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Container Medium pH in a Pine Tree Substrate Amended with Peatmoss and Dolomitic Limestone Affects Plant Growth

Brian E. Jackson[1,4]
North Carolina State University, Department of Horticulture, 114 Kilgore Hall, Campus Box 7609, Raleigh, NC 27695

Robert D. Wright[2]
Department of Horticulture, Virginia Polytechnic Institute and State University, 301 Saunders Hall, Blacksburg, VA 24061

Nazim Gruda[3]
Institute for Horticultural Science, Faculty for Agriculture and Horticulture, Humboldt University of Berlin, Lentzeallee 55/57, 14195 Berlin, Germany

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***Abstract*. This work was conducted to evaluate the effect of limestone additions to pine tree substrate (PTS) and PTS amended with peatmoss on pH and plant growth. 'Inca Gold' marigold (*Tagetes erecta* L.) and 'Rocky Mountain White' geranium (*Pelargonium* ×*hortorum* L.H. Bailey) were grown in three PTSs—100% PTS, PTS plus 25% peatmoss (v/v), and PTS plus 50% peatmoss (v/v)—made from freshly harvested loblolly pine trees (*Pinus taeda* L.) chipped and hammermilled through a 4.76-mm screen and a peatmoss/perlite (4:1 v/v; PL) control. Each substrate was amended with various rates of dolomitic limestone and used to grow marigolds in 10-cm square (l-L) plastic containers and geraniums in round 15-cm (1.25-L) plastic containers in a glasshouse. Regardless of limestone rate, pH was highest in 100% PTS and decreased with peat additions with PL having the lowest pH. As percent peat increased from 25% to 50%, more limestone was required to adjust pH to a particular level showing that PTS is more weakly buffered against pH change than peatmoss. Adding limestone did not increase the growth of marigold in 100% PTS, but additions of limestone did increase growth of marigold when grown in PTS containing peatmoss or in PL. Geranium growth was higher in PTS containing peatmoss (25% or 50%) and PL than in 100% PTS at all limestone rates. This research demonstrates that PTS produced from freshly harvested pine trees has an inherently higher pH than PL, and the additions of peatmoss to PTS require pH adjustment of the substrate for optimal plant growth.**

Most all ornamental greenhouse crops (Nelson, 2003) and all house/foliage plants are grown in containers. The basis for most container substrates is peatmoss, aged pine bark (PB), and more recently coconut coir. All of these materials are naturally acidic in nature (pH 4.0 to 4.5; Rippy et al., 2007) and it is standard practice to adjust (raise) the pH of these materials with limestone to reach a desired pH range of 5.4 to 6.5 for most crops (Nelson, 2003). However, the liming requirements for wood-based container substrates have not been established. Several studies evaluating wood-based substrates have been reported in recent years that do not indicate if any liming material was used as an amendment for the successful production of woody plants (Bohne, 2004; Lumis, 1976; Riviere and Milhau, 1983), and herbaceous plants (Starck and Lukaszuk, 1991). Contrary to these references that did not mention the use or nonuse of lime amendments, there are studies that reported the incorporation of lime in wood substrates but do not signify why lime was being added or what effect it had on the results. Work by Conover and Poole (1983) described a wood-based substrate derived from paper bark trees (*Melaleuca quinquenervia* Cav.) that was amended with 4 kg·m^{-3} of dolomitic lime and a substrate made from ground tree ferns (*Dicksonia squarosa* Swartz.) was amended with 5.0 to 6.0 g·L^{-1} dolomite lime (Prasad and Maher, 2004) with no explanation of why the lime was added (it was not stated if the pH of the substrates used was lower than desired). Other work evaluating sawdust as successful container substrates have reported the incorporation of liming materials with no justification for doing so (Still et al., 1972). The addition of lime to substrates is probably based on tradition and common practice of using peat and bark-based substrates for the past three decades that require the addition of lime to increase pH for proper plant growth. The use of alternative (nonpeat or bark) substrates should be independently evaluated for their potential liming requirements as a result of initial pH, buffering capacity, and so on.

In one study in which lime rates were evaluated, Hicklenton (1982) reported that the growth of *Chrysanthemum morifolium* Ramat. 'Mountain Peak', 'Goldstar', and 'Cir Bronze' in a sawdust substrate was unaffected by preplant substrate treatments, including increasing lime rates. However, limestone was not used as a single amendment but instead as a combination with multiple amendments that were applied. Therefore, plant response could not be attributed to (or explained by) the lime addition.

The use of pine tree substrates (PTS), which are produced from pine trees that are chipped and ground (with or without bark, limbs, needles, and so on) in a hammermill (Fain et al., 2006; Laiche and Nash, 1986; Wright and Browder, 2005), and clean chip residual (≈40% pine wood, 50% bark, and 10% needles), which is produced from byproducts of the pine tree harvesting process (Boyer et al., 2006), has gained attention as alternative container substrates for greenhouse and nursery crop production. The interest in these wood-based substrates has generated many unanswered questions from nurserymen and scientists. Among the unknown issues that have emerged concerning the use of PTS are those relating to the limestone requirement and adjustment of pH for optimal plant growth.

In studies with PTS produced from delimbed loblolly pine trees (Jackson et al., 2008; Wright et al., 2006, 2008b), no lime was incorporated and pH was in the range of 5.5 to 6.4. Gruda and Schnitzler (2006) also used wood-based substrates without the addition of lime and the pH was in a range of 5.3 to 5.9, an acceptable range for most greenhouse crops. In a study by Fain et al. (2008), three species of pine trees (*P. taeda*, *P. elliottii*, and *P. palustris*) were processed (including limbs and needles) to make three PTSs (one from each species) and all were amended with dolomitic limestone at 1.78 kg·m^{-3}. The resulting pH (30 d after planting) of all substrates was between 6.9 and 7.2, which