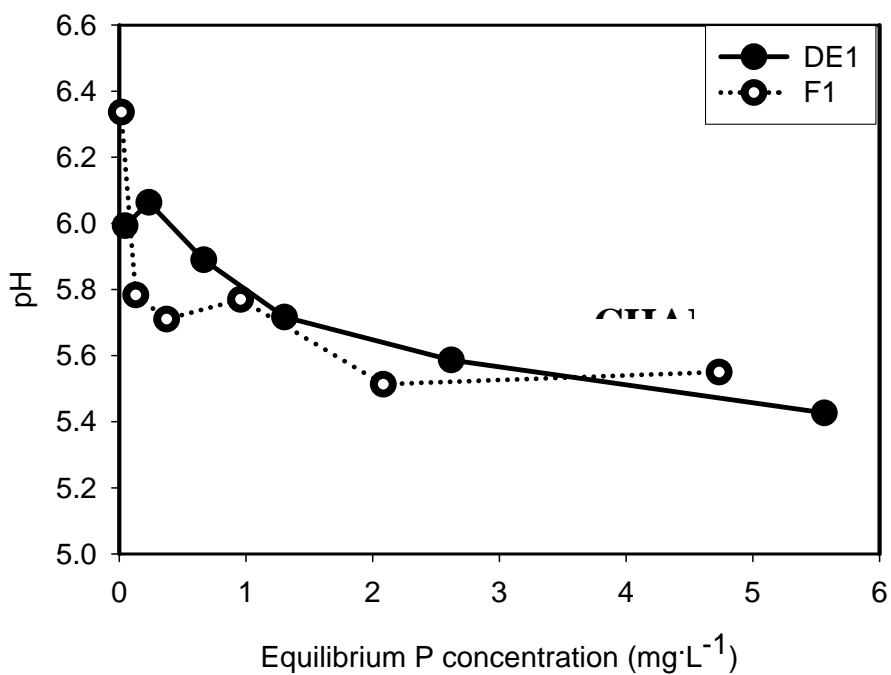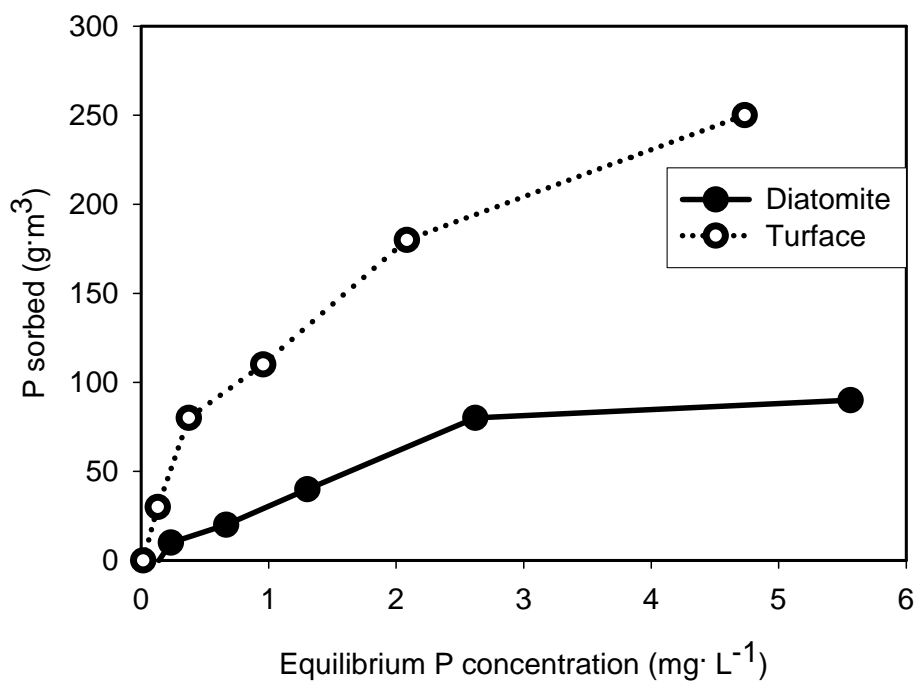
Figure 1.4 PO$_4$-P isotherms for Diatomaceous Earth and Turface test materials (A) and pH of solution at various equilibrium P concentrations (B).
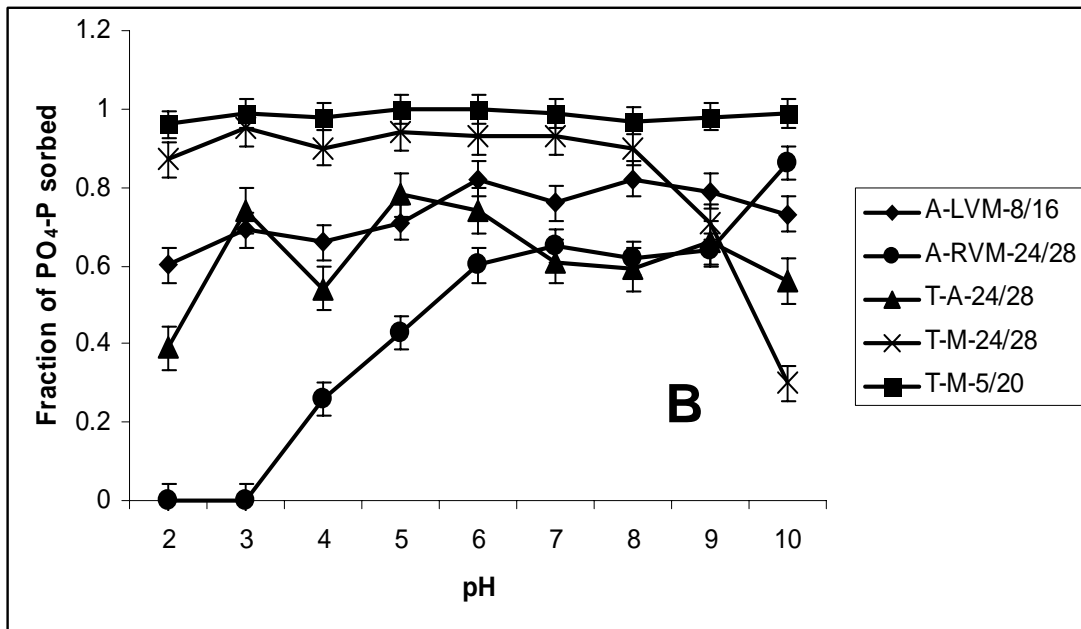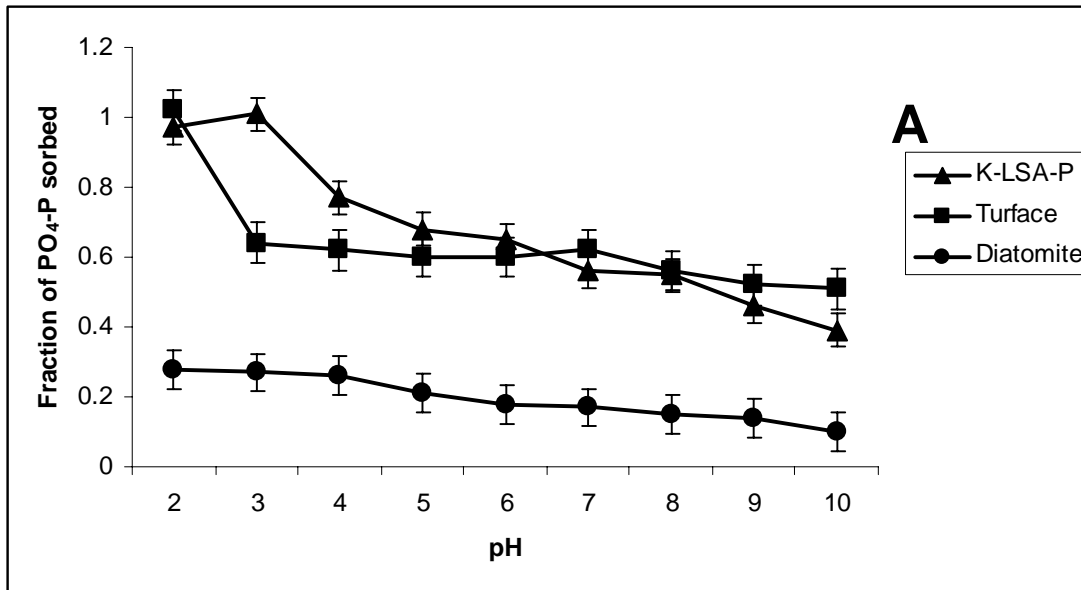
Figure 1.5 Adsorption envelopes of PO$_4$-P in suspensions containing 50 mg PO$_4$-P L^{-1} in 0.01 M KNO$_3$ solution. Adsorption is expressed as the fraction of the average PO$_4$-P adsorbed (mg·kg^{-1}) and maximum total PO$_4$-P concentration (mg·kg^{-1}).

Table 1.1 Calcined material trade names, sample codes, and descriptions of test materials provided by their sources

Trade name	Volatile matter characterization[z]	Mesh size (standard U.S. mesh)	Assigned code	Test material description[y]
Attasorb	LVM	8/16	A-LVM-8/16	1-10% quartz 90-99% fullers earth[x]. Is a hydrous magnesium
Attasorb	RVM	8/16	A-RVM-8/16	alumina silicate attapulgite. The deposits are on Florida-Georgia
Attasorb	LVM	24/28	A-LVM-24/48	border.
Attasorb	RVM	24/48	A-RVM-24/28	
Terra green attapulgite	LVM	24/48	T-A-24/28	10-20% quartz 80-90% fullers earth[x]; from Georgia mines
Terra green attapulgite	LVM	16/30	T-A-16/30	
Terra green attapulgite	LVM	5/20	T-A-5/20	
Terra green montmorillonite	LVM	24/48	T-M-24/28	7-10% quartz 90-93% montmorillonite; from Mississippi mines
Terra green montmorillonite	LVM	16/30	T-M-16/30	
Terra green montmorillonite	LVM	5/20	T-M-5/20	
Turface			Turface	Product of calcining a smectite clay at temperatures ranging from about 540° C. to about 1100° C.
Kaolin Hydrous		Powder	K-Hyd-P	Hydrous kaolin
Kaorock		Powder	K-LSA-P	Low surface area metakaolin
Kaocal		Powder	K-P	Full calcined at 980^0C
Kaocal LA		Powder	K-HSA-P	High surface area metakaolin calcined at <980^0C
Diatomite			Diatomite	Diatomaceous earth consists of fossilized remains of diatoms, typical chemical composition of diatomaceous earth is 86% silica, 5% sodium, 3% magnesium and 2% iron.

[z]LVM= Low Volatile material; Clays calcined at $\sim$ 470 ^{o}C. RVM= Regular Volatile Material; Clays calcined at $\sim$180° C
[y]Test material description was recorded as given in the material data sheets unless stated otherwise.

[x] Fuller's earth usually has a high magnesium oxide content. Two varieties of fuller's earth are mined, mainly in the southeastern states of the United States of America. These comprise the minerals montmorillonite or palygorskite (attapulgite) or a mixture of the two; some of the other minerals that may be present in fuller's earth deposits are calcite, dolomite and quartz.

Table 1.2 Particle size distriution of the 16 test materials.

| Code | Sieve no | [y]Percent (by weight) of given particle size | | | | | | | |
| | | No. 5 | No. 8 | No. 10 | No. 18 | No. 20 | No. 35 | No. 60 | No. 80 |
	Mesh size (standard U.S. mesh)	4.0 mm	2.38 mm	2.00 mm	1.00 mm	0.85 μm	0.5 μm	0.25 μm	0.18 μm
A-LVM-8/16	8/16		6[y]	39	55				
A-RVM-8/16	8/16		3	40	57				
A-LVM-24/48	24/28					1	73	26	
A-RVM-24/48	24/48				1	2	71	25	1
T-A-24/28	24/48					1	77	21	
T-M-24/28	24/28				1	4	78	17	
T-A-16/30	16/30				77	11	11	1	
T-M-16/30	16/30				44	20	35	1	
T-A-5/20	5/20	2	37	17	32	2	8	2	
T-M-5/20	5/20	3	52	14	29	1	1		
Turface		1	42	24	29	4			
K-Hyd-P	Powder								100
K-LSA-P	Powder								100
K-P	Powder								100
K-HSA-P	Powder								100
Diatomaceous earth		3	84	8	5				

[z]LVM= Low Volatile Material; Clays calcined at ~ 470C. RVM= Regular Volatile Material; Clays calcined at ~180C

[y]Percent (by weight) of given particle size

Table 1.3 Bulk weight, pH and amount of PO_4-P extracted from test materials. Three different chemical extractants were used: 0.5N HCl and 0.2N H_2SO_4, Mehlich III (M3) for available P, and salicyclic-sulphuric acid digest for total P. The pH measurements of clay samples were taken on 1:2 (v/v) clay sample : deionized water. Phosphate sorption index (PSI) was calculated form a single point isotherm based on 500 mg·L^{-1} PO_4-P concentration and DPS estimated from PSI and M3 P readings.

Code name	pH	Bulk Weight (g·cm^{-3})	Total-P[z] (mg·kg^{-1})	P[y] (mg·kg^{-1})	P[x] (mg·kg^{-1})	Degree of Phosphorus Saturation (DPS) %	P sorption Index (PSI) q*log C^{-1}
A-LVM-24/48	8.4ab	0.75c	1076 ± 198	306.0b	14 ± 0.5	0.91	1476
A-RVM-24/28	8.5ab	0.76bc	737 ± 156	534.0a	92 ± 0.5	6.75	1265
A-LVM-8/16	8.2b	0.76bc	2790 ± 147	230.5c	6 ± 0.5	0.44	1231
A-RVM-8/16	8.7a	0.80a	1770 ± 14	146.1d	45 ± 0.5	3.80	1140
A-LVM-5/25	8.4ab	0.76c	1227 ± 150	244.7c	20 ± 0.5	1.42	1354
T-A-24/28	5.7d	0.58g	1739 ± 212	166.3d	70 ± 0.5	7.22	893
T-A-16/30	5.6d	0.52h	1560 ± 97	249.8c	34 ± 0.5	2.88	1130
T-A-5/20	6.2c	0.67f	1947 ± 88	59.53ef	39 ± 0.5	3.22	1156
T-M-24/28	4.3gf	0.72d	377 ± 11	37.4fgh	107 ± 2.0	7.68	1285
T-M-16/30	4.0gh	0.71e	263± 31	19.0ghi	65 ± 2.0	4.01	1556
T-M-5/20	3.8h	0.77b	351 ± 21	77.7e	35 ± 3.5	1.84	1838
Turface	6.1c	0.22k	345 ± 22	21.8ghi	27 ±3.0	4.06	637
K-Hyd-P	4.2gf	0.19l	264 ± 40	0.1i	4 ± 0.0	0.54	736
K-LSA-P	4.6f	0.15m	656 ± 17	47.2efg	460 ± 20.0	27.73	1199
K-P	5.3ed	0.12n	652 ± 15	6.7hi	116 ± 0.5	13.91	725
K-HSA-P	4.5f	0.26i	581 ± 21	23.4ghi	93 ± 1.0	4.83	1832
Diatomite	5.1e	0.37j	259 ± 52	33.5fghi	24 ± 3.0	4.81	475
Diatomite (super absorbent)	5.4d	0.34j	179 ± 4.0	27.5ghi	20 ± 1.5	4.67	398
LSD$_{0.05}$[v]	**0.44**	**0.014**		**36.7**			

[z] From salicyclic-sulphuric acid digest
[y] 0.5N HCL and 0.2N H_2SO_4 acid extracted P. Data are means of three replications, SE = 12.7
[x] Mehlich extracted P
[w] Mean ± SD(n = 2)
[v] LSD, least significant difference. Differences between means greater than the LSD indicate significant differences at $p < 0.05$. Different letters indicate statistically significant differences.

Table 1.4 PO$_4$-P sorption parameters of the modified Freundlich model.

Test sample	Modified Freundlich equation		Amount adsorbed (P-sorption capacity) 'a' g·m^{-3}	Buffer capacity 'b' L·m^{-3}.	Correlation coefficient (r^2)
	Model form P=a C b	Linear form			
T-M-5/20	P=700 C $^{0.5095}$	Y=0.5095x + 0.2285	700	357	0.79
T-M-16/30	P= 590 C $^{0.500}$	Y= 0.5005 + 0.2489	590	295	0.79
A-LVM-24/48	P=495 C $^{0.487}$	Y= 0.4873X + 0.2535	495	241	0.78
T-M-24/28	P=425 C $^{0.475}$	Y= 0.475x + 0.2874	425	202	0.76
A-LVM-8/16	P=320 C $^{0.4679}$	Y=0.4679X + 0.2886	320	150	0.76
T-A-5/20	P=250 C $^{0.456}$	Y=0.4564x + 0.2663	250	114	0.78
A-RVM-24/28	P=230 C $^{0.462}$	Y = 0.4628x + 0.2742	230	106	0.77
T-A-16/30	P=240 C $^{0.4321}$	Y= 0.4321X + 0.3306	240	103	0.72
A-RVM-8/16	P= 220 C $^{0.459}$	Y= 0.4595x + 0.2729	220	102	0.77
T-A-24/28	P=210 C $^{0.439}$	Y = 0.4369x + 0.3002	210	97	0.74
K-HSA-P	P=130 C $^{0.408}$	Y= 0.4082x + 0.2774	130	53	0.75
K-LSA-P	P= 120 C $^{0.402}$	Y=0.402x + 0.2725	120	48	0.75
Turface	P=115 C $^{0.413}$	Y= 0.4132x + 0.2329	115	48	0.77
K-Hyd-P	P=100 C $^{0.3632}$	Y= 0.3632x + 0.3564	100	36	0.68
K-P	P=70 C $^{0.363}$	Y= 0.363x + 0.1976	70	25	0.77
Diatomite	P=28 C $^{0.3652}$	Y= 0.3652x + 0.0153	28	10	0.88

CHAPTER 2 - Calcined Clays as Soilless Root Medium Components in Greenhouse Production and Post-Production of *Impatiens wallerana*:

Part I. Phosphate Budgets

Abstract. Benefits of incorporating calcined materials into soilless root media could lead to less phosphate run off from greenhouses and reduced water use by plants. The effect of Terra Green montmorillonite (TG) and Attasorb (AS), with high phosphate (PO_4-P) sorption capacity, and diatomaceous earth (DE), with low PO_4-P sorption capacity, on plant growth, PO_4 leached and water use was determined during production of Impatiens wallerana Hook f. 'Tempo Rose' in two greenhouse experiments. In Expt. 1, the two clays were incorporated (by volume) into a mix of 5 peat : 2 perlite : 3 calcined materials, with the 30% calcined components consisting of 0%, 5%, 10% and 20% clay + DE. In Expt. 2, clays and DE were incorporated at 0%, 5% and 10% into peat and perlite mixes. Control plants (PP control) were grown in 7 peat: 3 perlite in both experiments. Physical properties of all mixes were characterized. Phosphate was applied as soluble fertilizer at rates of 0, 5, 15, and 45 $mg \cdot L^{-1}$ PO_4-P. The growth of the impatiens plants was optimal in the 7 peat : 3 perlite control plants in 1.26 L (6 inch pots) but did not differ significantly from the growth of impatiens in media with calcined materials at 15 and 45 $mg \cdot L^{-1}$ P-rate in 0.55 L pots (4.5 inch pots). Calcined materials increased bulk density, container capacity and air filled porosity of treatment mixes. The P budgets showed that percentage PO_4-P in leachate were greater in the 7 peat : 3 perlite control compared to the other treatments. The controls had the least amounts of PO_4-P (11%) retained in root medium compared to treatments (24%) in Expt. 1. The DE resulted in similar PO_4-P retention as AS and TG, apparently through a

physical as opposed to chemical sorption mechanism. The calcined materials reduced the amount of PO_4-P in leachate compared to the PP control (13 to 16% versus 19%, respectively in Expt.1). Twice the amount of PO_4-P per pot was lost in the PP control (10.5 mg) compared to the mixes with calcined materials (5.3 to 5.8 mg; Expt. 2).

Literature Review

Environmental concerns about nutrient run-off in effluent from container production operations and poor water use efficiency has spurred greenhouse growers to adopt best management practices that limit environmental impact, often to come into compliance with legislation. Re-engineering soilless root media may provide some solutions. Two properties of calcined materials that are notable are their nutrient and water retention, which they contribute to mixes without interfering with physical properties that are appropriate for container production. Work carried out with calcined clays as components of soilless root media (peat-lite and bark-based mixes) revealed enhanced PO_4-P and water retention. Warren and Bilderback (1992) compared rates (0, 27, 54, 67 and 81 kg m^{-3}) of arcillite in a pine bark substrate and reported curvilinear increases in available water and growth of *Rhododendron spp.* 'Sunglow' with increased rates of arcillite. Incorporation of 13% (by volume) of a calcined clay reduced the amount of PO_4-P leached from pine bark-based container media by 73% in production of *Loropelatum chinensis* var. rubrum 'Blush' over a 16 week period (Ruter, 2003). Reduction in fertilizer and water use in poinsettia (*Euphorbia pulcherrima*) with incorporation of calcined clays has been shown (Catanzaro et al., 2004; Catanzaro and Bhatti, 2005). Owen et al. (2003) found that amending a pine bark root medium with 8% (by volume) calcined clay increased nutrient retention and water buffering capacity in production of container-grown *Cotoneaster dammeri* 'Skogholm'. A root medium of 30 peat: 50 compost: 20 Turface (calcined arcillite clay)

(v/v) reduced PO_4-P leaching by 70% compared to a control of 30 peat: 50 compost: 20 sand in production of *Rudbekia hirta* L. (Bugbee and Elliot, 1998).

Properties that make calcined clays desirable as root medium components include their porosity, water holding capacity, and ability to adsorb phosphate. These commercial mineral aggregates are used for a wide range of industrial purposes, such as absorbents, fertilizer carriers, and barrier clays to remove or contain heavy metals or toxins (Murray, 2000).

The stability of granules of low volatile material (LVM) calcined clays coupled with ability of some calcined clays to sorb PO_4-P (see Chapter 1) justifies more extensive study of these clays as components of root media mixes. Calcined clays derived from parent materials of 2:1 clays, Attasorb (Engelhard Corp.) and Terra Green (Oil-Dri Co.) showed substantial PO_4-P retention during laboratory characterization, but 1:1 clays and diatomaceous earth did not.

Phosphorus is among nutrients required in relatively large amounts during crop production. The use of phosphate is being watched by the Environmental Protection Agency world wide (Environmental Protection Agency, 2005). Phosphate is more readily leached from container media composed of pine bark, sphagnum peat, vermiculite or sand (Yeager and Barett, 1984; Marconi and Nelson, 1984). The greenhouse industry is encouraging the use of Best Management Practices (BMPs) to reduce wastewater discharge volumes and P in greenhouse effluent. Incorporation of calcined clays as root medium components can ease the increasing regulatory pressure from federal and state agencies by retaining PO_4-P and reducing PO_4-P in wastewater discharged from greenhouses.

Specific objectives of the greenhouse study were to: 1) study the feasibility of using P-sorption isotherms to predict root medium PO_4-P retention of calcined materials; 2) evaluate PO_4-P retention of clays across PO_4-P fertilizer rates; 3) evaluate PO_4-P retention of clays across

percentages of clay incorporated; and 4) evaluate the effect of calcined materials in root media on plant growth and water use efficiency.

Materials and Methods

The two calcined clays used in these experiments exhibited considerable PO_4-P sorption capacity in laboratory characterization (Chapter 1). These 2:1 clays were an attapulgite (Attasorb; AS; Engelhard Corp., Quincy, Fla.) of 5/25 standard U.S. mesh and a montmorillonite (Terra Green; TG; Oil-Dri Co., Ripley, Miss.) of 5/20 mesh (Table 2.1). Both had been calcined at moderate temperatures to yield low volatile material (LVM) products. Diatomaceous earth (DE; Eagle Picher Minerals, Inc., Reno, Nev.) is not derived from clay, but consists of granules mined from sedimentary rock deposits resulting from accumulation of amorphous silica comprising the cell walls of dead, single-celled aquatic organisms called diatoms (Handreck and Black, 2002). Laboratory characterization revealed that DE resulted in virtually no PO_4-P sorption (Chapter 1). The usual commercial function of all of these materials is as an absorbent.

Two experiments (Expts. 1 and 2) were conducted in glass greenhouses of Kansas State University's Throckmorton Plant Sciences Range in Manhattan, Kans. (latitude 39° 05' N Longitude: 96° 35' W). Each experiment consisted of a production phase and a post-production phase. For both experiments, experimental design was a randomized complete block (RCBD) with four two-pot replicates of each treatment per block; one pot in each replicate was harvested at the end of the production phase and the second pot was harvested at the end of the post-production phase. *Impatiens wallerana* Hook. f. 'Tempo Rose' was the plant used in all experiments.

Treatments, Expt.1. The treatment structure was factorial with 2 calcined clays (TG and AS) x 3 percentages of incorporation (by volume; 5%, 10% and 20%) x 3 PO_4-P fertilization rates (5, 15 and 45 mg·L^{-1}). Diatomaceous earth was added to treatment recipes to bring the total volume of calcined clay + DE to 30% calcined materials (Table 2.2). An industry standard root medium (PP control) was 70% sphagnum peat moss (Conrad Fafard, Inc. Agawam, Mass.): 30% perlite. A second control (DE control) consisted of 30% DE with 50% peat and 20% perlite. This experiment was designed with the assumption that DE would not influence PO_4-P retention as observed during laboratory characterization of the materials (Chapter 1).

Treatments, Expt. 2. The treatment structure was factorial with 3 calcined materials (AS, TG and DE) x 2 percentages incorporation (by volume, 5%, and10%) x 3 PO_4-P fertilization rates (0, 15, and 45 mg·L^{-1}). Perlite was added to treatment recipes to bring the total volume of calcined material + perlite to 30% of the mix (Table 2.2). An industry standard root medium, PP control, was the same as described for Expt. 1.

Physical properties. The physical properties of the treatment mixes were characterized following the tube method of Niedziela and Nelson (1992; Table 2.2). Bulk density (BD), particle density (PD), air-filled porosity (AFP), container capacity (CC), and total porosity (TP) were determined on four replications of fallow pots of each treatment mix. The method does not disturb root media because water is introduced to the bottom of the mix through a tube.

Cultural practices. Impatiens seed was purchased from Ball Horticultural Co. (West Chicago, Ill.) and sown in 200-cell plug trays (TLC Polyform inc., Plymouth Minn.) in Fafard germinating media (Conrad Fafard Inc, Agawam, Mass.). A flow-chart of the experimental timelines is included in Appendix A. For Expt. 1, seeds were sown on 24 Mar. 2006. On 20 Apr. 2006, one plug was transplanted into a 10 cm deep, round, green plastic pot with volume of 1.26

L (ITML Horticultural Prod. Inc., Brantford, Ont.). One plant of each two-pot replicate was harvested on 14 June 2006 (52 days after transplant, DAT) at the end of the production phase and the second pot of the replicate was harvested on 15 July 2006 (84 DAT) at the end of the post-production phase. For Expt. 2, seeds were sown on 14 July 2007. On 21 Aug. 2007, one plug was transplanted into a 9.5 cm deep, round, green plastic pot with volume of 0.55 L (ITML Horticultural Prod. Inc., Brantford, Ont.). One plant of each two-pot replicate was harvested on 22 Sept. 2007 (30 DAT) at the end of the production phase and the second plant of the replicate on 24 Oct. 2007 (64 DAT) at the end of the post-production phase. For both experiments, each pot was placed on a clear, plastic saucer with raised ridge design for better drainage during leachate collection.

On the same day that the production phase ended, the post-production phase began with the remaining pot in each experimental unit. Only tap water was used during irrigations during the post-production phase. Two cycles of drought were imposed during both Expt. 1 and 2 by withholding water from pots. The dates of the drought cycles for Expt. 1 were designated 21 June to 2 July (Drought Cycle 1) and 2 July to 14 July 2006 (Drought Cycle 2). The dates of the drought cycles for Expt. 2 were 5 to 15 Oct. (Drought Cycle 1) and 16 to 24 Oct. 2007 (Drought Cycle 2). In both Expts. 1 and 2, the leachate was collected at the time of watering and the volume was recorded. Then a 1 ml sample was taken to analyze for PO_4-P. The PO_4-P content of leachate was determined colorimetrically (Murphy and Riley, 1962).

Fertilization and Irrigation. Root media treatment mixes were all amended with dolomitic lime, gypsum (Frit Industries, Ozark, Ala.), and Micromax (Grace-Sierra Hort. Prod., Milpitas, Calif.) at rates of 9 $g·L^{-1}$, 0.6 $g·L^{-1}$, and 0.6 $g·L^{-1}$, respectively. Amendments were incorporated into root media prior to transplant.

Fertilizer solutions consisted of PO_4-P rates of 0, 5, 15, or 45 mg·L^{-1} with 105 mg·L^{-1} N and 105 mg·L^{-1} K_2O. Containers were watered by pouring a volume of 400 ml per irrigation and 300 ml per irrigation to the surface of the pot in Expts. 1 and 2, respectively, which maintained a leaching fraction of about 20%. In Expt. 1, the treatments that contained calcined materials were irrigated 10 times and the PP control was irrigated 13 times, in every instance with the fertilizer solution. In Expt. 2, the treatments that contained calcined materials were irrigated 7 times and the PP control was irrigated 10 times; however, all treatments received fertilizer solutions only 7 times. The additional three irrigation applications to the PP control consisted of plain tap water. Two representative pots per treatment from different blocks were monitored daily to determine when to irrigate each treatment. When the weight of these sentinel pots fell below 30% of pot weight at container capacity, all pots of that treatment were irrigated.

Growth data. Height and width measurements of impatiens plants were taken three times during production and at the end of the production phase in both experiments. Plant height was measured from the rim of the pot to the top of the foliage canopy and plant width was determined as an average of two measurements taken at right angles to each other. Fresh weight, dry weight, and total number of open flowers were measured at the end of the production period. In Expt. 2, number of buds was also measured. Whole above-ground shoots of impatiens plants were weighed for fresh weight. Shoots were washed in a weak acid solution, rinsed under warm tap water, washed for 30 s in distilled water, placed in a paper bag and dried in a forced-air oven (Thermo Fisher Scientific Inc., Rockford, Ill.) for 3 days at 70 $^{\circ}$C; then dry weights were measured. Flowers were considered 'open' at the time of counting if buds had begun to unfurl. Buds were counted if they were greater than 10 mm in length but not yet unfurling.

Tissue and root media analyses. The dried shoots were ground using a Wiley mill (Scientific Apparatus, Philadelphia, Pa.) to pass a 20-mesh (1.3 mm) screen. The dried, ground plant tissue was analyzed for N, P, and K using a sulfuric peroxide digestion (Linder and Harley, 1942; Thomas et al., 1967).

In Expt. 2, the root media were oven dried at 80 $^{\circ}$C for three days and then weighed. Total phosphorus of media were analyzed using the salicylic-sulfuric acid digestion (Bremner and Mulvaney, 1982). The extract was analyzed by colorimetric procedures using the Technicon Auto Analyzer II (Technicon Industrial Syst., Tarrytown, NY).

Root medium solution. Leachate was collected for analysis after each irrigation. Five ml of leachate was removed with a syringe for PO_4-P analysis. The remaining leachate was poured into a large plastic container and stored separately to eventually determine the total volume and PO_4-P leached; several drops of a saturated solution of phenylmercuric acetate were added to the leachate storage containers to prevent microbial or algal growth. Pots did not sit in the leachate solution for more than 30 min after solution application. The leachate was analyzed for PO_4-P using a UV-VIS spectrophotometer (Perkin-Elmer, Norwalk, Conn.) following the colorimetric technique of Murphy and Riley (1962).

Phosphorus budgets. Budgets for Expt. 1 were calculated as:

$$PO_4\text{-}P_{fertilizer} = PO_4\text{-}P_{leachate} + P_{shoots} + P_{estimated\ in\ roots} + P_{root\ medium}$$

PO_4-P applied as fertilizer, PO_4-P in leachate, and P in shoot tissue were measured; P in root tissue was generously estimated by assuming that root mass was 25% of shoot mass and the nutrient concentration was the same in both tissues (Ericsson 1995; Duncan et al., 2007). Therefore, P remaining in the root medium at the end of the production phase was calculated by

subtracting all other P sources from the total PO_4-P applied as fertilizer. The budget for Expt. 1 is presented as % P of the total applied for each of these categories (Table 2.5).

The P budget for Expt. 1's post-production phase was different in two ways: it included PO_4-P recovered in leachate after the production phase ended, and $P_{shoots} + P_{estimated\ in\ roots}$ were determined from harvest of the second plant in each two-pot replicate, as follows:

$$PO_4\text{-}P_{fertilizer} = PO_4\text{-}P_{leachate\ (production)} + PO_4\text{-}P_{leachate\ (post\text{-}production)} + P_{shoots} + P_{est.\ roots} + P_{root}$$

$$medium$$

The budgets for Expt. 2 took into consideration the initial P in the calcined materials and were calculated as:

$$P_{initial\ root\ medium} + PO_4\text{-}P_{fertilizer} = PO_4\text{-}P_{leachate} + P_{shoots} + P_{root\ medium+\ roots}$$

Initial P in the root media was determined and total PO_4-P applied as fertilizer was known. At the end of the production phase, PO_4-P recovered in the leachate, shoots, and root medium + roots were determined. The budgets indicate that of the initial P in the root medium + PO_4-P applied as fertilizer, 85% to 97% of P was recovered in leachate, shoots, and root media + roots (Table 2.6).

The P budget for Expt. 2's post-production phase was different in two ways: it included PO_4-P recovered in leachate after the production phase ended, and P_{shoots} was determined from harvest of the second plant in each two-pot replicate, as follows:

$$P_{initial\ root\ medium} + PO_4\text{-}P_{fertilizer} = PO_4\text{-}P_{leachate\ (production)} + PO_4\text{-}P_{leachate\ (post\text{-}production)} +$$

$$P_{shoots} + P_{root\ medium+\ roots}$$

Statistical analyses. Data were analyzed using the general linear model procedure (PROC GLM, SAS ver. 9.1; SAS Inst., Cary, NC). Multiple comparisons among treatments were made using Fisher's LSD with an experiment-wise α level of 0.05. The treatment variable 'percent of

incorporation' was nested within the treatment variable 'calcined material'. Some growth data and PO_4-P in leachate was measured over time and analyzed using repeated measures analysis (PROC GLM, SAS ver. 9.1; SAS Inst., Cary, NC)

Results and Discussion

Physical properties. In Expt. 1, the treatment mixes that contained calcined materials all had similar physical properties. The calcined materials increased the bulk density, container capacity and total porosity of treatment mixes in relation to the PP control (Table 2.2). Incorporating 30% of calcined material into 70% peat : 30% perlite increased total porosity by 15 to 19%. Air filled porosity (AFP) was not different between the mixes and PP control; therefore, differences in total porosity between the PP control and mixes with calcined materials was as a result of increases in container capacity, a measure of how much plant available water the root media can hold. In Expt. 2, however, the bulk density, container capacity and air filled porosity of treatment mixes with 5% DE and 5% TG were not significantly different from the PP control. Mixes with 10% DE, TG and AS and 5% AS had different physical properties compared to the PP control (Table 2.2).

The increased bulk density provided by the calcined materials would stabilize containers during production, shipping, and marketing, but it would also increase freight costs if more than 5% calcined material is incorporated. The increased porosity and container capacity provided by the calcined materials may translate to a reduced need for watering during production and post-production. The relatively high total porosities indicate a significant contribution of internal pore space by the aggregates of the calcined materials to the media.

Growth response, Expt. 1. The 'clay' x 'P rate' interaction was significant. The PP

control resulted in the largest plants at 5 mg·L^{-1} PO$_4$-P based on height, width, and fresh and dry

shoot weights compared to the treatments with calcined materials (Table 2.3). This suggests that,

at the lowest rate of P applied, calcined materials reduced the PO$_4$-P concentration in the root

medium solution, thus decreasing PO$_4$-P availability to plants. At 45 mg·L^{-1} PO$_4$-P, calcined

materials did not result in different plant height or dry weights compared to the PP control. At 15

mg·L^{-1} PO$_4$-P, the treatment containing TG resulted in similar height as in the PP control, but

plants with AS clay and DE only were shorter than the PP control. The dry weight of plants in

the PP control, however, were higher with 15 mg·L^{-1} PO$_4$-P compared to plants grown in

calcined materials. It is important to note that plants grown in the PP control received three

additional fertilizer applications compared to plants in other treatments because they dried down

more frequently, and this difference may partially explain this result.

Across P rates, plants grown in the DE control were not different from plants

grown in treatments with either of the calcined materials with the exception of TG at 15 mg·L^{-1}

PO$_4$-P based on height, width, fresh and dry weight. Diatomaceous earth resulted in a similar

plant response as calcined clays.

Not surprisingly, the 'P rate' main effect was highly significant. Plant fresh and

dry weights increased relative to increasing PO$_4$-P rates. Five mg·L^{-1} PO$_4$-P resulted in plants

that were small due to P deficiency. Height, width, and number of flowers was similar between

plants grown at 15 and 45 mg·L^{-1} PO$_4$-P, but fresh and dry weights were greater at the highest

PO$_4$-P rate (Table 2.3, Fig. 2.2A and 2.3A).

The effect of 'percent of incorporation (clay)' was significant for all growth

measurements except height. The DE control and 5% rate of clay incorporation resulted in

smaller width, fewer flowers, and lower fresh and dry weights compared to 10% and 20% incorporation rates; plants grown in mixes with 10% AS were sometimes the exception (Table 2.3). This interaction is complicated by the fact that all treatments except the PP control contained 30% calcined materials; DE and calcined materials were combined in different ratios.

The 'clay' main effect was significant for all growth measurements. The PP control resulted in largest plants based on all growth parameters, followed by TG based on height, flower number, and fresh weight (Table 2.3, Fig 2.4).

Growth response, Expt. 2. The 'clay' by 'P rate' interaction was significant for all growth measurements except number of flowers (Table 2.4). Similarly, the 'P rate' main effect was highly significant for all growth measurements. Plants receiving no PO_4-P were, not surprisingly, severely P deficient, resulting in very small plants compared to those receiving 15 or 45 mg·L^{-1} PO_4-P. The '0 PO_4-P' treatments were included not to assess plant growth, but to provide a means to measure PO_4-P in leachate from the calcined materials.

Based on the 'P rate' main effect, plants receiving 15 and 45 mg·L^{-1} PO_4-P were not different based on any growth measurement (Table 2.4). In the 'clay' by 'P rate' interaction, plants receiving 15 and 45 mg·L^{-1} PO_4-P were not different based on height, width, fresh or dry weight regardless of treatment mix, except for DE (Table 2.4; Fig. 2.2B and 2.3B). Plants grown in mixes with DE were smaller based on dry weight when fertilized with 15 mg·L^{-1} PO_4-P compared to 45 mg·L^{-1} PO_4-P. It appears that DE is making some PO_4-P unavailable for plant uptake which results in a growth reduction. This is surprising because DE did not appear to sorb PO_4-P in the laboratory experiments (Chapter 1).

The 'percent of incorporation (clay)' was significant only for plant height. The PP control resulted in comparable plants as 5% AS and 10% AS and TG. The 10% TG treatment resulted in larger plants than the 5% TG treatment (Table 2.4).

The 'clay' main effect was significant based on all growth measurements. Plants grown in treatment mixes with DE were smaller based on fresh and dry weights and number of flowers compared to plants produced in other mixes (Table 2.4). Plants grown in AS and TG treatment mixes were similar to the PP control with the inconsequential exception of height of TG plants, which were 0.5 cm shorter than the PP control plants. Similar plant growth occurred in the PP control and treatment mixes suggesting that incorporation of calcined materials at 10% or less does not compromise plant growth.

Tissue Analyses, Expt. 1. Not surprisingly, the main effect of 'P rate' was highly significant. The amount of P in impatiens tissue increased as PO_4-P fertilizer rate increased. The lowest rate of PO_4-P application, 5 $mg \cdot L^{-1}$, resulted in P tissue concentrations of only 0.18%, which suggests deficiency. Phosphorus values reported in healthy *Impatiens wallerana* leaves are 0.71% (Nelson, 1994) and 0.77 to 0.92% (Mills and Jones, 1996). Plants fertilized with 15 and 45 $mg \cdot L^{-1}$ PO_4-P resulted in whole shoot tissue P concentrations of 0.40% and 0.79%, respectively (Table 2.5). Therefore, P tissue concentrations of only the plants receiving 45 $mg \cdot L^{-1}$ PO_4-P fell within this range, though it is not possible to directly compare our results from whole shoots with the standards, which were determined on leaves only. Although plants fertilized with 15 and 45 $mg \cdot L^{-1}$ PO_4-P resulted in comparable growth, those receiving 45 $mg \cdot L^{-1}$ PO_4-P had nearly twice the amount of P in the shoot tissue (Table 2.5). This result supports the widely-held belief that the greenhouse industry generally applies more PO_4-P fertilizer than is necessary for maximum growth response.

The tissue P concentration in the PP control plants was similar as in all other treatment mixes at each PO_4-P rates (Table 2.5) despite receiving three additional applications of fertilizer solution.

Interestingly, the PP control resulted in plants with lower tissue nitrogen (N) concentration than other treatments (Table 2.5). This response may be explained as a factor of dilution: the PP control plants were larger, so the similar amount of N applied to all treatments was more diluted in their tissue. Levels of N reported in leaves of healthy impatiens is 3.9% (Nelson) and 3.6 to 5.8% (Mills and Jones, 1996), which the plants in this experiment were generally just below. Because we analyzed whole shoots, which have lower tissue nutrient concentrations than leaves, tissue N levels of our experimental plants were adequate.

Potassium (K) in tissue was greatest at the highest percent of clay incorporation, 20% (Table 2.5). This may have occurred because the clays themselves contributed additional K to the production system. Levels of K reported in leaves of healthy impatiens is 3.47% (Nelson, 1994) and 1.37 to 2.35% (Mills and Jones, 1996); K in impatiens whole shoot tissue in this experiment ranged from 2.2 to 3.3% (Table 2.5).

Tissue analysis, Expt. 2. There was an interaction of 'clay' by P rate' for Total N and P in shoots after both the production and post-production phase. The amount of P in Impatiens tissue increased as PO_4-P fertilizer rate increased. Treatments receiving no PO_4-P (0 mg·L^{-1} treatment) resulted in P tissue concentrations of only 0.06% to 0.09%, which falls within the minimum critical range of 0.08% (Gibson et al., 2007) and indicates severe P deficiency. Plants fertilized with 45 mg·L^{-1} PO_4-P resulted in twice as much P in tissue compared to those fertilized with 15 mg·L^{-1} PO_4-P (Table 2.6), but between AS and TG clays, this difference was not significant. The

P tissue concentrations of plants receiving 45 mg·L^{-1} PO$_4$-P fell within the range of values for healthy impatiens leaves (Nelson, 1994; Mills and Jones, 1996).

Treatments with no PO$_4$-P (0 mg·L^{-1} treatment) resulted in N tissue concentrations of only 1.3% to 2.0% at the end of the production phase. Plants fertilized with 15 and 45 mg·L^{-1} PO$_4$-P resulted in similar tissue N concentrations between PP controls and the clays (2.7% to 3.2%). In DE controls, however, the 45 mg·L^{-1} PO$_4$-P treatment had lower tissue N (3.3%) than plants receiving 15 mg·L^{-1} PO$_4$-P (3.8% tissue N; Table 2.6).

In the post-production phase, only plants receiving 15 and 45 mg·L^{-1} PO$_4$-P were used. Phosphorus tissue results from the production and post-production phases are not directly compared.

PO$_4$-P in leachate, Expt. 1. Phosphate in leachate changed over time (Table 2.7), and interactions occurred between 'clay' and 'time' as well as 'P rate' and 'time' (Table 2.7; Figs. 2.6A, 2.7A, 2.8A, 2.9A). The 'clay' by 'time' interaction indicates that the DE control sorbed a significant amount of PO$_4$-P compared to the clays and PP control at week 1 (Fig. 2.6A). Thereafter, clay and the DE control resulted in PO$_4$-P leachate concentrations that were similar except at week 3 where the DE control had significantly more PO$_4$-P in leachate. The PP control had significantly higher PO$_4$-P leachate concentrations compared to other treatments from the second week after transplanting and forward (Fig. 2.6A).

The 'P rate' by 'time' interaction at 5 mg·L^{-1} PO$_4$-P (Fig. 2.7A) shows that the PP control resulted in PO$_4$-P concentrations in the leachate similar to the other treatments except at week three when the PP and DE controls had significantly more PO$_4$-P in leachate than clay-containing treatments. Therefore, at very low rates of PO$_4$-P application, the calcined materials do not affect PO$_4$-P in leachate.

However, at 15 mg$\cdot$L^{-1} rate of PO$_4$-P application, the PP control resulted in more PO$_4$-P in leachate compared to other treatments with the exception of the DE control at weeks 3 and 5 (Fig. 2.8A). This trend was even more pronounced when 45 mg$\cdot$L^{-1} PO$_4$-P was applied (2.9A). The calcined materials reduced the amount of PO$_4$-P in leachate at rates of PO$_4$-P fertilizer application of 15 mg$\cdot$L^{-1} PO$_4$-P and higher.

Although DE did not exhibit ability to sorb PO$_4$-P in laboratory characterization (Chapter 1), it reduced PO$_4$-P in leachate similar to the media with calcined clays. This observation is complicated by the fact that all treatment media had DE in the root medium mix in Expt. 1. However, the DE control with 30% DE resulted in the most pronounced reduction in PO$_4$-P in leachate at week 1 for all three rates of PO$_4$-P application (Fig. 2.7A, 2.8A, and 2.9A)—a result that was contrary to its lack of PO$_4$-P sorption capacity.

PO$_4$-P in leachate, Expt. 2. As in Expt. 1, PO$_4$-P in leachate changed over time (Table 2.7), and interactions occurred between 'clay' and 'time' as well as 'P rate' and 'time' (Table 2.7; Figs. 2.6B, 2.7B, 2.8B, 2.9B). The 'clay' by 'time' interaction shows that the PP control resulted in the highest amount of PO$_4$-P in leachate across the entire production period with about 5 mg$^.$L^{-1} more PO$_4$-P in the leachate at every irrigation compared to the mixes with calcined materials. All of the calcined materials performed similarly in reducing the amount of PO$_4$-P in leachate (Fig. 2.6B), including DE, which in Expt. 2 was a separate treatment mix. Therefore, it appears that DE's absorbent properties result in PO$_4$-P retention when root medium solution is absorbed by the calcined material. This physical mechanism of PO$_4$-P sorption was not a component of the laboratory characterization studies that evaluated chemical mechanisms of PO$_4$-P sorption (Chapter 1).

The 0 mg·L $^{-1}$ PO$_4$-P fertilizer rate was included to evaluate whether the root media themselves contributed to and leached PO$_4$-P from the production system. We found that the while the PP control resulted in slightly higher PO$_4$-P concentrations in leachate over the course of the production cycle, none of the mixes resulted in more than 1.6 mg·L $^{-1}$ PO$_4$-P leached (2.7B).

At both 15 and 45 mg·L $^{-1}$, the PP control resulted in the highest PO$_4$-P in leachate over the entire production period (2. 8B and 2.9B). The trend of PO$_4$-P leached by mixes with DE showed that the greatest PO$_4$-P sorption occurred at the beginning of the production cycle and then decreased slightly. This was in contrast to the relatively steady PO4-P sorbed by the mixes with clays. This observation may indicate differences in PO$_4$-P sorption mechanisms between the clays and DE.

Production phase P budget, Expt. 1. Leachate. During the production phase, a three way interaction of 'clay' x P rate' x 'percent (clay)' was significant for PO$_4$-P in leachate (Table 2.8). The main effects 'P rate', 'percent (clay)', and 'clay' were significant. The PO$_4$-P in leachate increased as rate of PO$_4$-P fertilizer increased. The greatest percent of PO$_4$-P that was leached occurred from the PP control and 5% AS root media fertilized with 45 mg·L^{-1} PO$_4$-P (22 to 24% PO$_4$-P; Table 2.8). A similar result occurred at the 5 mg·L^{-1} PO$_4$-P rate: more PO$_4$-P leached from treatments with 5% AS (11%) and the PP control (13%) than any of the other treatments. Most of the 15 mg·L^{-1} PO$_4$-P treatments resulted in less PO$_4$-P in leachate compared to those receiving 45 mg·L^{-1} PO$_4$-P; the exception was treatments with 10% and 20% AS that had similar PO$_4$-P in leachate at both 15 and 45 mg·L^{-1} PO$_4$-P (Table 2.8).

The effect of 'percent (clay)' was confounded in Expt. 1 because DE was in the treatment recipes. The DE control (30% DE) resulted in similar PO$_4$-P in leachate as 10% and 20% AS and

5% and 20% TG. However, at the 45 mg·L^{-1} PO$_4$-P rate, root media with 10% TG resulted in significantly less PO$_4$-P in leachate compared to those with 5% and 20% TG (Table 2.8).

The 'clay' main effect was significant. The calcined materials reduced the amount of PO$_4$-P in leachate compared to the PP control (13 to 16% versus 19%, respectively; Table 2.8). Root media with TG reduced the amount of PO$_4$-P leached by almost 6% compared to the PP control. Unexpectedly, the DE control reduced PO$_4$-P in leachate similarly to the mixes with clays. The reduction of PO$_4$-P in leachate occurred when labile PO$_4$-P (H$_2$PO$_4^-$ and HPO$_4^{2-}$) was adsorbed to mineral surfaces (precipitation and adsorption), which we speculate occurs by TG and AS, or absorbed by the root medium components, which we speculate occurs by DE, TG, and AS.

Phosphorus in shoot tissue. Phosphorus in shoot tissue was different due to main effects of 'percent (clay)', 'clay' and 'P rate' in Expt. 1 (Table 2.8). The PP control resulted in the greatest percent of applied PO$_4$-P to be taken up by the shoots (37%) and media with 5% AS resulted in the lowest percent of P in shoots (19%; Table 2.8).

Calcined materials resulted in similar percent P in shoot tissue. The PP control resulted in almost 10% more P in shoots compared to plants in media with calcined materials. PO$_4$-P was more available for plant uptake in media that did not sorb it, which may have resulted in a higher root medium solution PO$_4$-P concentration and increased PO$_4$-P uptake. In addition, the PP control received three additional fertilizer applications which amounted to about 30% more PO$_4$-P applied per pot compared to the media with calcined materials (Table 2.8).

Estimated PO$_4$-P in root medium after production. The main effects of 'percent(clay)', 'clay' and 'P rate' were significant for percent PO$_4$-P remaining in the root medium (Table 2.8). The PP control resulted in the least amount of PO$_4$-P remaining in the pot compared to media

with clays and the DE control; a difference of 11% to 24% PO_4-P retained by the root medium occurred between the PP control and all other treatments.

The main effect of 'P rate' showed that percent PO_4-P remaining in the root medium was much greater for the 5 mg·L^{-1} PO_4-P rate (63%) compared to the 15 and 45 mg·L^{-1} PO_4-P rates (42% and 49%, respectively; Table 2.8). This suggests that—especially at low rates of P application—sorptive root media can deprive plants of PO_4-P.

Post-production phase P budget, Expt. 1. Leachate during post-production. The three-way interaction of 'clay', 'percent(clay)' and 'P rate' was significant; the significant main effects of 'clay' and 'P rate' contributed to this interaction (Table 2.9). The percent of PO_4-P in leachate increased as P fertilizer rate increased in the PP and DE controls. The 45 mg·L^{-1} PO_4-P treatments resulted in most percent PO_4-P lost. The 5 and 15 mg·L^{-1} PO_4-P treatments had similar percent PO_4-P in leachate when 10% and 20% AS and 20% TG were in root media. The 5% AS and TG and 10% TG treatments had higher percent PO_4-P in leachate when 5 mg·L^{-1} PO_4-P was applied compared to the 15 mg·L^{-1} PO_4-P rate (Table 2.9).

The 'clay' by 'P rate' interaction was also significant. Treatments that leached the most PO_4-P were the PP control when 15 and 45 mg·L^{-1} PO_4-P was applied and the DE control at 45 mg·L^{-1} PO_4-P (3.2% to 3.6%; Table 2.9). Compared to all treatments with clays, the PP controls leached more PO_4-P. The percent PO_4-P lost at 5 mg·L^{-1} PO_4-P from the PP control was comparable to percent PO_4-P lost at 45 mg·L^{-1} PO_4-P rate in clays. The clays were very effective at reducing percent PO_4-P lost at 15 and 45 mg·L^{-1} PO_4-P.

There was a difference between PO_4-P leached from the DE control and mixes with clays at PO_4-P rates of 15 and 45 mg·L^{-1}. The percent PO_4-P lost at the 15 mg·L^{-1} PO_4-P rate in the DE control was similar to that lost at 45 mg·L^{-1} PO_4-P in clay treatments (Table 2.9). This suggested

that the PO_4-P retained by DE during the production phase may be due to its high absorbency and the porosity of its structure. We hypothesize that the DE granules absorb large amounts of the root medium solution, carrying PO_4-P and other ions into the porous structure and retaining it by a physical rather than chemical means. During the post-production phase when plain water was used for irrigation, therefore, the PO_4-P was leached out of the DE control, but the calcined clays were perhaps still retaining some PO_4-P via chemical mechanisms.

Phosphorus in shoot tissue during post-production. The main effect of 'clay' was significant for P tissue in shoots (Table 2.9). The treatments resulting in greatest P in shoots were the PP control and those with calcined clays (15% to 21%). The DE control had P in shoots comparable to the treatments with AS clays but significantly less than mixes with TG or the PP control.

The main effect of 'P rate' was also significant for P tissue in shoots (Table 2.9). The treatments receiving 5 mg·L^{-1} PO_4-P had lower P in shoots compared the 15 and 45 mg·L^{-1} PO_4-P rates. The lower percent of PO_4-P in shoots and, as discussed previously, the higher percent PO_4-P in leachate for the 5 mg·L^{-1} PO_4-P treatment suggests that mixes with calcined materials may reduce plant-available PO_4-P, especially at low rates of application. Bunt (1988) noted that calcined clays altered the physical attributes of media in a positive way, but also decreased the level of water-soluble PO_4-P in the mix; therefore, fertilizer application rates may need to be modified if calcined aggregates were incorporated into root media.

Estimated PO_4-P in root medium after post-production. The main effects of 'clay' and 'P rate' were significant for PO_4-P estimated to remain in the root medium at the end of the post-production phase (Table 2.9). More than 65% of PO_4-P applied remained in mixes with TG and

AS calcined clays as components, followed by up to 58% in the DE control. The PP control retained the least amount of PO_4-P at 51% (Table 2.9). The 'P rate' main effect is explained by the result that the 5 mg·L^{-1} PO_4-P treatment had more PO_4-P remaining in the root medium (72%) compared to the 15 and 45 mg·L^{-1} PO_4-P rates (53% to 57%; Table 2.9).

Production phase P budgets, Expt. 2. Leachate. The interaction of 'clay' by 'P rate' and main effects of 'percent(clay)', 'clay' and 'P rate' were significant for PO_4-P in leachate during production in Expt. 2 (Table 2.10). Not surprisingly, PO_4-P in leachate increased as P rate applied increased. Treatments with no PO_4-P applied had very low PO_4-P in the leachate. Among the clay treatments, amounts of 0.1 to 0.2 mg PO_4-P were recovered in the leachate when no PO_4-P fertilizer was applied. The PP control fertilized with 45 mg·L^{-1} PO_4-P resulted in the highest amount of PO_4-P in leachate, 22.9 mg. At both 15 and 45 mg·L^{-1} PO_4-P rates, leachate PO_4-P was higher in the PP controls compared to calcined materials fertilized at the same PO_4-P rate. At 15 mg·L^{-1} PO_4-P, the PP control had twice as much PO_4-P in leachate compared to mixes with calcined materials.

Just as in Expt. 1, the 'clay' main effect showed that about twice the amount of PO_4-P was lost in the PP control (10.5 mg) compared to the mixes with calcined materials (5.3 to 5.8 mg; Table 2.10). The DE behaved very similarly to the clays in reducing PO_4-P in leachate during the production phase. This response is clear in Expt. 2 because the treatment mixes contained only one calcined material and not combinations of clays + DE, as in Expt. 1.

Phosphorus in shoot tissue. The interaction between 'clay' and 'P rate' and the 'clay' and 'P rate' main effects were significant (Table 2.10). The amount of P in shoots increased as P rate applied increased. Amounts of P recovered in plant shoots when no PO_4-P was applied were 0.1

to 0.4 mg. The PP control and treatments with DE and TG that were fertilized with 45 mg·L^{-1} PO$_4$-P resulted in the highest amount of P in shoot tissue (23.6 to 26.7 mg), though the AS clay had lower P in shoot tissue (18.1 mg) at this highest P rate. At PO$_4$-P rates of 15 mg·L^{-1}, the PP control, AS and TG had a similar amount of P in shoot tissue (8.1 to 12.5 mg). The mixes with DE and AS resulted in the lowest amount of P in shoot tissue (7.5 to 8.1 mg).

The 'clay' main effect showed that AS and DE calcined materials had comparable amounts of P in shoot tissue (8.9 and 10.5 mg, respectively), which was less than P in shoots from root media with TG and the PP control (11.9 and 13.1 mg, respectively; Table 2.10). .

Phosphorus in root medium after production. The interaction of 'clay' by 'P rate' and main effects of 'percent(clay)', 'clay' and 'P rate' were significant for P in the root media at the end of the production cycle in Expt. 2 (Table 2.10). At the 45 mg·L^{-1} PO$_4$-P rate, AS had the most P in the root medium followed by TG and DE which had similar P. The PP control resulted in the least P remaining in the mix. The trend was similar at PO$_4$-P rates of 0 and 15 mg·L^{-1} PO$_4$-P.

The main effect of 'percent(clay)' showed that at the end of the production phase, mixes with AS retained the most P in the root medium: 277 mg at the 10% incorporation rate and 110 mg at the 5% incorporation rate. Mixes with 5% and 10% TG and 10% DE retained 81 to 87 mg P at the end of the production phase. The PP control only had 35 mg P left in the mix. Phosphorus remaining in the mix decreased as AS and DE incorporation rates decreased from 10% to 5%, but this change did not occur as incorporation rate of TG decreased.

Post-production phase P budget, Expt. 2. Leachate during post-production. The interaction of 'clay' and' P rate' and main effect of 'percentage(clay)' were significant for

amount of PO_4-P leached during post production in Expt. 2 (Table 2.11). At the 45 mg·L^{-1} PO_4-P

rate, the PP control and mixes with DE had higher PO_4-P in leachate than the those with TG and

AS clays. At the 15 mg·L^{-1} PO_4-P rate, mixes with AS and DE were not different from the PP

control; mixes with TG, however, resulted in less PO_4-P in leachate. Generally, the P rate of 45

mg·L^{-1} PO_4-P resulted in more PO_4-P in leachate than 15 mg·L^{-1} PO_4-P. Interestingly, mixes with

10% clays leached a greater amount of PO_4-P compared to mixes with 5% clays. The trend was

similar, but not significant, for DE. Plants were irrigated with plain water in the post-production

phase, and it appears that higher rates of clay incorporation resulted in greater PO_4-P release.

Phosphorus in shoot tissue during post-production. The main effects of 'clay' and 'P

rate' were significant for P in shoots (Table 2.11). The PP control resulted in 3 mg more P in

shoots than in the other treatments that had calcined materials as components. The P retention by

the calcined materials reduced the P in the root medium solution, reducing the amount of P for

plant uptake. The P in shoots increased with as PO_4-P rate increased.

Phosphorus in root medium after post-production. The main effects of 'clay',

'percent(clay)' and 'P rate' were significant for P recovered from the root medium at the end of

the post-production phase (Table 2.11). The root media with AS clay had the most P (191 mg),

followed by those with DE and TG calcined materials (89 to 99 mg); the PP control had the least

P remaining in the mix (only 34 mg). This trend was consistent with the amounts of P recovered

in the root media at the end of the production phase. Higher percentages of AS and TG clays

resulted in more P remaining in the root medium (Table 2.11).

This study revealed differences of calcined materials (calcined clays and DE) and

standard 70 peat: 30 perlite media with regard to P retention. Despite the short growth cycle of 4

and 8 weeks of production, there was a significant difference in PO_4-P leachate among the media mixes compared to the PP controls. Although the isotherm studies on the AS, TG clays and DE revealed very low sorption of PO_4-P by DE as compared to the two clays under study (Fig 1), it was evidenced that DE 'retained' or 'fixed' phosphate with equal magnitude as the clays. Technically the DE and the calcined clays retained PO_4-P, making our design of Expt. 1 become a comparison between 30% substrate components and the standard 70 peat : 30 perlite soilless media. The calcined materials and DE can have a great effect in reduction of P in greenhouse effluents. Questions therefore arise concerning the mechanisms of P retention at play, from the study, we hypothesize the mechanism of retention between DE and the 2:1 calcined clays is different but more comparable to that of PP media (2.6A). Sorptive properties of DE could be responsible and PO_4-P could be retained along with the water (in solution). The effects obtained may be ascribed to specific chemical characteristics of the clays or physical effects that come as a result of calcining and seemed to play an important role in effectiveness of PO_4-P sorption of calcined material in mixtures. Calcining enhanced the sorptivity of these materials. More studies should be carried out to evaluate the effect of heating on the surface area, pore structure etc. of these calcined materials.

The study also suggested that an optimal rate of clay incorporation would be 10 to 20%. Calcined clays not only improved PO_4-P retention but also water retention (water use efficiency) while still maintaining optimal physical properties. The growth of the impatiens plants was optimal in the PP control but did not differ significantly from the growth of the impatiens in the clay amended root medium at 15 mg L^{-1} P-rate. The particle sizes used did not influence media performance in most cases.

It would, therefore, be beneficial to use clay in media because of the PO_4-P retention shown. This study points out that benefits of incorporating clays into media could lead to less PO_4-P run off from greenhouses and reduced water use by plants. Of primary concern, however, is the cost effectiveness of incorporating calcined materials into root media at recommended percentages and the lack of uniformity in performance. A balance develops between P availability, uptake, fixation and release depending on the physical and chemical characteristics of the resulting root media with incorporated calcined materials. The treatment with DE had least available PO_4-P.

Further study of this project could include different species of plants with the various root media and gauge post-production plant performance. The major question to be addressed concerns whether the PO_4-P retained in the root medium is available to the plant during post-production and the effect this would have in post-harvest longevity and tolerance to water stress. Reduced P availability during production is a potential method for preconditioning plants to cope with post-production stresses. Future studies should rate the benefit that the PO_4-P in the root medium is likely to confer to the post-production quality of plant.

Acknowledgements

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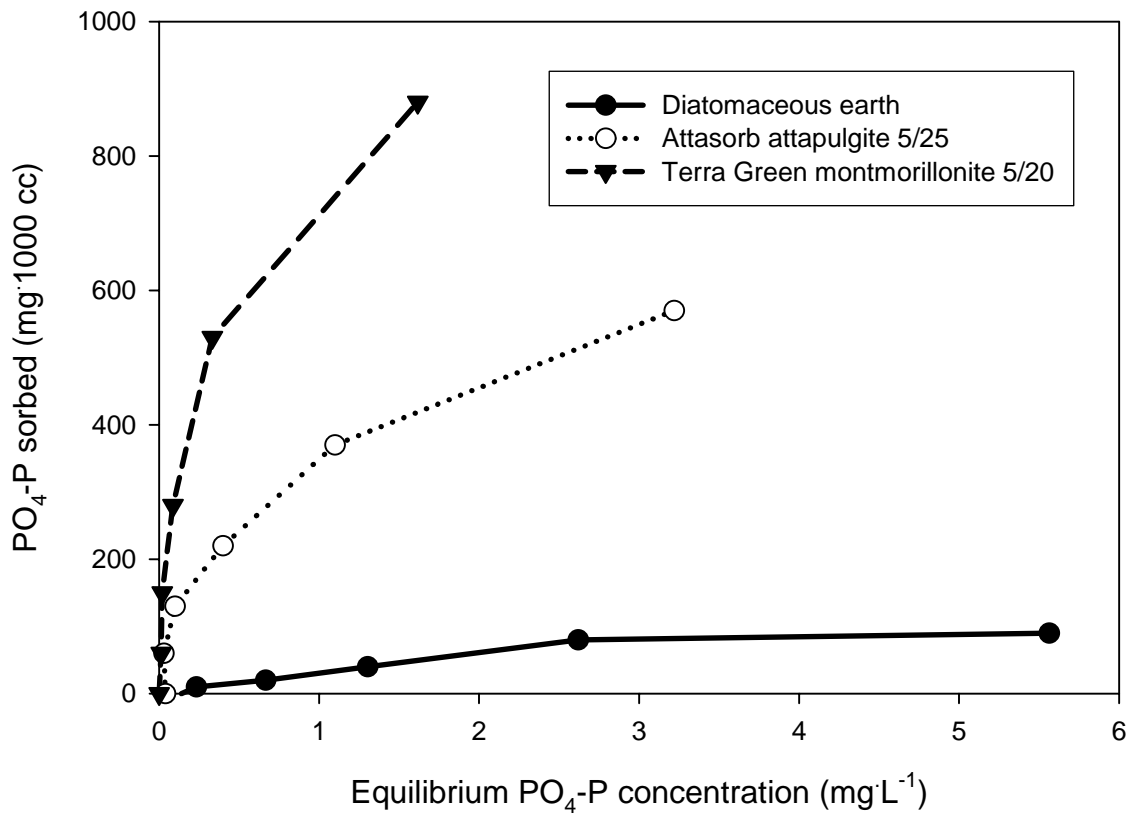
Figure 2.1 PO$_4$-P isotherm results of three absorbent products: diatomaceous earth (DE), Attasorb clay (AS) and Terra Green clay (TG) from batch experiments.
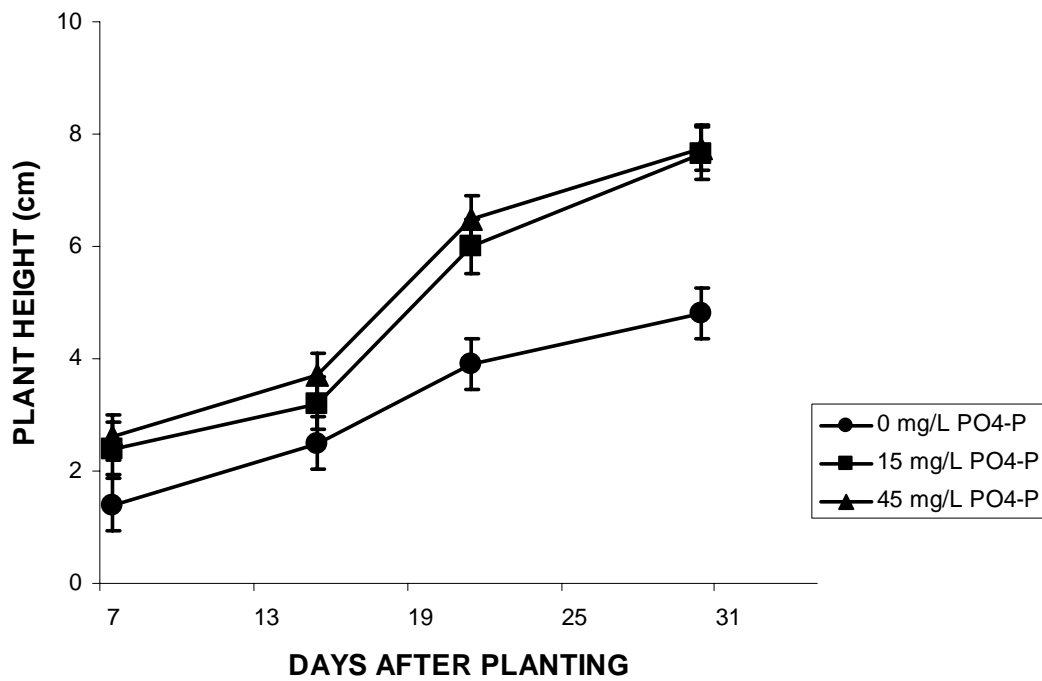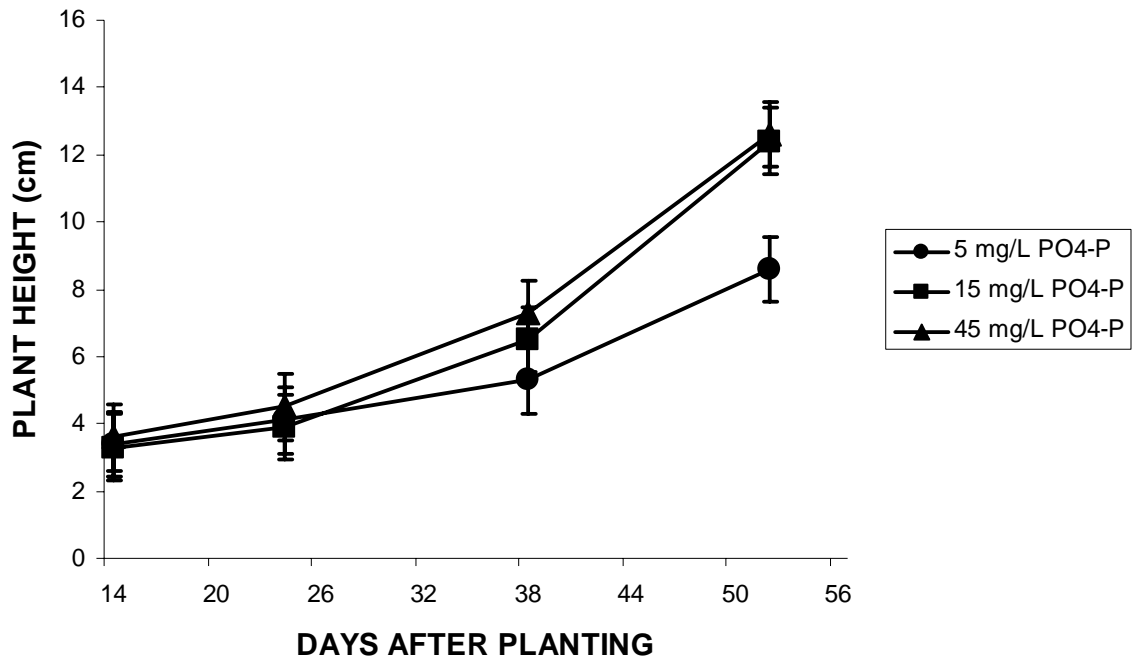
Figure 2.2 Plant heights taken over time during the production phase on days 14, 24, 38 and 52 days after transplant (DAT) in Expt. 1(A) and on 7, 15, 21 and 30 DAT in Expt. 2 (B).
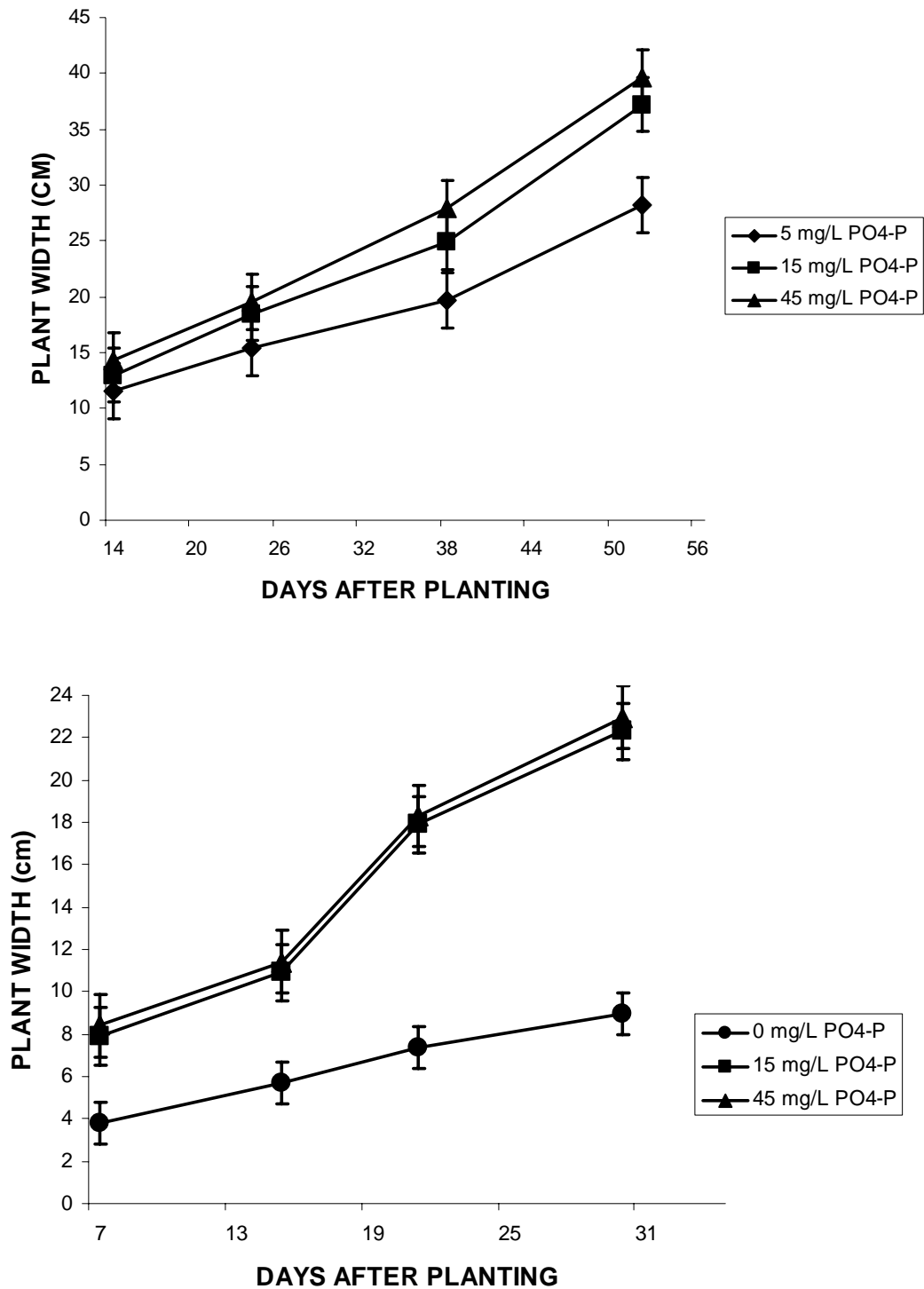
Figure 2.3 Plant widths taken over time during the production phase on 14, 24, 38 and 52 days after transplant (DAT) in Expt. 1 (A) and on days 7, 15, 21 and 30 DAT in Expt. 2 (B). The average of two width measurements taken at right angles to each other are reported.
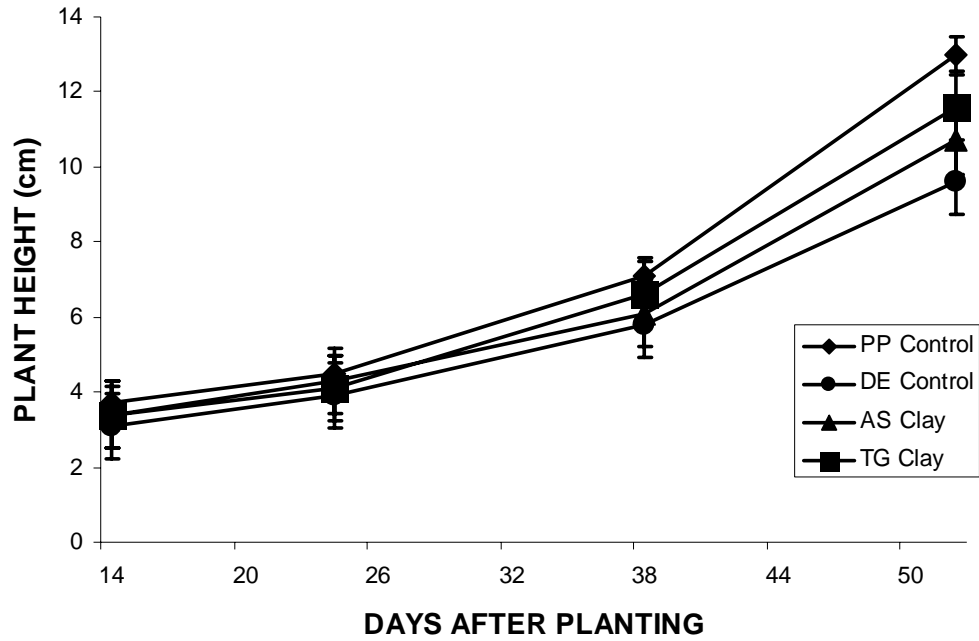
Figure 2.4 Effect of calcined material incorporation on height of *Impatiens wallerana* over time (Clay * Time). Plant heights were taken on days 14, 24, 38 and 52 days after transplant (DAT) in Expt. 1. Height was measured from the rim of the pot to the top of the foliage canopy.
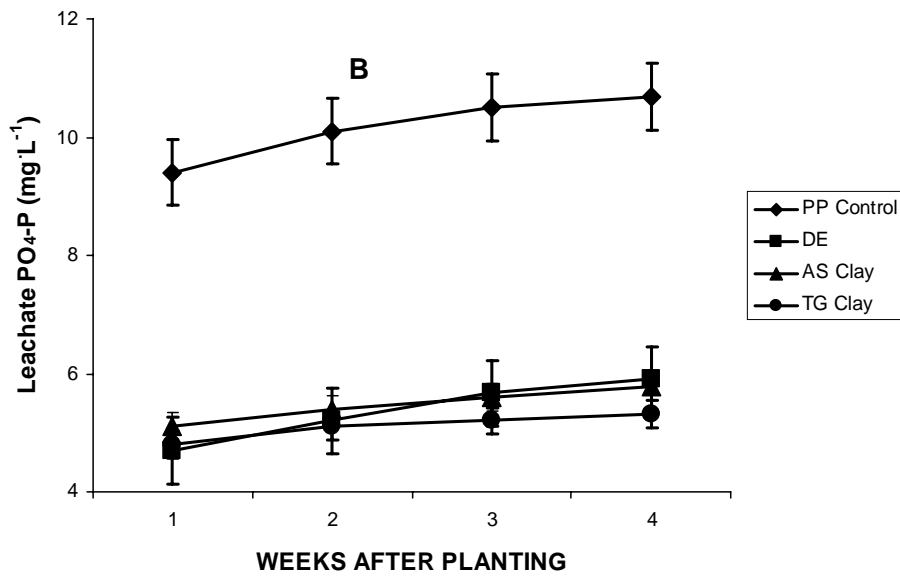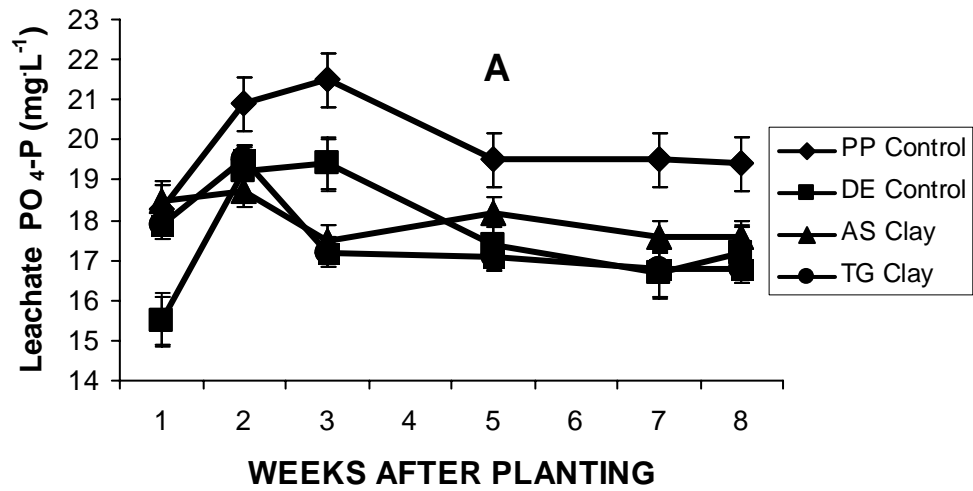
Figure 2.5 Changes in PO$_4$-P concentration in leachate collected from root media over time (Clay * Time) in Expt. 1 (A) and Expt. 2 (B).
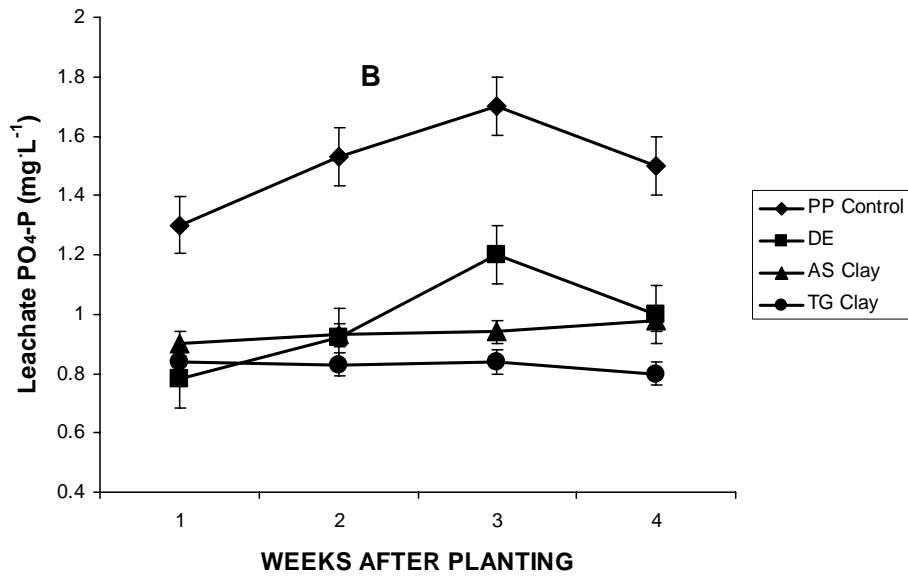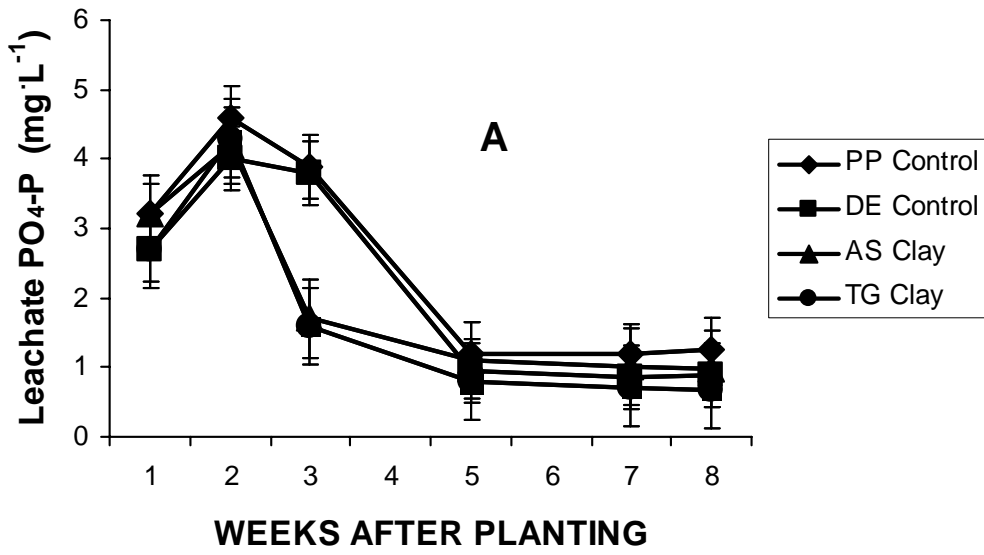
Figure 2.6 Changes in PO$_4$-P concentration in leachate collected from media fertilized with 5 mg$^.$L^{-1} (Expt. 1, A) and 0 mg$^.$L^{-1} PO$_4$-P (Expt. 2, B) over time (Clay * Time).
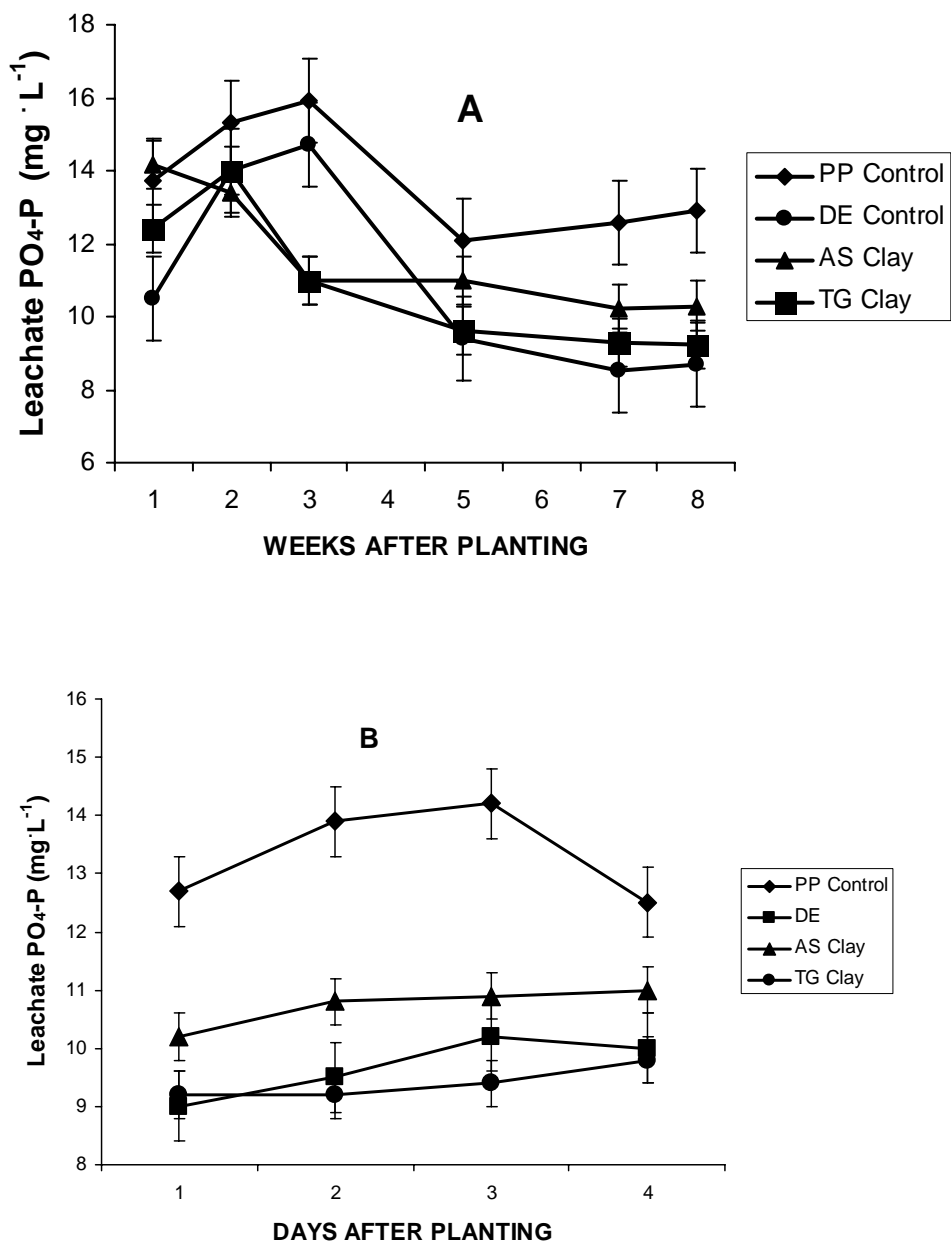
Figure 2.7 Changes in PO$_4$-P concentration in leachate collected from media fertilized with 15 mg·L^{-1} PO$_4$-P over time in Expt. 1 (A) and Expt. 2 (B) (Clay * Time).
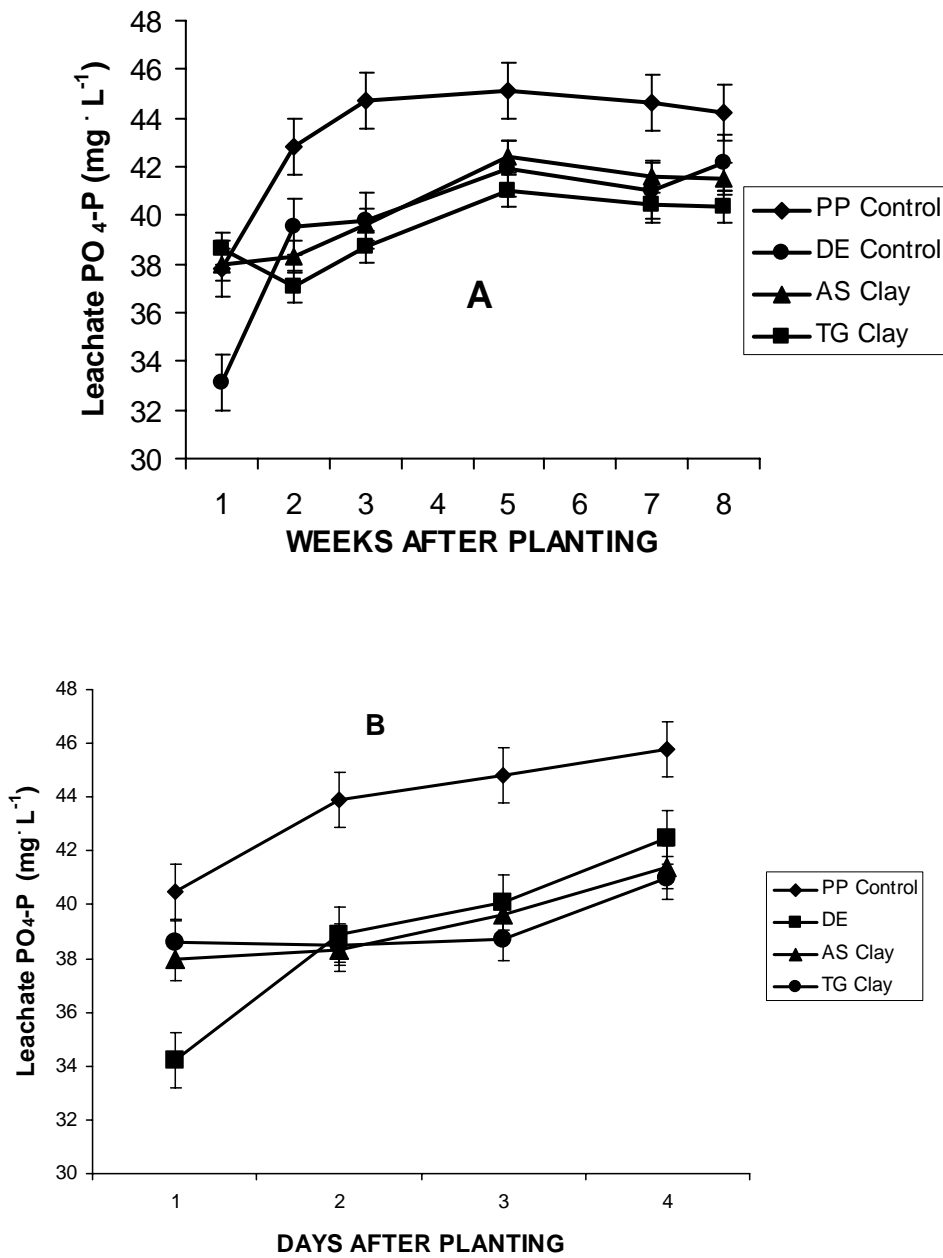
Figure 2.8 Changes in PO_4-P concentration in leachate collected from media fertilized with 45 $mg \cdot L^{-1}$ PO_4-P over time in Expt. 1 (A) and Expt. 2 (B) (Clay * Time).

Table 2.1 Calcined material characteristics from laboratory characterization in which bulk weight, pH, Total-P, PO_4-P sorption and Degree of Phosphorous Saturation (DPS) were established from batch experiments. Codes for the calcined materials include abbreviated trade name, clay type and mesh size.

Trade name and Code	Bulk Weight (g·1000 cm^{-3})	pH	PO_4-Psorption capacity g·m^{-3}	P-Mehlich extraction (mg/kg)[y]	Degree of phosphorous saturation % (DPS)	Comments
Attasorb A-LVM-5/25[z]	760ab	8.40a	620	19.5b	1.42	1-10% quartz 90-99% fullers earth
Terra Green montmorillonite T-M-5/20[z]	772a	3.75b	700	38.5 a	1.84	7-10% quartz 90-93% montmorillonite; from Mississippi mines
						BET[x] Surface area for Terra green LVM is 102 m^2.g^{-1}
Diatomite DE	370c	5.13c	28	19.5b	4.67	Diatomaceous earth
LSD$_{0.05}$[w]	13.5	0.44		14.8		

[z] Code name includes standard mesh size mesh size
[y] P extraction Mehlich III procedure.
[x] Specific surface area obtained from the standard Brunauer, Emmet and Teller (BET) procedure
[w] LSD, least significant difference. Differences between means greater than the LSD indicate significant differences at $p < 0.05$. Different letters indicate statistically significant differences.

Table 2.2 Physical properties of root media measured in 10 cm deep, 1.26 L round pots in Expt. 1 and 9.5 cm deep, 0.55 L round pots in Expt. 2 following the procedures of Niedziela and Nelson (1992).

Medium mix (v/v)	Bulk Density ($g \cdot cm^{-3}$)	Particle Density ($g \cdot cm^{-3}$)	Air Filled Porosity (%)	Container Capacity (%)	Total Porosity (%)
Experiment 1					
5 peat : 2 perlite : 3 DE	0.29a	0.35a	16.9	73.8a	90.8a
5 peat : 2 perlite : 2 AS : 1 DE	0.33a	0.40a	16.3	79.0a	95.3a
5 peat : 2 perlite : 2 DE : 1 AS	0.32a	0.37a	14.9	78.0a	92.9a
5 peat : 2 perlite : 2.5 DE : 0.5 AS	0.30a	0.39a	17.7	75.8a	93.5a
5 peat : 2 perlite : 2 TG : 1 DE	0.30a	0.38a	16.7	77.0a	93.7a
5 peat : 2 perlite : 2 DE : 1 TG	0.32a	0.39a	18.1	74.4a	92.5a
5 peat : 2 perlite : 2.5 DE : 0.5 TG	0.34a	0.42a	16.9	75.0a	91.9a
7 peat : 3 perlite	0.17b	0.20b	15.5	63.2b	78.7b
LSD$_{0.05}$	* *	*	NS [z]	*	**
Experiment 2					
7 peat : 2 perlite : 1 AS	0.27a	0.35a	8.7a	87.0a	95.7
7 peat : 2 perlite : 1 DE	0.27a	0.34a	9.2a	85.9ab	95.0
7 peat : 2 perlite : 1 TG	0.26a	0.34a	9.6a	88.4a	97.9
7 peat : 2.5 perlite : 0.5 AS	0.26a	0.33a	8.6a	86.1a	94.7
7 peat : 2.5 perlite : 0.5 DE	0.20b	0.29b	14.0ab	82.3ab	96.3
7 peat : 2.5 perlite : 0.5 TG	0.20b	0.27b	10.7a	79.5b	90.3
7 peat : 3 perlite	0.18b	0.25b	11.0a	79.6b	90.6
LSD$_{0.05}$	*	*	**	*	NS [z]

[z] NS, *, **, Nonsignificant or significant at P= 0.05, 0.01, respectively
  Different letters indicate statistically significant differences.

Table 2.3 Plant growth characteristics at the end of the production period (52 DAT; Expt. 1) of impatiens grown in 5 peat: 2 perlite: 3 calcined materials, the latter consisting of Attasorb (AS) or Terra Green (TG) clays at 5, 10 and 20% + DE. Controls had either inert diatomaceous earth (DE) incorporated at 30% (by volume) or consisted of 7 peat: 3 perlite.

	Height (cm)	Width (cm)	Number of flowers (no.)	Fresh shoot weight (g)	Dry shoot weight (g)
Block	NS[x]	NS	*	NS	NS
Clay	**	***	***	***	***
Percent (Clay)	NS	**	***	***	***
P rate	***	***	***	***	***
Clay * P rate	*	NS	*	*	*
Clay * Percent (Clay)* P rate	NS	NS	NS	NS	NS

Clay * Percent (Clay)* P rate

Controls

70 peat : 30 perlite [z] Control

5	12.0	18.8	54	123.3	6.8
15	14.8	21.2	62	170.1	7.9
45	12.3	20.4	50	169.8	8.6

30 Diatomite : 50 peat : 20 perlite[y]

5	6.5	11.9	20	36.9	1.5
15	10.3	17.5	39	101.2	5.2
45	12.0	19.5	45	127.3	7.3

Attasorb Clay (A-5/25)

5% AS : 25% DE

5	5.3	8.9	8	18.9	1.0
15	10.0	14.9	23	68.6	2.7
45	14.2	19.5	39	125.2	6.4

10% AS : 20% DE

5	7.5	12.8	20	36.5	1.7
15	12.3	17.9	46	108.0	5.0
45	12.3	19.0	51	132.8	6.3

20% AS : 10% DE

5	9.3	13.9	31	45.10	3.2
15	12.8	18.7	49	127.8	5.8
45	13.5	21.3	61	161.8	6.9

Terra Green Clay (T-M-5/20)

5% TG : 25% DE

5	8.7	13.4	18	49.2	2.1
15	11.8	17.7	34	90.5	4.1
45	12.5	17.7	46	136.5	6.0

10% TG : 20% DE

5	8.2	14.3	31	62.4	2.6

15	13.2	20.0	52.	143.7	6.4
45	13.0	20.9	57	152.7	7.2
20% TG:10% DE					
5	9.7	14.5	34	55.2	2.6
15	13.3	18.5	53	117.6	5.7
45	13.5	20.4	58	139.2	6.4
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**

Clay * P rate

Controls
70 :30 peat : perlite[z]

5	12.0ab	18.8	54b	129.3c	6.8b
15	14.8a	21.2	62a	170.2a	7.8a
45	12.3ab	20.4	50bc	169.8a	8.6a

30 Diatomite : 50 peat : 20[y] perlite[y]

5	6.5c	12.9	20e	36.9d	1.5d
15	10.3b	17.5	38bc	101.2bc	5.2c
45	12.0ab	19.5	45bc	127.3b	7.3ab

Attasorb Clay (A-5/25)

5	7.3c	12.9	19e	33.5d	1.9d
15	11.7b	17.2	39bc	101.5bc	4.5c
45	13.3ab	19.9	50bc	139.9b	6.5ab

Terra green Clay (T-M-5/20)

5	8.9bc	14.0	28d	55.6d	2.4d
15	12.8a	18.7	46bc	117.2bc	5.3c
45	13.0a	19.6	53b	142.8b	6.5b
LSD$_{0.05}$	**2.23**	**NS**	**6.87**	**20.91**	**1.31**

Percent (Clay)

0%					
70 :30 peat : perlite	9.6	20.1a	55a	156.4a	7.7a
30 Diatomite : 50 peat : 20 perlite	13.0	16.3b	34bc	88.5c	4.6bc
5%					
A-5/25	9.8	14.4b	23c	70.9cd	3.3c
T-M-5/20	11.0	16.2b	32c	92.0c	4.0c
10%					
A-5/25	10.7	16.6ab	39bc	92.4c	4.4c
T-M-5/20	11.5	18.4a	47a	119.6b	5.4b
20%					
A-5/25	11.8	17.9a	47a	111.6b	5.3b
T-M-5/20	12.2	17.8a	48a	104.0b	4.9b
LSD$_{0.05}$	**NS**	**1.86**	**8.89**	**14.74**	**0.97**

Clay

70 :30 peat : perlite[z]	13.0a	20.1a	55a	156.4a	7.7 a
30 Diatomite : 50 peat : 20[y] perlite	9.6c	16.3bc	34c	88.5c	4.6b
A-5/25	10.8bc	16.8bc	36c	91.6c	4.3b
T-M-5/20	11.6b	17.5bc	42b	105.2b	4.8b
LSD$_{0.05}$	**1.28**	**1.61**	**7.26**	**12.07**	**0.77**

P rate

5	8.7b	14.2b	30b	63.8c	3.2c
15	12.4a	18.6a	46a	122.5b	5.7b
45	12.6a	19.0a	49a	145.0a	7.2a
LSD$_{0.05}$ n=24	**1.1**	**1.38**	**6.29**	**10.45**	**0.63**

[z] Control containing 70 peat : 30 perlite of 7: 3 Peat perlite (industry standard)

[y] Control containing 30 Diatomite : 50 peat : 20 perlite

[x] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively.
Different letters indicate statistically significant differences.

Table 2.4 Plant growth characteristics at the end of the production period (30 DAT; Expt. 2) of impatiens grown in 7 peat: 2 perlite or 7 peat: 2.5 perlite media with diatomaceous earth (DE), Attasorb (AS), or Terra Green (TG) calcined materials at 5 or 10 % (by volume). The control consisted of 7 peat: 3 perlite.

	Height (cm)	Width (cm)	No. of buds	No. of flowers	Fresh shoot weight (g)	Dry shoot weight (g)
Block	*	*	NS [y]	*	NS	**
Clay	***	***	***	***	***	***
Prate	***	***	***	***	***	***
Percent (Clay)	*	NS	NS	NS	NS	NS
Clay*P rate	NS	NS	*	*	*	**
Percent (Clay)* P rate	NS	NS	NS	NS	NS	NS
Clay* Percent (Clay)*P rate	NS	NS	*	NS	NS	NS
Clay * Percent (Clay)* P rate						
Controls						
70 peat : 30 perlite [y]						
Control						
0	5.5	15.3	7b	3	3.5	0.2
15	7.5	22.3	15a	19	57.5	3.1
45	7.8	22.0	14a	25	59.5	3.1
30 Diatomite : 50 peat : 20 perlite						
5 Percent						
0	4.0	4.5	3c	2	3.1	0.9
15	7.5	22.3	12ab	13	39.0	2.0
45	7.3	24.0	16a	14	47.8	2.6
10 Percent						
0	3.8	4.0	3c	2	1.7	0.2
15	7.8	22.0	10ab	7	32.9	1.7
45	7.5	23.5	13ab	10	50.1	2.7
Attasorb Clay (A-5/25)						
5 Percent						
0	4.8	7.8	8b	3	2.9	0.2
15	9.0	24.3	15a	19	48.7	2.7
45	9.0	24.5	15a	25	45.5	2.5
10 Percent						
0	4.8	6.8	5c	2	16.8	0.2
15	7.3	23.0	16a	12	53.0	2.8
45	9.0	22.5	13ab	20	48.8	2.7

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Terra Green Clay (T-M-5/20)						
5 Percent						
0	4.8	9.3	7b	3	3.5	0.3
15	7.0	22.3	18a	17	53.6	2.7
45	6.5	22.0	16a	20	56.0	3.1
10 Percent						
0	5.3	9.0	7b	4	4.6	0.3
15	7.8	20.8	15a	20	60.0	3.0
45	7.3	20.8	20a	17	61.0	3.3
LSD$_{0.05}$	**NS**	**NS**	**5**	**NS**	**NS**	**NS**
Clay * P rate						
Controls						
70 :30 peat : perlite [y]						
0	5.5b	15.3b	7bc	3d	3.5d	0.2d
15	7.5a	22.0a	15a	20a	57.5a	3.1a
45	7.7a	23.3a	14a	20a	59.5a	3.1a
Diatomite						
0	3.9b	4.3d	3d	2d	2.36d	0.2d
15	7.6a	22.1a	11b	10c	35.9b	1.9c
45	7.4a	23.8a	15a	12a	48.9b	2.6ab
Attasorb Clay (A-5/25)						
0	4.9b	7.3c	6bc	3d	9.9c	0.20d
15	8.1a	23.6a	15a	15b	50.8a	2.7ab
45	9.0a	23.5a	14a	22a	47.2ab	2.6ab
Terra green Clay (T-M-5/20)						
0	5.0b	9.1c	7bc	3d	2.4d	0.3d
15	7.4a	21.5a	16a	18ab	35.9b	2.8ab
45	6.9a	21.4a	18a	18ab	48.9ab	3.18a
LSD$_{0.05}$	**NS**	**NS**	**4.2**	**4.8**	**6.1**	**0.52**
Percent (Clay)						
0%						
70 :30 peat : perlite [y]	6.9b	16.9b	10.3b	16a	40.1	2.1
5%						
Diatomite	6.25c	18.8ab	12a	9b	29.9	1.7
A-5/25	7.6ab	17.8b	13a	15a	32.4	1.8
T-M-5/20	6.08c	17.8b	13a	13a	37.6	2.0
10%						
Diatomite	6.3c	16.5b	9ab	6b	28.2	1.5
A-5/25	7.0b	17.4b	11a	11a	39.6	1.9
T-M-5/20					41.9	2.2
LSD$_{0.05}$	**0.9**	**NS**	**NS**	**NS**	**NS**	**NS**

Clay

70 :30 peat : perlite [y]	6.9a	20.2a	12a	16a	40.1a	2.1a
Diatomite	6.3b	16.7b	9ab	8b	29.1b	1.6b
A-5/25	7.3a	18.1a	12a	13a	36.0a	1.8a
T-M-5/20	6.4b	17.3ab	14a	13a	39.8a	2.1a
LSD$_{0.05}$	**0.65**	**1.3**	**2.1**	**5.3**	**10.1**	**0.4**

P rate

0	4.8b	9.0b	6b	3b	4.5b	0.2b
15	7.7a	22.3a	14a	16a	45.0a	2.6a
45	7.8a	23.0a	15a	19a	51.1a	3.6a
LSD$_{0.05}$	**0.6**	**1.0**	**1.1**	**4.2**	**8.4**	**0.23**

[z] Control containing 70 peat : 30 perlite of 7: 3 Peat perlite (industry standard)

[y] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences.

Table 2.5 Total N, P and K in plant shoot tissue analyzed using sulfuric peroxide digestion from shoots harvested 52 DAT in Expt.1.

	Total N (%)	Total P (%)	Total K (%)
Block	**	NS	NS
Clay	***	NS	NS
Percent (Clay)	***	NS	**
P rate	***	***	*
Clay * P rate	NS [y]	NS	NS
Clay * Percent(Clay) * P rate	*	NS	NS
Clay * Percent (Clay)* P rate			
Controls			
70 peat : 30 perlite [z] Control			
5	2.96d	0.15	2.95
15	3.04d	0.41	2.85
45	2.90d	0.84	2.91
30 Diatomite : 50 peat : 20 perlite [x]			
5	3.58b	0.20	2.76
15	3.35cd	0.42	2.91
45	3.34cd	0.72	2.94
Attasorb Clay (A-5/25)			
5% AS : 25% DE			
5	3.52bc	0.17	2.21
15	3.87a	0.47	3.17
45	3.08d	0.80	2.75
10% AS : 20% DE			
5	3.72ab	0.21	2.93
15	3.40c	0.37	3.26
45	3.10d	0.86	2.93
20% AS : 10% DE			
5	3.35cd	0.16	3.17
15	3.35cd	0.35	3.29
45	3.01d	0.83	2.96
Terra Green Clay (T-M-5/20)			
5% TG : 25% DE			
5	3.82ab	0.20	2.61
15	3.76ab	0.42	3.03
45	3.26 d	0.76	3.27
10% TG : 20% DE			
5	3.33cd	0.17	2.86
15	3.17 d	0.44	2.76
45	3.03d	0.83	2.83
20% TG:10% DE			
5	3.34cd	0.17	3.05
15	3.12 d	0.29	3.33
45	3.17 d	0.77	3.31
LSD$_{0.05}$	**0.32**	**NS**	**NS**

Percent (Clay)

0%			
70 :30 peat : perlite[z]	2.96cd	0.47	2.90b
30 Diatomite: 50 peat: 20 perlite[x]	3.42b	0.44	2.87b
5%			
A-5/25	3.49ab	0.48	2.71bc
T-M-5/20	3.62a	0.46	2.97b
10%			
A-5/25	3.40b	0.48	3.04ab
T-M-5/20	3.17c	0.48	2.82b
20%			
A-5/25	3.24bc	0.45	3.14a
T-M-5/20	3.21bc	0.41	3.22a
$LSD_{0.05}$	**0.18**	**NS**	**0.11**
Clay			
70 :30 peat : perlite[z]	2.96b	0.47	2.90
30 Diatomite: 50 peat: 20 perlite[x]	3.42 a	0.45	2.87
A-5/25	3.38a	0.47	2.96
T-M-5/20	3.33a	0.45	3.01
$LSD_{0.05}$	**0.18**	**NS**	**NS**
P rate			
5	3.39a	0.18a	2.82ab
15	3.32a	0.40b	3.00a
45	3.11b	0.79c	2.96a
$LSD_{0.05}$ n=24	**0.13**	**0.55**	**0.09**

[z]Control of 7: 3 Peat perlite (industry standard)

[x]Control containing 30 Diatomite : 50 peat : 20 perlite

[y] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences.

Table 2.6 Total N and P in plant shoot tissue analyzed using sulfuric peroxide digestion from shoots harvested at the end of the production phase (30 DAT) and post-production phase (64 DAT) in Expt. 2.

	Total N (%) 30 DAT	Total P (%) 30 DAT	Total N (%) 64 DAT	Total P (%) 64 DAT
Clay	***	*	***	*
Prate	***	***	***	*
Percent (Clay)	NS [y]	NS	NS	***
Clay*P rate	*	***	NS	*
Percent (Clay)* P rate	NS	NS	NS	NS
Clay* Percent (Clay)*P rate	NS	NS	NS	NS
Clay * Percent (Clay)* P rate				
Controls				
70 peat : 30 perlite [y] Control				
0	1.97	0.06		
15	2.89	0.41	2.00	0.28
45	2.78	0.89	1.84	0.88
30 Diatomite : 50 peat : 20 perlite				
5 Percent				
0	1.73	0.06		
15	3.70	0.42	2.38	0.28
45	3.30	0.88	2.22	0.78
10 Percent				
0	1.39	0.06		
15	3.90	0.42	2.70	0.32
45	3.30	0.90	2.22	0.79
Attasorb Clay (A-5/25)				
5 Percent				
0	1.97	0.07		
15	2.93	0.31	2.09	0.26
45	2.97	0.60	2.09	0.89
10 Percent				
0	1.72	0.07		
15	3.10	0.31	2.29	0.26
45	3.10	0.80	2.09	0.76
Terra Green Clay (T-M-5/20)				
5 Percent				
0	1.10	0.09		
15	3.18	0.50	2.19	0.30
45	2.60	0.75	1.83	0.74
10 Percent				
0	1.60	0.09		
15	3.20	0.35	2.2	0.26
45	2.79	0.74	2.0	0.70

LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**
Clay * P rate				
Controls				
70 :30 peat : perlite [z]				
0	1.97c	0.06d		
15	2.89b	0.41b	2.38	0.28b
45	2.78bc	0.89a	2.22	0.87a
Diatomite				
0	1.56c	0.06d		
15	3.80a	0.42b	2.54	0.30b
45	3.30b	0.89a	2.22	0.79a
Attasorb Clay (A-5/25)				
0	1.84c	0.07d		
15	3.01b	0.31bc	2.19	0.26b
45	3.03b	0.70ab	2.09	0.82a
Terra green Clay (T-M-5/20)				
0	1.35c	0.09d		
15	3.19b	0.31bc	2.19	0.28b
45	2.70bc	0.70ab	1.91	0.73ab
LSD$_{0.05}$	**1.34**	**0.22**	**NS**	**0.11**
Percent (Clay)				
0%				
70 :30 peat : perlite [z]	2.54	0.45	1.92	0.58a
5%				
Diatomite	2.91a	0.45	2.30	0.53ab
A-5/25	2.62	0.33	2.09	0.57a
T-M-5/20	2.29	0.45	2.00	0.51b
10%				
Diatomite	2.87	0.41	2.47	0.56a
A-5/25	2.65	0.39	2.20	0.51b
T-M-5/20	2.51	0.39	2.11	0.49bc
LSD$_{0.05}$	**NS**	**NS**	**NS**	**0.075**
Clay				
70 :30 peat : perlite [z]	2.54b	0.45a	1.922c	0.58a
Diatomite	2.89a	0.43a	2.38a	0.55ab
A-5/25	2.64b	0.36ab	2.14b	0.54b
T-M-5/20	2.40b	0.42a	2.06bc	0.50bc
LSD$_{0.05}$	**0.2**	**0.08**	**0.17**	**0.04**
P rate				
0	1.64c	0.07c		
15	3.27b	0.39b	2.26a	0.28b
45	2.97a	0.79a	2.04b	0.79a
LSD$_{0.05}$	**0.18**	**0.06**	**0.08**	**0.035**

[z] Control containing 70 peat : 30 perlite of 7: 3 Peat perlite (industry standard)
[y] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively.
Different letters indicate statistically significant differences.

Table 2.7 P-values generated by repeated-measures ANOVA performed on plant height, width, number of flowers and PO_4-P leachate attributes of impatiens during production in Expt. 1. The type 3 tests for Fixed Effects on the first order autoregressive covariance model are displayed.

Effect	PO_4-P concentration in Leachate over time	Height	Width	No. of flowers
	P-values			
Block	0.001	0.4970	0.0496	0.1157
Clay	<.0001	0.0024	<.0001	<.0006
%(Clay)	0.0229	0.0175	<.0001	<.0001
Prate	<.0001	<.0001	<.0001	<.0001
Clay*Prate	0.0828	0.0047	0.0074	0.0428
Clay*Percent (Clay)*Prate	0.3930	0.5352	0.6872	0.9486
Time	<.0001	<.0001	<.0001	<.0001
Clay*Time	<.0001	0.0005	<.0383	<.0001
Percent (Clay) *Time	0.0704	0.3793	<.5334	<.0001
Prate*Time	<.0001	<.0001	<.0001	<.0001
Clay*Prate*Time	0.0513	0.1591	0.1560	0.0020
Clay*Percent(Clay)*Prate*Time	0.2756	0.535	0.4774	0.9985

Table 2.8 Phosphorus budgets by percentage for impatiens at the end of the production phase, 52 DAT (Expt. 1), grown in 5 peat: 2 perlite: 3 calcined materials, the latter consisting of Attasorb (AS) or Terra Green (TG) clays at 5, 10 and 20% + DE. Controls had either inert diatomaceous earth (DE) incorporated at 30% (by volume) or consisted of 7 peat: 3 perlite.

	Total Applied (mg^{-1}/pot)	PO$_4$-P recovered in Leachate[v] (%)	PO$_4$-P in Shoots (%)	Estimated PO$_4$-P in roots[x] (%)	Estimated PO$_4$-P remaining in pot/substrate[w] (%)
Block		NS[t]	NS	NS	NS
Clay		**	**	**	***
Percent (Clay)		**	**	**	*
P rate		***	***	***	***
Clay * P rate		NS	NS	NS	NS
Clay * Percent * P rate (Clay)		*	NS	NS	NS
Clay * Percent (Clay)* P rate					
Controls					
70 peat : 30 perlite[z] Control					
5	26	13.2de	39.1	9.8	37.9
15	78	20.2b	41.8	10.4	27.7
45	234	24.2a	30.7	7.7	37.5
30 Diatomite : 50 peat : 20 perlite[y]					
5	20	8.1dfg	14.9	3.7	73.4
15	60	17.9c	36.6	9.2	36.5
45	180	20.7b	28.4	7.1	43.9
Attasorb Clay (A-5/25)					
5% AS : 25% DE					
5	20	10.6f	8.4	2.1	79.0
15	60	19.3bc	20.6	5.2	54.9
45	180	22.3a	28.1	7.0	42.6
10% AS : 20% DE					
5	20	6.1g	17.0	4.3	72.8
15	60	17.9c	31.7	7.9	42.6
45	180	18.9bc	29.6	7.4	44.1
20% AS : 10% DE					
5	20	5.8g	26.0	6.6	61.8
15	60	15.7cd	34.7	8.7	40.9
45	180	19.8bc	31.6	7.9	40.7
Terra Green Clay (T-M-5/20)					
5% TG : 25% DE					
5	20	5.9g	20.3	5.1	68.7
15	60	17.5c	28.5	7.1	46.9
45	180	20.2b	25.2	6.3	48.4
10% TG : 20% DE					
5	20	6.7g	22.4	5.6	65.3
15	60	14.4d	45.0	11.3	29.4
45	180	17.2dc	33.2	8.3	41.4

20% TG:10% DE					
5	20	5.2g	21.0	5.3	68.7
15	60	11.8de	27.5	6.9	53.9
45	180	20.7b	27.4	6.8	45.1
LSD$_{0.05}$		**3.07**	**NS**	**NS**	**NS**
Percent (Clay)					
0%					
70 :30 peat : perlite[z]	112.7	19.2a	37.2a	9.3a	34.3b
30 Diatomite: 50 peat: 20 perlite[y]	86.7	15.6b	26.6b	6.7b	51.2a
5%					
A-5/25	86.7	17.4a	19.0c	4.8c	58.9a
T-M-5/20	86.7	14.5b	24.7b	6.2b	54.7a
10%					
A-5/25	86.7	14.3b	26.1b	6.5b	53.2a
T-M-5/20	86.7	12.8bc	33.5ab	8.4a	45.3b
20%					
A-5/25	86.7	13.8b	30.8ab	7.7ab	47.8b
T-M-5/20	86.7	12.6c	25.3b	6.3b	55.9a
LSD$_{0.05}$		**1.77**	**7.78**	**1.95**	**9.77**
Clay					
70 :30 peat : perlite[z]	112.7	19.2a	37.2a	9.3a	34.3a
30 Diatomite: 50 peat: 20 perlite[y]	86.7	15.6b	26.6b	6.7b	51.2b
A-5/25	86.7	15.1b	25.3b	6.3b	53.36b
T-M-5/20	86.7	13.3c	27.8b	7.0b	52.0b
LSD$_{0.05}$		**1.45**	**6.35**	**1.59**	**7.98**
P rate					
5	20	8.7a	23.1	5.8a	62.5a
15	60	17.6b	35.2	8.8b	42.2b
45	180	21.1c	29.4	7.3c	49.5c
LSD$_{0.05}$		**1.25**	**NS**	**1.38**	**6.91**

[z]Control of 7: 3 Peat perlite (industry standard)

[y]Control containing 30 Diatomite : 50 peat : 20 perlite

[x]Estimation of P in roots was calculated by assuming that root weight was 25% of the shoot dry weight and P concentration in roots was same as in tops.

[w]Calculated by subtracting P recovered in plants and leacheate from P applied

[t]NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences.

Table 2.9 Phosphorus budgets by percentage for impatiens at end of post-production phase, 84 DAT (Expt. 1), grown in 5 peat: 2 perlite: 3 calcined materials, the latter consisting of Attasorb (AS) and Terra Green (TG) clays at 5, 10 and 20% + DE. Controls had either inert diatomaceous earth (DE) incorporated at 30% (by volume) or consisted of 7 peat: 3 perlite. The PO_4-P rate treatments consisted of 5, 15 and 45 mg L⁻1 during the production period and only water was added during the post-production period.

	Total P in pot (mg pot⁻¹)	PO_4-P in Leachate during production (%)	PO_4-P in Leachate during post production (%)	PO_4-P in Shoots (%) at day 85	Estimated PO_4-P in roots[x] (%) at day 85	Estimated PO_4-P remaining in pot/root medium[w] (%) at day 85
Block		*	NS[t]	NS	NS	NS
Clay		***	***	***	***	***
Percent (Clay)		**	NS	NS	NS	NS
P rate		***	***	**	**	***
Clay * P rate		NS	***	NS	NS	NS
Clay * Percent * P rate (Clay)		**	**	NS	NS	NS
Clay * Percent (Clay)* P rate						
Controls						
7 peat : 3 perlite [z] Control						
5	26e	13.2de	2.3c	17.9	4.5	62.1
15	78c	20.2b	3.2b	25.0	6.3	45.4
45	234a	24.2a	3.6a	20.7	5.2	46.4
3 Diatomite : 5 peat : 2 perlite [y]						
5	20f	8.1dfg	1.65efg	14.8	3.7	71.7
15	60d	17.9c	2.3c	25.0	6.2	48.6
45	180b	20.7b	3.2ab	18.1	4.5	53.5
Attasorb Clay (A-5/25)						
5% AS : 25% DE						
5	20f	10.6f	1.7def	10.2	2.6	74.9
15	60d	19.3bc	1.0hij	9.9	2.5	67.4
45	180b	22.3a	1.9cde	13.0	3.3	59.5
10% AS : 20% DE						
5	20f	6.1g	1.2ghi	9.2	2.3	81.2
15	60d	17.9c	0.84ij	14.2	3.6	63.5
45	180b	18.9bc	2.1cd	13.9	3.5	61.7
20% AS : 10% DE						
5	20f	5.8g	0.9ij	8.4	2.1	82.8
15	60d	15.7cd	1.0hij	15.3	3.8	64.2
45	180b	19.8bc	2.1cd	21.7	5.4	50.9

Terra Green Clay (T-M-5/20)

5% TG : 25% DE						
5	20f	5.9g	1.7def	10.6	2.7	79.1
15	60d	17.5c	1.50.76j	17.0	4.3	60.38
45	180b	20.2b	1.97cde	19.5	4.9	53.5
10% TG : 20% DE						
5	20f	6.7g	1.4fgh	14.2	3.5	74.2
15	60d	14.4d	0.7j	13.1	3.3	68.6
45	180b	17.2dc	2.26c	16.9	4.2	59.4
20% TG:10% DE						
5	20f	5.2g	0.85ij	18.0	4.5	71.4
15	60d	11.8de	0.8j	10.4	2.6	74.4
45	180b	20.7b	2.1cde	17.0	4.3	55.6
LSD$_{0.05}$		**3.07**	**0.43**	**NS**	**NS**	**NS**

Clay * P rate
Controls

7 peat : 3 perlite [z]						
5	20f	13.2c	2.3b	17.9	4.5	62.1
15	60d	20.1ab	3.2a	25.0	6.3	45.4
45	180b	24.2a	3.6a	20.7	5.2	46.4
3 Diatomite : 5 peat : 2 perlite						
5	20f	8.1d	1.7c	14.8	3.7	71.7
15	60d	17.9b	2.3b	24.9	6.2	48.6
45	180b	20.6a	3.2a	18.1	4.5	53.5
Attasorb Clay (A-5/25)						
5	20f	7.5d	1.3cd	9.3	2.3	79.7
15	60d	17.6b	0.9d	13.1	3.3	65.0
45	180b	20.3a	2.0b	16.2	4.0	57.3
Terragreen Clay (T-M-5/20)						
5	20f	5.9d	1.3cd	14.3	3.5	74.9
15	60d	14.6c	0.7d	13.5	3.4	67.8
45	180b	19.4ab	2.1b	17.9	4.5	56.1
LSD$_{0.05}$		**NS**	**0.34**	**NS**	**NS**	**NS**

Percent (Clay)

0%						
7 :3 peat : perlite [z]	112.7a	19.2a	3.0a	11.0c	5.3c	51.3b
3 Diatomite: 5 peat: 2 perlite [y]	86.7b	15.6b	2.4b	19.1ab	4.8ab	57.9b
5%						
A-5/25	86.7b	17.4a	1.6c	12.4c	2.8c	67.3a
T-M-5/20	86.7b	14.5b	1.5c	14.7b	3.9b	64.3a
10%						
A-5/25	86.7b	14.3b	1.4c	15.1ab	3.1ab	68.8a
T-M-5/20	86.7b	12.8bc	1.4c	15.2ab	3.7ab	67.4a
20%						
A-5/25	86.7b	13.8b	1.3c	15.7ab	3.8ab	66.0a
T-M-5/20	86.7b	12.6c	1.2c	21.2a	3.8ab	67.1a
LSD$_{0.05}$		**1.77**	**NS**	**NS**	**NS**	**NS**
Clay						
70 :30 peat : perlite [w]	112.7a	19.2a	3.02a	19.3a	4.8a	51.3b
3 Diatomite: 5 peat: 2 perlite [y]	86.7b	15.6b	2.39b	12.9b	3.2b	57.9ab
A-5/25	86.7b	15.1b	1.42c	15.2ab	3.8ab	67.4a
T-M-5/20	86.7b	13.3c	1.38c	21.2a	5.3a	66.2a
LSD$_{0.05}$		**1.45**	**0.5**	**4.25**	**1.85**	**8.34**
P rate						
5	20f	8.7a	1.6b	14.0b	3.5b	72.1a
15	60d	17.6b	1.8b	19.2a	4.8a	56.7b
45	180b	21.1c	2.7a	18.2a	4.6a	53.4b
LSD$_{0.05}$		**1.25**	**0.72**	**3.2**	**0.5**	**7.89**

[z] Control containing 7 peat : 3 perlite

[y] Control containing 3 Diatomite : 5 peat : 2 perlite

[x] Estimation of P in roots was calculated by assuming that root weight was 25% of the shoot dry weight and P concentration in roots was same as in tops.

[w] Calculated by subtracting P recovered in plants and leacheate during production and post production from total P applied

[t] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences.

Table 2.10 Phosphorus budgets for impatiens at the end of the production phase, 30 DAT (Expt. 2), grown in 7 peat: 2 perlite or 7 peat: 2.5 perlite media with diatomaceous earth (DE), Attasorb (AS), or Terra Green (TG) calcined materials as components at 5 or 10 % (by volume). The control consisted of 7 peat: 3 perlite soilless media.

	PO$_4$-P applied^z from Fertigation (mg·pot^{-1})	Total P^y (mg·pot^{-1})	PO$_4$-P recovered in Leachate (mg·pot^{-1})	PO$_4$-P in Shoots (mg·pot^{-1})	PO$_4$-P remaining in substrate^x (mg·pot^{-1})
Clay			***	**	***
Percent (clay)			*	NS^w	***
P rate			***	***	***
Clay*P rate			***	*	***
Clay* Pct*Prate			NS	NS	NS
Clay * Percent (Clay)* P rate					
Controls					
70 peat : 30 perlite Control					
0	0	24.0	0.1	0.1	21.7
15	31.95	55.5	8.5	12.5	29.9
45	94.95	118.5	22.9	26.7	55.1
30 Diatomite : 50 peat : 20 perlite					
5 Percent					
0	0	58.2	0.3	0.7	49.1
15	31.82	89.7	5.3	8.0	62.9
45	94.82	152.7	11.5	22.7	110.0
10 Percent					
0	0	74.8	0.1	0.1	64.1
15	31.82	106.3	4.4	7.0	80.6
45	94.82	169.3	10.6	24.5	121.3
Attasorb Clay (A-5/25)					
5 Percent					
0	0	96.3	0.1	0.5	82.3
15	31.82	127.8	4.93	7.9	103.0
45	94.82	190.8	12.89	15.2	146.0
10 Percent					
0	0	261.0	0.1	0.1	249.4
15	31.82	292.5	4.6	8.2	269.9
45	94.82	355.5	12.1	21.1	310.9

Terra Green Clay (T-M-5/20)					
5 Percent					
0	0	65.6	0.1	0.2	56.0
15	31.82	97.1	3.9	13.5	70.3
45	94.82	160.1	11.0	22.8	116.1
10 Percent					
0	0	71.6	0.2	0.3	63.0
15	31.82	103.1	4.0	10.3	78.0
45	94.82	166.1	12.8	24.6	118.9
LSD$_{0.05}$			**NS**	**NS**	**NS**
Clay * P rate					
Controls					
70 :30 peat : perlite					
0	0	24.0	0.1d	0.1e	21.7g
15	31.95	55.5	8.5b	12.5c	29.9g
45	94.95	118.5	22.9a	26.7a	55.0f
Diatomite					
0	0	66.5	0.8d	0.4e	56.6f
15	31.82	98.0	4.9c	7.5d	71.7e
45	94.82	161.0	11.0b	23.6a	115.7cd
Attasorb Clay (A-5/25)					
0	0	178.7	0.1d	0.3e	165.9c
15	31.82	210.6	4.8c	8.1cd	186.5b
45	94.82	273.6	12.5b	18.1b	228.4a
Terra green Clay (T-M-5/20)					
0	0	68.6	0.1d	0.3e	59.5f
15	31.82	100.1	3.9c	11.9c	74.2e
45	94.82	163.1	11.9b	23.7a	117.5c
LSD$_{0.05}$			**2.17**	**4.87**	**7.11**
Percent (Clay)					
0%					
70 :30 peat : perlite	42.3	66.0	10.5a	13.1a	35.5e
5%					
Diatomite	42.21	100.2	5.7b	10.5ab	74.0d
A-5/25	42.21	138.3	6.0b	7.8b	110.4b
T-M-5/20	42.21	107.6	5.0bc	12.2ab	80.8cd
10%					
Diatomite	42.21	116.8	5.7b	10.5ab	88.7c
A-5/25	42.21	303.0	5.6b	9.9ab	276.8a
T-M-5/20	42.21	113.6	5.6b	11.7ab	86.7c
LSD$_{0.05}$			**0.92**	NS	**30.4**

Clay

70 :30 peat : perlite	42.3	66.0	10.5a	13.1a	35.5c
Diatomite	42.21	108.5	5.4b	10.5ab	81.3b
A-5/25	42.21	220.7	5.8b	8.9b	193.6a
T-M-5/20	42.21	110.6	5.3b	11.9a	83.7b
LSD$_{0.05}$			**0.91**	**3.8**	**28.0**

P rate

0	0	84.4c	0.1c	0.3c	75.9c
15	31.9	115.9b	5.5b	10.0b	90.55b
45	94.8	178.9a	14.6a	23.0a	129.15a
LSD$_{0.05}$			**0.8**	**2.9**	**14.7**

[z] PO_4-P applied from fertigation includes 0.15 mg·L^{-1} P from tap water

[y] Total = Total native P and + PO_4-P applied

[x] Substrate and roots analyzed for total P

[w] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences.

Table 2.11 Phosphorus budgets for impatiens at the end of the post-production phase, 64 DAT (Expt. 2), grown in 5 peat: 2 perlite or 7 peat: 2.5 perlite media with diatomaceous earth (DE), Attasorb (AS), or Terra Green (TG) calcined materials as components at 5 or 10% (by volume). The control consisted of 7 peat: 3 perlite soilless medium. The PO$_4$-P rate treatments consisted of 5, 15 and 45 mg·L^{-1} during the production period and only water was added during the post-production period. The budget accounts for about 85% of the total (inherent to the clays + applied as fertilizer) P applied.

	Total Applied (mg·pot^{-1})	PO$_4$-P in Leachate during production (mg·pot^{-1})	PO$_4$-P in Leachate during post-production (mg·pot^{-1})	PO$_4$-P in Shoots (mg·pot^{-1})	PO$_4$-P remaining in pot/root medium (mg·pot^{-1})
Clay		***	*	*	***
Percent (Clay)		NS ^{y}	*	NS	***
P rate		***	***	***	***
Clay * P rate		***	*	NS	NS
Clay * Percent * P rate (Clay)		NS	NS	NS	NS
Clay * Percent * P rate (Clay)					
Controls					
70 peat : 30 perlite Control					
15	55.51	8.5	4.2	10.7	20.8
45	118.51	22.7	13.5	32.86	47.1
30 Diatomite : 50 peat : 20 perlite					
5 Percent					
15	89.72	5.3	4.0	8.8	70.7
45	152.72	11.5	10.0	27.8	104.6
10 Percent					
15	106.25	4.4	3.8	8.0	72.7
45	169.25	10.6	9.8	28.2	108.1
Attasorb Clay (A-5/25)					
5 Percent					
15	127.76	4.9	3.1	9.0	95.0
45	190.76	12.9	8.6	31.3	121.0
10 Percent					
15	292.54	4.6	3.9	9.7	252.0
45	355.54	12.1	6.9	25.2	297.0
Terra Green Clay (T-M-5/20)					
5 Percent					
15	97.12	4.0	2.0	11.2	72.98
45	160.12	10.98	8.4	27.6	126.9
10 Percent					
15	103.13	4.0	3.0	9.2	88.7

45	166.1	12.8	8.0	27.0	107.9
LSD$_{0.05}$		**NS**	**NS**	**NS**	**NS**
Clay * P rate					
Controls					
70 :30 peat : perlite[z]					
15	55.51	8.5c	4.2bc	10.7	20.8
45	118.51	22.9a	13.5a	32.9	47.1
Diatomite					
15	97.99	4.9d	3.9bc	8.4	71.7
45	160.99	11.0b	9.9a	28.0	106.3
Attasorb Clay (A-5/25)					
15	210.15	4.8d	3.5cd	9.3	173.5
45	273.15	12.48b	7.8b	28.2	209.0
Terra green Clay (T-M-5/20)					
15	100.13	3.9d	2.5d	10.1	80.8
45	163.13	11.9b	8.2b	27.3	117.4
LSD$_{0.05}$		**1.64**	**1.4**	**NS**	**NS**
Percent (Clay)					
0%					
70 :30 peat : perlite[z]	66.01	10.5	8.9a	21.8	34.0e
5%					
Diatomite	100.22	5.7	7.0ab	18.3	87.7d
A-5/25	138.26	6.0	5.9b	20.1	108.0c
T-M-5/20	107.62	5.0	5.9b	19.4	99.94d
10%					
Diatomite	116.8	5.7	7.5a	18.1	90.4d
A-5/25	303.04	5.6	8.3a	17.5	274.5a
T-M-5/20	113.63	5.6	8.36a	18.1	196.6b
LSD$_{0.05}$		**NS**	**1.5**	**NS**	**35.4**
Clay					
70 :30 peat : perlite[z]	66.010c	10.5a	8.9a	21.8a	33.95c
Diatomite	108.485b	5.4b	7.3ab	18.1b	89.02b
A-5/25	220.650a	5.8b	7.1ab	18.8b	191.3a
T-M-5/20	110.625b	5.3b	7.1ab	18.7b	99.1b
LSD$_{0.05}$		**1.2**	**1.3**	**4.8**	**32.2**
P rate					
15	115.94b	5.5b	3.52b	9.7b	96.1b
45	178.94a	14.7a	9.85a	29.1a	130.4a
LSD$_{0.05}$		**1.1**	**1.1**	**3.2**	**30.4**

[z] Control containing 70 peat : 30 perlite

[y] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences.

CHAPTER 3 - Calcined Clays as Soilless Root Medium Components in Greenhouse Production and Post-Production of *Impatiens wallerana*: Part 2. Water Retention and Release

Abstract. Relatively little research has been done to determine the effects that the root media has on plant growth after plants are shipped from the greenhouse for sale. Earlier research showed that three calcined materials, Terra Green montmorillonite (TG), Attasorb attapulgite (AS), and a diatomaceous earth (DE), which were included as components of a sphagnum peat and perlite soilless root medium, decreased leaching of phosphorus compared to a control of 70% peat : 30% perlite (PP control). The present research was done to determine the effects that these components had on the water relations of *Impatiens wallerana* f. Hook. 'Tempo Rose' during the production and post-production phases. Two experiments were done in which plants were exposed to two drought cycles in each. Amount of water leached, stomatal conductance, and water use efficiency were measured. The PP control plants wilted sooner than the plants grown in the media with the calcined materials. Mixes with calcined materials contributed to plants that survived drought better because the root media adsorbed more water. This allowed the plants grown in the calcined materials to have higher stomatal conductance at the end of drought cycles, because more water was available for plant uptake. The water use efficiency of plants grown in the calcined materials was greater than that of plants grown in the PP control. This showed that if the calcined materials are used in greenhouse production, growers are going to get more growth for the same amount of water used.

Literature Review

The previous research (Chapter 2) showed that reduced amounts of PO_4-P leached from pots with impatiens plants grown with calcined clays and diatomaceous earth (DE) compared to control plants grown in a standard root medium of 70% peat and 30% perlite. We hypothesized that the regulated amount of PO_4-P uptake, which we observed in the experimental plants, can increase the plants' capacity to handle stress, mainly moisture stress. Borch et al. (1998) found that plants were more resistant to water stress when grown at very low PO_4-P levels as maintained by alumina in the root medium. The PP control plants had higher amounts of P in them and grew larger in the 6-inch-diameter (15-cm diameter) pots and yet leached more phosphate (PO_4-P) compared to the plants in pots with calcined clays and DE. The clays and DE retained PO_4-P, reducing the root medium solution PO_4-P, and thus regulating PO_4-P uptake. The control plants also showed lower water use efficiency. Therefore, we wanted to know how these plants would respond to drought during post-production.

By "post-production" we mean the handling of plants after they leave the greenhouse. After production, plants are sold to retail outlets where customers buy them. The post-production quality and performance of potted plants purchased by consumers is ultimately the major concern of the floricultural industry, because it wants to improve marketability and provide customer satisfaction. About 20% of annual and perennial products entering the retail market become unsaleable or are damaged, and, consequently, must be reduced in price (USDA report, 2006). The greenhouse environment is designed to provide optimum conditions for forcing plants to grow and flower as rapidly as possible, leading to overuse of inputs. The conditions in the retail display and in the customer's care are frequently the opposite and place plants under stress from a variety of sources, including water stress from small pot size.

Among the decisions made by the grower in planning crop production and during the production process is choice of root medium. The results that we obtained regarding PO_4-P use (see Chapter 2) suggested that the characteristics of the different calcined clays, due to different parent clays and the calcining process, should result in porous aggregate structures with improved water-holding capacity that are appropriate for use in containers because they maintain appropriate physical properties of the mix. These media, whose primary commercial function is as absorbents, may retain more water than standard media.

Relatively little research has been done concerning the response of plants post-production as it relates to the root medium affecting PO_4-P and plant water use. Hansen and Nielsen (2001) found that reduced PO_4-P availability improved plant tolerance to post-production stress by delaying floral senescence and reducing root dieback of in potted miniature roses (*Rosa hybrida*). Such results are important to the horticultural industry and to the consumer, because most cultivated flowering plants have inadequate keeping quality when grown with the traditionally high PO_4-P availability (Hansen and Nielsen, 2001). Apparently, no research has been done to determine the growth and tolerance to drought of plants post-production in the calcined materials, as described in Chapter 2. Therefore, the objectives of this research were to determine 1) water use efficiency during production and 2) if impatiens plants grown in media with these components survived drought better than plants grown in a control media (70% peat : 30% perlite). To assess the plants' response to water stress, we measured stomatal conductance.

Materials and Methods

Post-production treatment was done on greenhouse grown *Impatiens wallerana* Hook. f. 'Tempo Rose' in pots that were in the same experimental set up as described previously (see Chapter 2).

As explained in Chapter 2, two different experiments were carried out. Expt. 1 was seeded on 24 Mar. 2006 and Expt. 2 was seeded on 14 July 2007. In Expt. 1, the two clays were incorporated by volume into a mix of 5 peat : 2 perlite : 3 calcined materials, with the 30% calcined components consisting of 0%, 5%, 10%, and 20% clay and diatomaceous earth (DE). In Expt. 2, clays and DE were incorporated at 0%, 5%, and 10% into peat and perlite mixes. Control plants were grown in 70% peat : 30% perlite in both experiments. In Expt. 1, pot size was 1.2 L (10 cm height) and in Expt. 2 pot size was 0.55 L (9.5 cm height).

During the production period, there were three rates of PO_4-P in both Expts. 1 and 2. In Expt. 1, the rates were 5, 15, and 45 mg·L^{-1} PO_4-P, and in Expt. 2, the rates were 0, 15, and 45 mg·L^{-1} PO_4-P. All the treatments from Expt. 1 were studied in the post-production experiment. However, in Expt. 2, because the plants grown with 0 mg·L^{-1} PO_4-P were so small, they were not included in the post-production experiment.

In the production phase, the plants were transplanted into the different experimental media on 20 Apr. 2006 and 21 Aug. 2007 for Expt. 1 and Expt. 2, respectively. The experimental design was such that half the pots were harvested at the end of the production period. The other half of the pots was carried into the post-production experiment. The harvest dates for Expt. 1 and Expt. 2 were 14 June 2006 (52 days after transplanting) and 22 Sept. 2007 (30 days after transplanting). On the same day that the experiments were harvested, the remaining plants for the post-production experiment in Expt. 1 were weighed, watered with 400

ml per pot, and then weighed again on the same day (on 14 June 2006). The amount of water retained was recorded and designated "rewet volume" for this one day (14 June 2006). The leachate was collected for PO_4-P analysis, to be described later. In Expt. 2, no water was added to plants on the day of harvest.

Stomatal conductance. The stomatal conductance was measured on plants in both experiments at the beginning of the post-production period, which was designated as 14 June 2006 for Expt. 1 (after watering) and 22 Sept. 2007 for Expt. 2. Stomatal conductance of mid-sized leaves that were generally the youngest, fully-expanded leaves was taken using a porometer (Model SC-1, Decagon Devices, Pullman, Wash.) following the manufacturer's directions (Decagon Devices, 2006) on the day of harvest of the production experiment. The measurements were taken midday on all plants on 14 June 2006 and 22 Sept. 2007. Plants in Expt. 2 were watered on 26 Sept.

After the stomatal conductance was measured, the plants in each experiment were taken to a dark, cool room with low light of 8 μmol·m^{-2}·s^{-1} and temperatures of 16 to 17°C for three days to simulate transportation, as suggested by Borch et al. (1998). These dates were 15 to 18 June 2006 for Expt. 1 and 27 to 30 Sept. for Expt. 2. Plants were then transferred to the greenhouse (on 18 June and 29 Sept. for Expts. 1 and 2, respectively) and placed randomly on a bench under 50% shade, provided by black, woven shade cloth, with greenhouse temperatures set at 21/18 ^{o}C day/night to simulate a post-production environment with low light. The air distribution in the greenhouse consisted of ventilation fans and air vents. Environmental conditions were monitored in the greenhouse with a data logger (Onset Computer Corp., Bourne, Mass.) to register temperature and humidity during the post-production period. In Expt. 2, two evaporation pans measuring 25 cm in diameter and 3 cm in depth were placed in the

experimental area among the pots on the bench, to monitor the amount of water lost by evaporation. Data for daily evaporation from pans were gathered throughout the two drought cycles in Expt. 2. The evaporation rate in cm·day^{-1} from each dish was calculated by taking the difference in weight between two daily measurements, converting that to cm^3 (assuming the density of water is 1 g·cm^{-3}) and dividing that value by the area of the pan in cm^2 and then the values in cm/day were reported as mm/day. A summary of greenhouse environmental conditions is shown in Tables 3.1 and 3.2 for Expts.1 and 2, respectively. For Expt. 1, day temperatures ranged between 21 and 29 ^{o}C (avg. 24.4 ^{o}C) and night temperatures ranged between 19 to 26 ^{o}C (avg. 20.0 ^{o}C). For Expt. 2, day temperatures ranged between 19 to 30°C (avg. 22.1^{o}C) and night temperatures ranged between 14.8 to 26.5 ^{o}C (avg. 18.4^{o}C). For Expt. 1, the day and night relative humidity averaged 79.9 and 68.4%, respectively (Table 3.1). For Expt. 2, the day and night relative humidity averaged 60.0 and 63.6%, respectively (Table 3.2). Pan evapotranspiration rates during the first and second drought cycles averaged 2.0 and 1.0 mm·day^{-1}, respectively.

Two cycles of drought were imposed during each experiment on the plants by with-holding water from pots. The dates of the drought cycles for Expt. 1 were designated 21 June to 2 July (Drought Cycle 1) and 2 July to 14 July 2006 (Drought Cycle 2). On 2 July the pots were weighed and re-watered with 400 ml tap water added to each pot. The pots were weighed again after re-watering on 2 July. The dates of the drought cycles for Expt. 2 were 5 to 15 Oct. (Drought Cycle 1) and 16 to 24 Oct. 2007 (Drought Cycle 2). On 15 Oct., 300 ml of tap water was added to each pot. On 15 Oct. the weight of the pots before watering was measured and the weight of the pots was measured after watering. In both Expts. 1 and 2, the leachate was collected at the time of watering and the volume was recorded. Then a 1 ml sample was taken to

analyze for PO_4-P. The PO_4-P content of leachate was determined colorimetrically (Murphy and Riley, 1962).

In Expt. 1, stomatal conductance was measured again (after removal from the transportation environment) daily starting on 19 June until 14 July. On these dates, stomatal conductance was measured two times each day: in the morning between 10:00 and 12:00 hr and in the afternoon between 16:00 to 18:00 hr. In Expt. 2, measurements were taken daily from 30 Sept. to 24 Oct. only at mid-day (12:00 and14:00 hr).

Plant height, width, flower numbers, and flower bud numbers (unopened flowers with tinge of color showing) were taken before harvest near the end of the post-production period. These measurements were recorded on 5 July 2006 (76 DAP) in Expt. 1 and on 21 Oct. 2007 (60 DAP) in Expt. 2. Plant height was measured from the top rim of the pot to the top of the un-extended shoot. Plant width of the foliage canopy was the average of two measurements taken at right angles to each other. The plants were harvested on 15 July 2006 and 25 Oct. 2007 for Expts. 1 and 2, respectively. The shoots (consisting of leaves, stems, and flowers) were cut at the root medium surface and fresh weight of the entire shoot was measured. The shoots were washed in a weak acid solution and rinsed in de-ionized water as described in Chapter 2. Then the shoots were dried ($70^{o}C$) for three days and weighed to obtain dry weight.

Percent leached and water use efficiency. The percent of volume of applied water that was leached was determined by dividing the total leachate volume at the end of the production or post-production phase by total volume of water applied during that phase. For example, if the total leachate from a pot during the production period was 1350 ml and the total volume of water applied was 4000 ml, the percent leached was (1350 ml/4000 ml) x 100 = 33.75%.

Total plant dry weight was estimated to determine water use efficiency. Total plant dry weight was the sum of the shoot dry weight plus the estimated root dry weight. Root dry weight is estimated by assuming it to be 25% of the shoot dry weight (Ericsson 1995; Duncan et. al., 2007). Water use efficiency (mg·L^{-1}) was calculated by dividing the total plant dry weight (mg) at harvest by water retained (ml). Percent leached and water use efficiency were determined only for the production experiment and not the post-production experiment.

Data were analyzed using the general linear model procedure of SAS (SAS ver. 9.1; SAS Inst., Cary, NC). Multiple comparisons among treatments were made using Fisher's LSD with an experimental-wise α level of 0.05. Repeated measures were used to analyze the stomatal conductance over time and data were subjected to regression of the dependent variable against time. In SAS, the first order autoregressive covariance model was used and type 3 tests for fixed effects were determined for the stomatal conductance data. In the tables for growth and leachate data, interactions are indicated.

Results and Discussion

Plant growth. The impatiens plants in the treatment mixes survived drought better than the plants in the control media (Table 3.1). The calcined materials (Attasorb, Terra Green, and DE) had an effect on wilting. In Expt. 1, the pots (1.2 L) with 30% DE and the pots with 5% TG and 5% AS clays, which also contained 25% DE, delayed post-production wilting by 3 days (3.1). In Expt. 2, the pots (0.55 L) with 5 and 10% incorporated calcined materials delayed post-production wilting by two days. Fig. 3.1. shows the plants in Expt. 1 on July 11, 2006, which was designated Day 8 of the Drought Cycle 2. These plants were treated with 15 mg·L^{-1} PO$_4$-P during production. The plant on the left was grown the PP control; the middle plant had 5%

calcined clay incorporated; and the plant on the right had 10% calcined clay incorporated. Water retention by the clays kept the plant leaves turgid for a longer period of time.

The wilting of the control plants did not decrease their growth. All growth variables in Expt. 1 showed significantly bigger plants in terms of height, canopy width, flower number, flower bud number, and fresh and dry shoot weight in post-production PP control plants compared to plants grown in media with calcined materials (Table 3.3). The PP control had received more water per pot during production (a difference of 1.2 $L \cdot pot^{-1}$ and 0.9 $L \cdot pot^{-1}$ in Expt. 1 and Expt. 2, respectively). We had concluded from the production phase of Expt. 1 (see Chapter 2) that PO_4-P retention by calcined materials had contributed to a more checked growth in all media with incorporated calcined materials. In Expt. 2, all treatments received the same amount of PO_4-P, according to their PO_4-P fertilizer rate. So in Expt. 2, the controls had fresh and dry weights similar to the plants grown in media with calcined materials (Table 3.4).

Total leachate volume, percentage volume leached, and rewet volumes. Plants grown in media with the calcined materials survived drought better because the media adsorbed more water. In Expt. 1, the PP control leached 30% of the applied water, while the pots with the calcined materials leached about 22% (Table 3.5, 'clay'). In Expt. 2, the PP control leached 33.5% of the applied water, while the pots with the calcined materials leach about 23% (Table 3.6, 'clay'). There was no difference in water leached among the pots with the different calcined materials incorporated (Tables 3.5 and 3.6) which is explained because all the treatments contained 30% calcined materials. Leachate volume varied with PO_4-P rate. Generally, the 5 $mg \cdot L^{-1}$ PO_4-P rate resulted in plants with a higher leachate volume.

In both Expts. 1 and 2, the rewet volume of the PP control was less than that of mixes with the calcined materials (Tables 3.5 and 3.6, 'clay'). This indicated that root media

with the calcined materials had higher retention of the water. In Expt. 1, the calcined materials

increased rewet volume as follows (Table 3.5): DE by 22% (307 vs 251 ml, drought cycle 1) and

45% (298 vs 205 ml, drought cycle 2); AS clay by 12% (283 vs 251 ml for drought cycle 1) and

38% (284 vs 205 for drought cycle 2); and TG clay by 20% (302 vs 251 ml for drought cycle 1)

and 37.5% (283 vs 205 ml for drought cycle 2). In Expt. 2, the calcined materials increased rewet

volume as follows (Table 3.6): DE by 9% (227 vs 208 ml, drought cycle 1) and 23% (234 vs 190

ml, drought cycle 2); AS clay by 11% (231 vs 208 ml, drought cycle 1) and 19% (226 vs 190 ml,

drought cycle 2); and TG clay by 12% (233 vs. 208 ml, drought cycle 1) and 23% (233 vs. 190

ml, drought cycle 2). The results of Expts. 1 and 2 showed that, with 5% to 30% calcined

material incorporation, a rapid and uniform wetting of root media during initial wetting can be

ensured compared to the PP control.

Stomatal conductance (SC). The stomatal conductances of plants grown in media

with calcined materials were similar, so results will be presented only for pots with 30% DE

(Figs. 2) The stomatal conductances declined as the drought cycles progressed, as expected. The

main effect of 'time' was highly significant for all drought cycles (Table 3.7). Also, the main

effect of 'clay' was highly significant for all drought cycles, except for the first drought cycle in

Expt. 1. The changes in SC over time of plants in media with DE were significantly different

from those of plants in the PP control (Figs. 2 and 3). During the first 6 to 7 days of each drought

cycle, the SC did not differ between DE and control treatments, but at the end of the cycles

plants grown in the PP control had lower stomatal conductances compared to plants grown in

media with DE. The PP control plants also showed wilting (see Fig. 3.1). At the end of each

drought cycle, the stomatal conductances of the control plants were lowest, ranging from 9 to 18

$mmol·m^{-2}·s^{-1}$ in Expt. 1 and between 7 to 20 $mmol·m^{-2}·s^{-1}$ in Expt. 2. These SC values were

about two times lower than those of the treatments with calcined materials. The SC values show that incorporation of the calcined materials at a rate of > 10% increased days to wilting by two days.

Percent leached and water use efficiency. In Expt. 1 (Table 3.8), the PO_4-P rate affected percent leached. At the lowest P rate (5 mg·L^{-1}) plants were small and the pots leached more water than at the higher PO_4-P rates of 15 and 45 mg·L^{-1}. In Expt. 1, the water use efficiency was increased by the presence of the calcined materials. The water use efficiency of the PP control was 0.73 mg·ml^{-1}, which was lower than the water use efficiency of the calcined materials (av: 0.90 mg·L^{-1}). There was no difference in water use efficiency among the plants grown in pots with the calcined materials.

In Expt. 2 (Table 3.9), again the PO_4-P rate affected the percent water leached. The plants with no PO_4-P added (0 mg·L^{-1}) leached the most water (19%, Table 3.9). Also, in Expt. 2, the PP control pots leached more water (23%) than the pots with the calcined materials (av: 14.8%). In Expt. 2, the water use efficiency again was increased by the presence of the calcined materials. The water use efficiency of the PP control was 0.89 mg·ml^{-1}, which was lower than the water use efficiency of the plants grown in media with calcined materials (av: 1.05 mg·ml^{-1}).

Plants grown in the PP control wilted sooner than plants grown in root media with the calcined materials (Fig. 3.1). The plants grown with calcined materials survived drought better because the media adsorbed more water. This allowed the plants grown in the calcined materials to have higher stomatal conductances at the end of drought cycles because more water was available for plant uptake. The water use efficiency of plants grown in the calcined materials was greater than that of plants grown in the PP control. This shows that if the calcined materials

are used in greenhouse production, growers are going to get more growth for the same amount of water used.

Acknowledgements

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Figure 3.1 Plants on day 8 of Drought Cycle 2 (July 11, 2006; Expt. 1). These plants were treated with 15 mg·L^{-1} PO$_4$-P during production. The plant on the left was the PP control; the middle plant had 5% calcined clay incorporated; and the plant on the right had 10% calcined clay incorporated. Water retention by the clays kept the plant leaves turgid for a longer period of time.
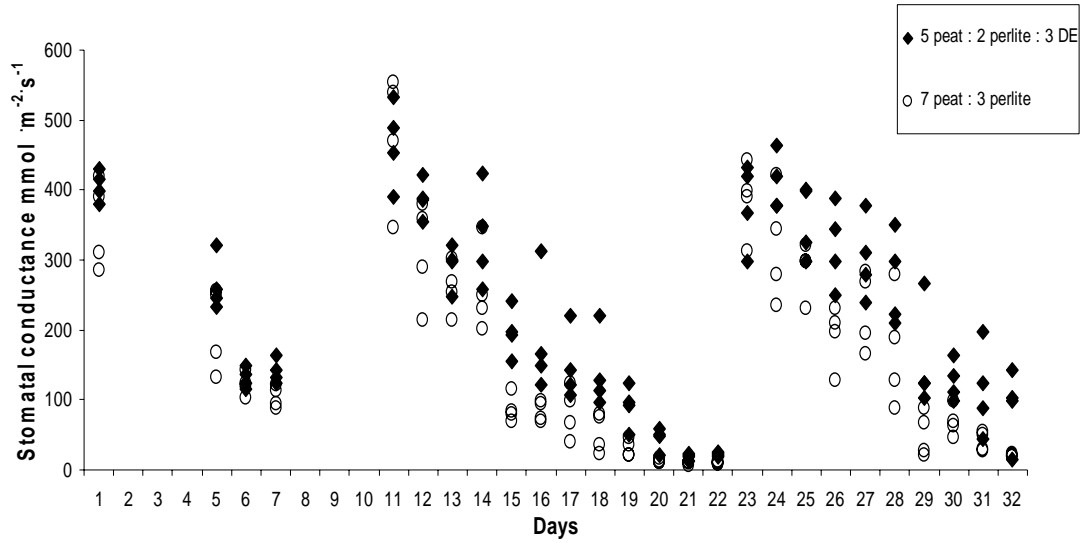
Figure 3.2 The interaction of 'clay', 'P rate' and 'time' on stomatal conductance (SC) showing the changes in SC of plants grown with 15 mg·L^{-1} PO$_4$-P.
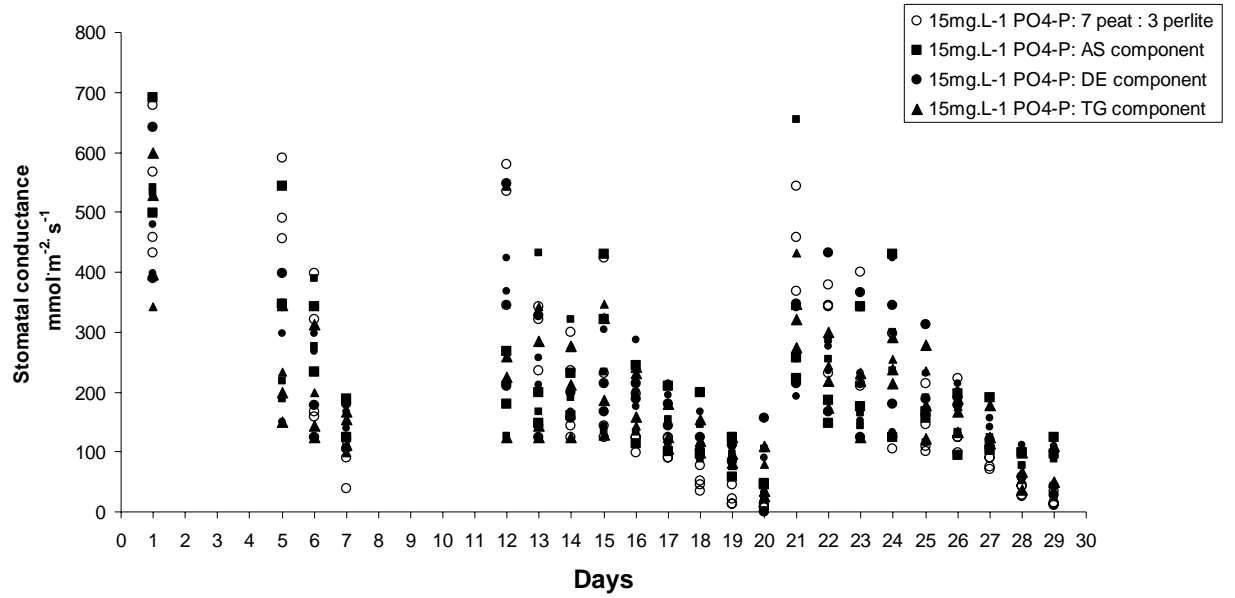
Figure 3.3 The interaction of 'clay', 'P rate' and 'time' on stomatal conductance (SC) showing the changes in SC of plants grown with 15 mg·L⁻¹ PO₄-P.

Table 3.1 Summary of environment in Expt. 1 monitored using a data logger during two drought cycles. Drought cycle 1 was carried out between 21 June to 2 July and cycle 2 was between 2 July and 15th July. The greenhouse temperatures were set at 21/18 °C day/night.

Day	Day[z] Temp. (°C)	Night[z] Temp. (°C)	Day Relative humidity (%)	Night Relative humidity (%)
		Drought cycle 1 (21 June to 2 July)		
1[y]	27.3	20.6	73.2	68.6
2	25.3	25.5	75.4	72.5
3	28.5	19.9	78.3	63.9
4	27.7	20	69.5	69.9
5	25.7	18	57	66.8
6	22.8	22	58.1	59.4
7	26.6	20	64.4	58.3
8	22	20.4	76	71.2
9	25.3	20.5	67.5	60.6
10	25.3	20.6	82.1	78.5
11	23	18.4	73.2	74.6
12	20.9	19.9	69.5	68.5
13	24.7	20.2	63	75.2
Average[x]	**25.0**	**20.5**	**68.9**	**68.3**
		Drought cycle 2 (2 July to 15 July)		
1[y]	24.7	20.2	63	75.2
2	23.4	19.1	74	71.2
3	25.4	19.4	71	70.5
4	25.8	18.3	76	69.7
5	27.2	21.7	67	54.9
6	20.2	20.5	71	72.1
7	20.6	19.41	69	67.1
8	23.2	18.9	68	74.5
9	24.0	19.5	70.4	69.0
10	23.5	19.8	68.7	70.4
11	25.3	18.5	70.3	68.9
12	22.4	18.9	71.4	70.3
Average[x]	**23.7**	**19.5**	**70.6**	**69.0**

[z]Day = 8:15 to 18:15 h, [z]Night = 18:15 to 8: 15h

[y]1 = Onset of drought cycle 1 and drought cycle 2, respectively, Dry weight and wet weights taken.

[x]Average= Temp, RH

Table 3.2 Summary of environment in Expt. 2 monitored using a data logger during two drought cycles and pan evaporation averages. Drought cycle 1 was carried out between Oct 7 to Oct 15 and cycle 2 was between Oct 16 and Oct 25. The greenhouse temperatures were set at 21/18 ^{o}C day/night.

Day	Day[z] Temp. (^{o}C)	Night[z] Temp. (^{o}C)	Day Relative humidity (%)	Night Relative humidity (%)	Average daily Pan evaporation[z] (mm· day^{-1})
			Drought cycle 1 (7 Oct 5 to 15 Oct 15)		
1	29.3	24.6	73.2	63.2	3.7
2	27.3	26.5	75.4	73.3	2.7
3[y]	29.5	19.8	78.3	66.9	3.5
4	20.7	16.6	69.5	64.5	3.9
5	23.7	18	57	56.8	1.0
6	19.8	14.8	58.1	49.2	2.0
7	19.6	18.4	64.4	48.3	1.4
8	20	18.5	76	61.9	1.8
9	20.3	19.2	67.5	70.6	1.0
10	20.3	18.6	82.1	73.7	0.4
11	20	17.2	73.2	71.1	1.0
Average[x]	**22.7**	**17.9**	**69.5**	**62.5**	**1.7**
		Drought cycle 2 (16 Oct to 24 Oct.)			
1	20.3	18.9	57	70.1	0.4
2	20.4	18.1	76.8	73.2	2.0
3	19.4	16.4	66.3	72.9	0.2
4	21.8	17.3	42.4	64.7	0.8
5	26.2	22.7	45.7	51.1	3.3
6	20.2	17.4	50.1	62.3	0.6
7	19.6	15.1	49.5	57.1	1.0
8	21.4	18	40.7	64.5	1.6
9	21.0	17.5	40.5	64.0	0.2
Average	**21.1**	**18.9**	**53.6**	**70.1**	**1.12**

[z]Day = 8:15 to 18:15 h, [z]Night = 18:15 to 8: 15h
[y]3 = Onset of drought cycle 1
[x]Average= Temp, RH and Pan evaporation averages from onset of drought cycle

Table 3.3 Height and width measurements and flower and bud counts of impatiens 4 d after being subjected to the second drought cycle (74 DAT) in Expt.1. Plants had been produced in 5 peat: 2 perlite: 3 calcined materials, the latter consisting of Attasorb (AS) or Terra Green (TG) clays at 5, 10 and 20% + DE. Controls had either inert diatomaceous earth (DE) incorporated at 30% (by volume) or consisted of 7 peat : 3 perlite.

	Plant height (cm)	Plant width (cm)	Number of flowers [x]	Number of flower buds [x]	Fresh shoot weight (g)	Dry shoot weight (g)
Clay	***	***	***	***	NS [w]	NS
Percent (Clay)	NS	***	**	**	**	*
P rate	***	***	***	***	*	**
Clay * P rate	*	NS	**	**	*	*
Clay * Percent * P rate (Clay)	NS	NS	NS	NS	NS	NS
Clay * Percent (Clay)* P rate						
Controls						
70 peat : 30 perlite Control [z]						
5	14	18.7	4	8	102.7	6.1
15	15.3	21.4	4	7	126.5	6.5
45	12.5	20.2	4	6	109.4	5.4
30 Diatomite : 50 peat : 20 perlite [y]						
5	7.0	12.7	9	7	46.4	2.9
15	11.5	17.9	10	12	79.5	3.9
45	11.3	18.1	7	10	86.7	4.2
Attasorb Clay (A-5/25)						
5% AS : 25% DE						
5	5.8	8.5	3	3	26.5	0.9
15	11.5	15.8	12	15	55.9	2.5
45	13.5	17.2	6	10	80.9	3.8
10% AS : 20% DE						
5	8.3	13.4	5	8	37.6	1.7
15	12.5	16.4	13	14	73.0	3.6
45	10.8	15.4	15	14	73.9	3.1
20% AS : 10% DE						
5	9.0	15.6	3	7	40.9	1.8
15	13.5	17.8	3	9	79.7	4.3
45	13.0	19.9	2	4	100.4	5.0
Terra Green Clay (T-M-5/20)						
5% TG : 25% DE				7	41.7	1.6
5	7.0	11.2	7	12	78.5	3.4
15	12.5	15.9	11	11	93.2	3.9
45	13.3	17.6	8			
10% TG : 20% DE						
5	11.5	13.3	5	9	52.4	2.7
15	12.8	18.0	7	6	72.0	2.9
45	13.3	19.1	5	8	79.7	3.8

20% TG:10% DE						
5	9.5	13.6	5	7	48.2	2.3
15	14.8	16.8	5	13	67.3	3.5
45	13.8	18.9	5	8	83.8	3.9
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

Clay * P rate

Controls

70 :30 peat : perlite[z]

5	14.0ab	18.7	4b	8ab	102.7b	6.1a
15	15.3a	21.4	4b	7b	126.5a	6.5a
45	12.5ab	20.2	4b	6b	109.4b	5.4ab

30 Diatomite : 50 peat : 20 perlite[y]

5	7.0c	12.6	9a	7b	46.4d	2.9c
15	11.5b	17.9	10a	12a	79.5c	4.0b
45	11.3b	18.2	7a	10a	86.7c	4.2b

Attasorb Clay (A-5/25)

5	7.7c	12.5	3b	6b	35.0de	1.4d
15	12.5b	16.7	9a	12a	69.6c	3.5bc
45	12.4b	17.4	7a	9a	85.1c	4.0b

Terragreen Clay (T-M-5/20)

5	9.3bc	12.6	6ab	8ab	47.4d	2.2cd
15	13.3ab	16.9	8a	10a	72.6c	3.3bc
45	13.4ab	18.6	6ab	9a	85.6c	3.9b
LSD$_{0.05}$	**2.9**	**NS**	**4.4**	**2.6**	**1.41**	**1.1**

Percent (Clay)

0%

70 :30 peat : perlite[z]	13.9	20.0a	4bc	6.9	112.9a	6.0a
30 Diatomite : 50 peat : 20 perlite[y]	9.9	16.2b	9a	9.8	70.9b	3.7b

5%

A-5/25	10.3	13.8c	7b	9.1	54.5c	2.4c
T-M-5/20	10.9	14.9bc	10a	11.8	71.0b	3.0bc

10%

A-5/25	10.5	15.0bc	3c	6.7	61.5bc	2.8c
T-M-5/20	12.5	16.8b	9a	9.8	68.0b	3.7b

20%

A-5/25	11.8	17.75b	5bc	7.4	73.7b	3.7b
T-M-5/20	12.7	16.4b	5bc	9.3	66.4b	3.2b
LSD$_{0.05}$	**NS**	**1.65**	**3.62**	**NS**	**9.82**	**0.69**

Clay

70 :30 peat : perlite[z]	13.9a	20.0a	4b	7b	112.9a	6.0a
30 Diatomite : 50 peat : 20 perlite[y]	12.0ab	16.2b	9a	10a	70.9b	3.7b
A-5/25	9.9c	15.6b	7a	9a	63.2b	3.0b
T-M-5/20	10.9bc	16.1b	6ab	9a	68.5b	3.2b
LSD$_{0.05}$	**0.98**	**1.08**	**1.92**	**2.01**	**7.5**	**0.58**

P rate						
5	9.5a	14.1a	6	7	57.9b	3.1b
15	13.1b	18.7b	8	11	87.0a	4.3a
45	12.4b	18.55b	6	9	91.7a	4.4a
LSD$_{0.05}$	**1.2**	**1.15**	**NS**	**NS**	**6.94**	**0.49**

[z]Control containing 7 peat : 3 perlite (industry standard)
[y]Control containing 3 Diatomite : 5 peat : 2 perlite
[x]Means from flower and flower buds counts recorded to the nearest whole number
[w]NS, *, **, *** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively.
Different letters indicate statistically significant differences.

Table 3.4 Height and width measurements and flower and bud counts of impatiens 5 d after being subjected to the second drought cycle (60 DAP) in Expt. 2. Plants had been produced in either 7 peat: 2 perlite or 7 peat: 2.5 perlite media with diatomaceous earth (DE), Attasorb (AS), or Terra Green (TG) calcined materials at 5 or 10 % (by volume). The control consisted of 7 peat: 3 perlite.

	Height (cm)	Width (cm)	Number of flowers [z] (no.)	Number of flower buds [z] (no.)	Fresh shoot weight (g)	Dry shoot weight (g)
Clay	*	NS [x]	**	**	**	**
Prate	NS	NS	NS	NS	NS	NS
Clay*Pct	NS	NS	NS	NS	NS	NS
Clay*Prate	NS	NS	NS	NS	*	*
Clay* Pct*Prate	NS	NS	*	NS	NS	NS
Calcined material * Percent * P rate (Calcined material)						
Controls						
70 peat : 30 perlite [z]						
15	8.3	24.5	22ab	45	68.3	3.8
45	9.0	25.5	28a	45	64.7	3.7
30 Diatomite : 50 peat : 20 perlite						
5 Percent						
5 Percent	8.5	24.5	14c	35	60.0	3.1
15	7.5	27.0	16bc	48	67.0	3.6
45						
10 Percent						
15	8.0	23.9	8c	29	48.7	2.5
45	8.0	25.9	11c	39	66.5	3.5
Attasorb Clay (A-5/25)						
5 Percent						
15	9.5	26.1	24a	44	65.8	3.5
45	9.5	26.0	28a	45	63.7	3.5
10 Percent						
15	7.8	25.3	13c	45	72.2	3.8
45	10.0	25.8	24a	38	60.0	3.4
Terra Green Clay (T-M-5/20)						
5 Percent						
15	9.0	25.1	20b	53	74.5	3.8
45	7.5	23.5	23ab	47	69.4	3.7
10 Percent						
15	8.6	25.9	22ab	44	70.6	3.5
45	8.8	26.0	20b	58	72.8	3.8
LSD$_{0.05}$	**NS**	**NS**	**6.4**	**NS**	**NS**	**NS**

Calcined material * P rate

Controls

70 :30 peat : perlite [z]

15	8.3	24.5	45	22	68.32a	3.80a
45	9.0	25.5	45	18	64.67ab	3.77a

Diatomite

15	8.3	24.2	32	11	54.31c	2.81c
45	7.8	26.4	45	13	66.91ab	3.56a

Attasorb Clay (A-5/25)

15	8.6	25.7	45	19	68.99a	3.62a
45	9.8	25.9	41	26	61.86ab	3.43ab

Terra green Clay (T-M-5/20)

15	8.8	25.5	48	21	72.6a	3.56a
45	8.1	24.8	53	22	71.07a	3.56a
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**	**9.7**	**0.47**

Percent (Clay)

0%

70 :30 peat : perlite [z]

	8.62	25.0	45	25	66.49	3.79

5%

Diatomite	8	25.75	42	15	63.49	3.35
A-5/25	9.5	26.06	44	26	64.78	3.48
T-M-5/20	8.25	24.31	50	22	71.93	

10%

Diatomite	8.0	24.84	34	9	57.6	3.03
A-5/25	8.87	25.56	42	18	66.1	3.56
T-M-5/20	8.25	25.93	51	21	71.7	3.67
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

SE

Clay

70 :30 peat : perlite [z]	8.63ab	25.0	45a	25a	66.49a	3.7a
Diatomite	8.0bc	25.3	38b	12b	60.56b	3.19b
A-5/25	9.91a	25.8	43ab	22a	65.43a	3.53a
T-M-5/20	8.49ab	25.1	50a	21a	71.83a	3.724a
LSD$_{0.05}$	**0.92**	NS	**7.0**	**6.5**	**4.7**	**0.32**

P rate

15	8.5	24.96	42	18.2	66.1	3.5
45	8.7	25.65	46	22.2	66.1	3.6
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

[z] Means from flower and flower buds counts recorded to the nearest whole number

[y] Control containing 7 peat : 3 perlite (industry standard)

[x] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences

Table 3.5 Leachate volumes and rewet volumes during the post- production phase in Expt. 1.

	Total Leachate volume (ml)	% of applied water leached	Rewet volume^z (ml)	Rewet volume^y drought cycle-1 (ml)	Rewet volume^x drought cycle-2 (ml)
Clay	*	*	NS	*	*
Percent (Clay)	*	*	NS	*	*
P rate	NS ^{w}	NS	NS	NS	NS
Clay * P rate	NS	NS	NS	*	**
Clay * Percent * P rate (Clay)	NS	NS	NS	NS	NS
Clay * Percent* P rate (Clay)					
Controls					
70 peat : 30 perlite Control					
5	395	32.9	285	260	195
15	350	29.2	280	243	220
45	330	27.5	275	250	200
30 Diatomite : 50 peat : 20perlite					
5	280	23.3	320	300	295
15	265	22.1	310	321	310
45	250	20.8	315	300	290
Attasorb Clay (A-5/25)					
5% AS : 25% DE					
5	295	24.6	290	295	280
15	270	22.5	280	275	280
45	260	21.7	265	270	270
10% AS : 20% DE					
5	270	22.5	300	285	310
15	270	22.5	280	275	280
45	245	20.4	270	265	265
20% AS : 10% DE					
5	245	20.4	320	300	285
15	240	20.0	300	295	290
45	230	19.2	290	275	280

Terra Green Clay (T-M-5/20)					
5% TG : 25% DE					
5					
15	310	25.8	315	290	275
45	295	24.6	300	295	280
10% TG : 20% DE	280	23.3	290	275	260
5					
15	290	24.2	330	320	290
45	285	23.8	320	300	295
20% TG:10% DE	285	23.8	300	295	280
20 Percent					
5	260	21.7	335	320	295
15	265	22.1	330	325	290
45	250	20.8	320	300	280
LSD$_{0.05}$	NS	NS	NS	NS	NS
Clay * P rate					
Controls					
70 :30 peat : perlite					
5	395	32.9	285	260b	195b
15	350	29.2	280	243b	220ab
45	330	27.5	275	250b	200b
30 Diatomite : 50 peat : 20 perlite					
5	280	23.3	320	300a	295a
15	265	22.1	310	321a	310a
45	250	20.8	315	300a	290a
Attasorb Clay (A-5/25)					
5	270.0	22.5	303.3	293.3a	291.7a
15	260.0	21.7	286.7	281.7ab	283.3a
45	245.0	20.4	275.0	270.0b	271.7a
Terragreen Clay (T-M-5/20)					
5	286.7	23.9	326.7	310.0a	286.7a
15	281.7	23.5	316.7	306.7a	288.3a
45	271.7	22.6	303.3	290.0a	273.3a
LSD$_{0.05}$	**NS**	**NS**	**NS**	**54.4**	**60.5**

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Percent (Clay)

0%					
70 :30 peat : perlite	358.3a	29.9a	280.0	251.0b	205.0b
30 Diatomite : 50 peat : 20 perlite	265.0b	22.1b	315.0	307.0a	298.3a
5%					
A-5/25	275.0b	22.9b	278.3	280.0a	276.7a
T-M-5/20	295.0ab	24.6ab	301.7	286.7a	271.7a
10%					
A-5/25	256.7b	21.4b	285.0	280.0a	290.0a
T-M-5/20	286.7b	23.9b	316.7	305.0a	288.3a
20%					
A-5/25	258.3b	21.5b	328.3	315.0a	288.3a
T-M-5/20	258.3b	21.5b	328.3	315.0a	288.3a
LSD$_{0.05}$	**68**	**5.2**	**NS**	**40.1**	**52.2**
Clay					
70 :30 peat : perlite	358.3a	29.9a	280.0	251.0c	205.0b
30 Diatomite : 50 peat : 20 perlite	265.0b	22.1b	315.0	307.0a	298.3a
A-5/25	256.7b	21.4b	288.9	283.3b	283.9a
T-M-5/20	280.0b	23.3b	315.6	302.2a	282.8a
LSD$_{0.05}$	**46**	**4.7**	**NS**	**24**	**40.3**
P rate					
5	293.1	24.4	311.9	296.3	278.1
15	278.1	23.2	300.6	293.0	282.5
45	266.3	22.2	290.6	278.8	265.6
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**

[z]Rewet volume = Difference in pot weight before and after watering indicating volume of water retained from a 400 ml application at the onset of drought cycle1

[y]Rewet volume = volume of water retained from a 400 ml application during drought cycle 1.

[x]Rewet volume = volume of water retained from a 400 ml application drought cycle 2.

[w] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences

Table 3.6 Leachate volumes and rewet volumes during the post- production phase in Expt. 2.

	Total Leachate volume (ml)	% of applied water leached	Rewet volume[z] (ml)	Rewet volume[y] (ml)
Clay	***	***	*	**
Pct	*	**	NS	NS
Percent (Clay)	*	*	NS	*
P rate	NS [x]	NS	NS	NS
Clay * P rate	***	***	NS	NS
Pct*Prate	*	*	NS	NS
Clay * Percent * P rate (Clay)	NS	NS	NS	NS
Clay * Percent * P rate (Clay)				
Controls				
70 peat : 30 perlite Control				
15	193.5a	32.3a	212.5ab	197.8
45	208.8a	34.8a	203.8b	183.8
30 Diatomite : 50 peat : 20 perlite				
5 Percent				
15	132.5b	22.1b	219.0ab	242.7a
45	147.5b	24.6b	224.0ab	233.8a
10 Percent				
15	143.3b	23.7b	234.0a	219.5b
45	128.8b	21.5b	232.0ab	235.5a
Attasorb Clay (A-5/25)				
5 Percent				
15	161.3b	26.9b	220.5b	219.5b
45	130.0b	21.7b	238.0a	224.0a
10 Percent				
15	155.0b	25.8b	222.5ab	221.0b
45	117.5b	19.6b	241.0a	239.5a
Terra Green Clay (T-M-5/20)				
5 Percent				
15	144.5b	24.1b	226.0b	226.5b
45	140.3b	23.4b	231.0ab	227.8b
10 Percent				
15	137.5b	22.9b	235.5ab	232.3a
45	115.0b	19.2b	237.5a	246.0a
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**

Clay * P rate

Controls

70 :30 peat : perlite [x]

15	193.5a	32.3a	212.5	195.8b
45	208.7a	34.8a	203.7	183.8b

Diatomite

15	137.9b	23.0b	226.5	231.1a
45	138.1b	23.0b	228.0	236.1a

Attasorb Clay (A-5/25)

15	158.1b	26.4b	221.5	220.3ab
45	123.8b	20.6b	239.5	231.8a

Terra green Clay (T-M-5/20)

15	141.0b	23.4b	230.8	229.4a
45	127.6b	21.2b	234.3	236.9a
LSD$_{0.05}$	**40**	**7.8**	NS	**10.5**

Percent (Clay)

0%

70 :30 peat : perlite [x]	201.1a	33.5a	208.1b	189.8b

5%

Diatomite	140.0bc	23.3bc	221.5ab	238.3a
A-5/25	145.6b	24.3b	229.3a	221.8a
T-M-5/20	142.4b	23.7b	228.5a	227.1a

10%

Diatomite	136.0bc	22.6bc	233.0a	229.0a
A-5/25	136.3bc	22.7bc	231.8a	230.3a
T-M-5/20	126.3c	21.0c	236.5a	239.1a
LSD$_{0.05}$	**22**	**5.4**	**15.2**	**20.5**

Clay

70 :30 peat : perlite [x]	201.1a	33.5a	208.1b	189.8b
Diatomite	138.0b	23.0b	227.3a	233.6a
A-5/25	140.9b	23.5b	230.5a	226.0a
T-M-5/20	134.3b	22.4b	232.5a	233.1a
LSD$_{0.05}$	**13.44**	**2.24**	**12.06**	**17.47**

P rate

15	157.6	26.3	222.8	219.1
45	149.6	24.9	226.4	222.1
LSD$_{0.05}$	**NS**	**NS**	**NS**	**NS**

[z]Rewet volume = Difference in pot weight before and after watering indicating volume of water retained from a 300 ml application at the onset of drought cycle1

[y]Rewet volume = volume of water retained from a 300 ml application after drought cycles 1 and during dry cycle 2

[x]NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences

Table 3.7 P-values generated by repeated-measures ANOVA performed on stomatal conductance (SC) over time during the post- production phase. The type 3 tests for Fixed Effects from the first order autoregressive covariance model are displayed. Stomatal conductance was measured on a medium-sized leaf on each impatiens plant every morning (10:00 to 12:00 h) and afternoon (16:00 to 18:00 h) during Expt.1 and only at mid-day (12:00-14:00h) during Expt. 2.

	SC (morning) mmol m^{-2}·s^{-1}	SC (Evening) mmol m^{-2}·s^{-1}	SC (morning) mmol m^{-2}·s^{-1}	SC (Evening) mmol m^{-2}·s^{-1}
Main Effects and Interactions	P-values Experiment 2 (21 June to 15 July 2006)			
	Drought Cycle-1		Drought cycle 2	
	SC Morning data mmol m^{-2}·s^{-1}	SC Evening data mmol m^{-2}·s^{-1}	SC Morning data mmol m^{-2}·s^{-1}	SC Evening data mmol m^{-2}·s^{-1}
Clay	0.1334	0.0497	<.0001	<.0001
%(Clay)	0.0234	0.9747	0.0021	0.7798
Prate	0.0118	0.2016	0.0064	0.0006
Clay*Prate	0.6277	0.8945	0.4145	0.1927
Clay*Percent (Clay)*Prate	0.0107	0.0152	0.0084	0.0386
Time	<.0001	<.0001	<.0001	<.0001
Clay*Time	<.0001	0.0005	0.2291	<.0001
Percent (Clay) *Time	0.2288	0.4746	0.0174	0.7312
Prate*Time	<.0001	<.0001	0.0018	<.0001
Clay*Prate*Time	0.0725	0.0148	0.7291	0.3314
Clay*Percent(Clay)*Prate*Time	0.7720	0.7382	0.0031	0.0001
Experiment 1 (7 Oct. to 25 Oct 2007)				
	SC (morning) mmol m^{-2}·s^{-1}		SC (morning) mmol m^{-2}·s^{-1}	
	Drought Cycle-1		Drought cycle 2	
Clay	<.0001		<.0001	
%(Clay)	0.0446		0.0223	
Prate	<.0001		<.0001	
Clay*Prate	0.0003		0.0004	
Clay*Percent (Clay)*Prate	0.3468		0.2868	
Time	<.0001		<.0001	
Clay*Time	<.0001		<.0001	
Percent (Clay) *Time	0.3224		0.2924	
Prate*Time	<.0001		<.0001	
Clay*Prate*Time	0.0650		0.0019	
Clay*Percent(Clay)*Prate*Time	0.1100		0.1100	

Table 3.8 Leachate volume by percent irrigation water applied and water use efficiency in terms of amount of dry matter (mg) per liter of irrigation volume used (mg·L^{-1}) for production of impatiens in Expt 1.

	Percent of applied volume leached	WUE mg·L^{-1}
Block	***	***
Clay	NS ^{z}	*
Percent (Clay)	*	NS
P rate	***	***
Clay * P rate	NS	NS
Clay * Percent * P rate (Clay)	NS	NS
Clay * Percent (Clay)* P rate		
Controls		
70 peat : 30 perlite Control		
5	26.87	0.25
15	23.17	0.63
45	25.10	1.32
30 Diatomite : 50 peat : 20 perlite		
5	26.93	0.43
15	24.19	0.83
45	22.44	1.40
Attasorb Clay (A-5/25)		
5 Percent		
5	28.25	0.35
15	25.31	0.95
45	23.88	1.6
10 Percent		
5	28.13	0.45
15	24.81	0.75
45	22.13	1.67
20 Percent		
5	26.25	0.35
15	24.31	0.70
45	22.94	1.60

Terra Green Clay (T-M-5/20)

5 Percent		
5	29.06	0.4
15	25.19	0.85
45	22.93	1.5
10 Percent		
5	25.38	0.32
15	22.63	0.88
45	20.38	1.58
20 Percent		
5	27.91	0.33
15	23.88	0.58
45	25.10	1.50
LSD$_{0.05}$	**NS**	**NS**

Clay * P rate

Controls

70 :30 peat : perlite		
5	26.87	0.25d
15	23.17	0.63c
45	25.09	1.3a
30 Diatomite : 50 peat : 20 perlite		
5	26.94	0.43d
15	24.18	0.83b
45	22.44	1.4a

Attasorb Clay (A-5/25)

5	27.54	0.38d
15	24.81	0.8b
45	22.98	1.6a

Terragreen Clay (T-M-5/20)

5	27.45	0.35d
15	23.90	0.76b
45	22.35	1.53a
LSD$_{0.05}$	**NS**	**NS**

Percent (Clay)

0%		
70 :30 peat : perlite	25.0a	0.73
30 Diatomite: 50 peat: 20 perlite	24.5a	0.88
5%		
A-5/25	25.8a	0.97
T-M-5/20	25.8a	0.92
10%		
A-5/25	25.0a	0.96
T-M-5/20	22.8ab	0.93
20%		
A-5/25	24.5a	0.88
T-M-5/20	25.1a	0.80
LSD$_{0.05}$	**0.57**	**NS**
Clay		
70 :30 peat : perlite	25.05	0.73b
30 Diatomite: 50 peat: 20 perlite	24.52	0.88a
A-5/25	25.1	0.94a
T-M-5/20	24.57	0.88a
LSD$_{0.05}$	**NS**	**0.10**
P rate		
5	27.20	0.35c
15	24.01	0.75b
45	23.22	1.5a
LSD$_{0.05}$	**NS**	**0.08**

[z] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences

Table 3.9 Leachate volume by percent irrigation water applied and water use efficiency in terms of amount of dry matter (mg) per liter of irrigation volume used (mg·L^{-1}) for production of impatiens in Expt. 2.

	Percent of applied volume leached (%)	WUE (mg·L^{-1})
	P-values	
Clay	***	*
Percent(Clay)	NS ^{z}	NS
Prate	***	***
Clay*Prate	***	NS
Clay* Percent(Clay)*Prate	NS	NS
Clay * Percent (Clay)* P rate		
Controls		
70 peat : 30 perlite Control		
0	26.8	0.1
15	21.7	1.3
45	19.6	1.3
30 Diatomite : 50 peat : 20 perlite		
5 Percent		
0	16.0	0.5
15	15.1	1.1
45	13.2	1.4
10 Percent		
0	17.2	0.1
15	13.3	0.9
45	11.7	1.5
Attasorb Clay (A-5/25)		
5 Percent		
0	16.6	0.4
15	15.1	1.5
45	14.8	1.4
10 Percent		
0	16.3	0.1
15	15.2	1.5
45	14.3	1.5

Terra Green Clay (T-M-5/20)
 5 Percent

0	15.6	0.1
15	14.2	1.5
45	13.7	1.7

 10 Percent

0	15.9	0.2
15	14.2	1.7
45	13.6	1.8
LSD$_{0.05}$	**NS**	**NS**

Clay * P rate

Controls

 70 :30 peat : perlite

0	26.8	0.10
15	21.7	1.31
45	19.58	1.28

Diatomite

0	16.7	0.30
15	14.4	1.03
45	12.4	1.44

Attasorb Clay (A-5/25)

0	16.4	0.25
15	15.2	1.50
45	14.5	1.45

Terra green Clay (T-M-5/20)

0	15.8	0.16
15	14.2	1.58
45	13.6	1.76
LSD$_{0.05}$	**1.68**	**NS**

Percent (Clay)

0%		
70 :30 peat : perlite	22.7	0.89
5%		
Diatomite	14.9	1.03
A-5/25	15.5	1.09
T-M-5/20	14.9	1.11
10%		
Diatomite	14.1	0.81
A-5/25	15.3	1.05
T-M-5/20	14.6	1.22
LSD$_{0.05}$	**NS**	**NS**

Clay		
70 :30 peat : perlite	22.7a	0.89b
Diatomite	14.5b	0.92b
A-5/25	15.4b	1.07a
T-M-5/20	14.5b	1.16a
LSD$_{0.05}$	**1.58**	**0.13**
P rate		
0	18.9a	0.20b
15	16.3b	1.35a
45	15.04b	1.50a
LSD$_{0.05}$	**1.34**	**0.08**

[z] NS, *, **, ***, **** Nonsignificant or significant at P= 0.05, 0.001, or 0.0001, respectively. Different letters indicate statistically significant differences

Conclusions

This research project characterized the PO_4-P retention of 16 different commercially-available calcined materials. Though laboratory characterization did not suggest that diatomaceous earth (DE) would retain PO_4-P, greenhouse experiments suggested otherwise. The mechanism of PO_4-P retention by calcined materials can be by a physical mechanism whereby the calcined material absorbs root medium solution and its dissolved ions, as was the case with DE, or a combination of the physical mechanism in tandem with chemisorption, as was the case with Attasorb and Terra Green clays.
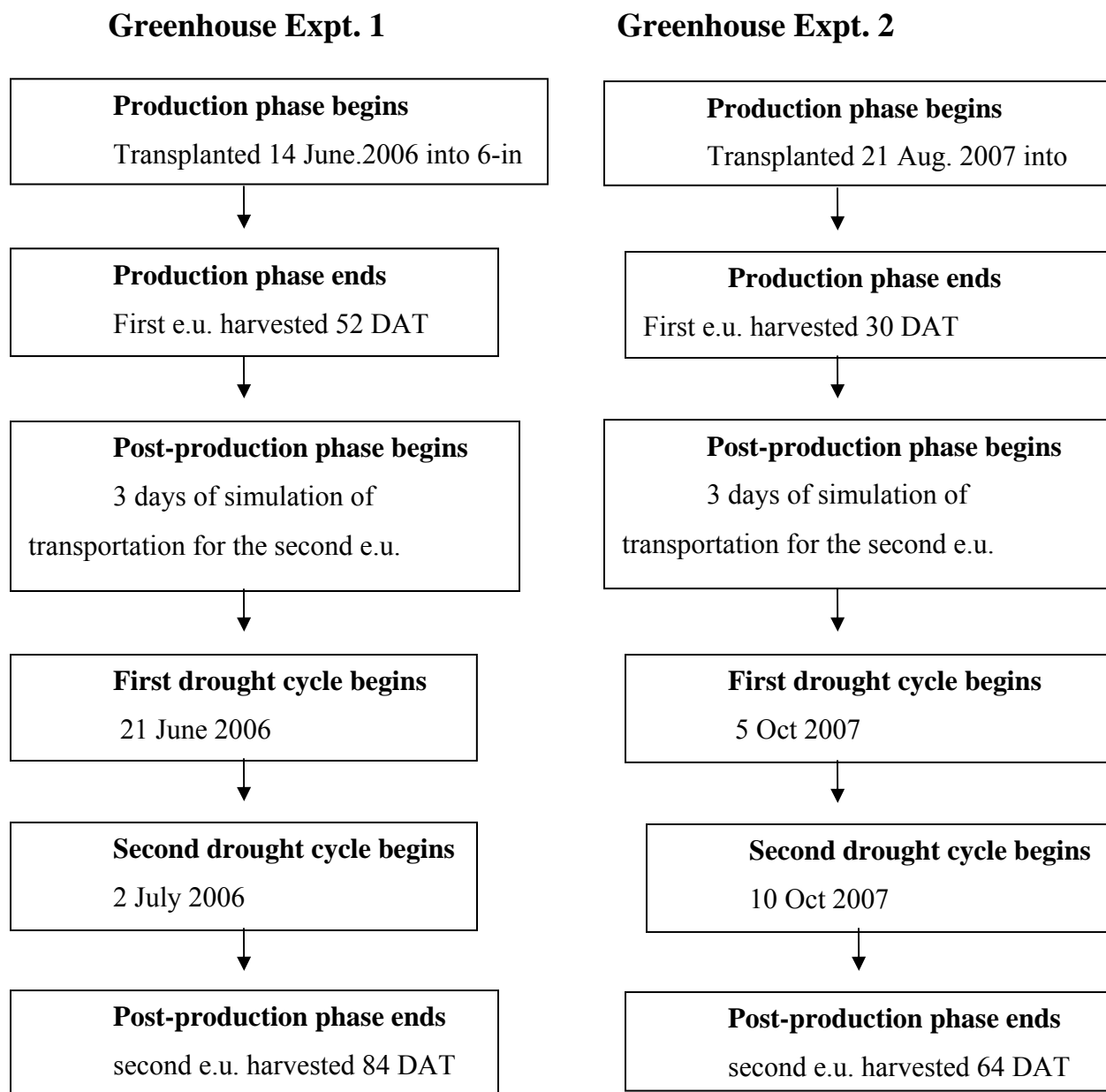
A benefit of using calcined materials beyond PO_4-P retention includes increased water retention. The calcined products have significant moisture sorption properties, which are related to their primary commercial use as absorbents. The temperatures of calcining are crucial in determining the extent to which the hardened aggregates maintain internal porosity. The primary purpose of using calcined clays is to control moisture in the root medium; that is, to absorb, retain, and release water depending upon plant needs at any given time. Other benefits of calcined clay use include decreased root medium shrinkage, especially if the mix is to be pasteurized for recycling, and increased re-wetting of soilless root media which often develop hydrophobic properties. Poor water relations in post-production can lead to premature wilting which may result in poor plant performance in the market channel. Consumer satisfaction after post-production is enhanced by delayed wilting as shown by our results where plants grown in media with calcined clays survived drought better because mixes could retain and release more water. The water use efficiency of plants grown in the calcined materials was greater than that of

plants grown in the PP control, an industry standard of 7 peat: 3 perlite. This indicates that if the calcined materials are used in mixes for greenhouse production, growers are going to get more growth for the same amount of water used.

Limitations of using calcined materials as soilless root medium components include the high cost of purchase and shipping, especially if used at high enough percentages in soilless mixes to impart benefits such as buffering against pH drift. Because the materials are mined, natural variability occurs at different mines and even mining depths within the same mine; this would contribute to lack of uniform and consistent quality attributes in the materials over years of use. Finally, if calcined materials with very high PO_4-P sorption capacity are used, the materials themselves may remove PO_4-P from root medium solution when used in tandem with very low rates of PO_4-P fertilization.

Future research should investigate the mechanism of PO_4-P sorption by the calcined materials is ambiguous and further research could elucidate these mechanisms. PO_4-P desorption of the materials should be further evaluated. Finally, the economic benefits of reduced PO_4-P run-off in greenhouse effluent and reduced water use during production should be evaluated to help growers make decisions about using calcined materials. Our research indicated that 10% incorporation rate of calcined materials into peat-based media confers beneficial physical properties, water retention, and PO_4-P retention to soilless root media.

Appendix A - Flow chart showing schedule of events for greenhouse experiments 1 and 2; DAT = days after transplant and e.u. = experimental unit.

Greenhouse Expt. 1

Production phase begins
Transplanted 14 June.2006 into 6-in

↓

Production phase ends
First e.u. harvested 52 DAT

↓

Post-production phase begins
3 days of simulation of transportation for the second e.u.

↓

First drought cycle begins
21 June 2006

↓

Second drought cycle begins
2 July 2006

↓

Post-production phase ends
second e.u. harvested 84 DAT

Greenhouse Expt. 2

Production phase begins
Transplanted 21 Aug. 2007 into

↓

Production phase ends
First e.u. harvested 30 DAT

↓

Post-production phase begins
3 days of simulation of transportation for the second e.u.

↓

First drought cycle begins
5 Oct 2007

↓

Second drought cycle begins
10 Oct 2007

↓

Post-production phase ends
second e.u. harvested 64 DAT

Appendix B - Fertilizer solution formulations for greenhouse Expts. 1 and 2.

Table B.1 Expt. 1. PO$_4$-P treatments of 5, 15 and 45 mg·L^{-1}

Salts used in g·L^{-1}	Treatment 1 (5 mg·L^{-1} P, 105 mg·L^{-1}N and 105 K$_2$O mg·L^{-1})	Treatment 2 (15 mg·L^{-1} P, 105 mg·L^{-1}N and 105 K$_2$O mg·L^{-1})	Treatment 3 (45 mg·L^{-1} P, 105 mg·L^{-1}N and 105 K$_2$O mg·L^{-1})
KNO$_3$	0.2222	0.2222	0.2222
NH$_4$H$_2$PO$_4$	0.0184	0.0552	0.1670
NH$_4$ NO$_3$	0.1840	0.1376	0.0352
(NH$_4$)$_2$SO$_4$	0.0251	0.0528	0.0733
Ca(NO$_3$)$_2$	0.0000	0.0299	0.0948
MgSO$_4$	0.1800	0.1800	0.1800
CaCl$_2$	0.1110	0.0787	0.0077

Table B.2 Expt. 2. PO$_4$-P treatments of 0, 15 and 45 mg·L^{-1}

Salts used in g·L^{-1}	Treatment 1 (0 mg·L^{-1} P, 105 mg·L^{-1}N and 105 K$_2$O mg·L^{-1})	Treatment 2 (15 mg·L^{-1} P, 105 mg·L^{-1}N and 105 K$_2$O mg·L^{-1})	Treatment 3 (45 mg·L^{-1} P, 105 mg·L^{-1}N and 105 K$_2$O mg·L^{-1})
KNO$_3$	0.2222	0.2222	0.2222
NH$_4$H$_2$PO$_4$	0.0000	0.1472	0.2940
NH$_4$ NO$_3$	0.1840	0.1376	0.0352
(NH$_4$)$_2$SO$_4$	0.0027	0.0528	0.0735
Ca(NO$_3$)$_2$	0.0000	0.0296	0.0948
MgSO$_4$	0.1800	0.1800	0.1800
CaCl$_2$	0.1110	0.0787	0.0077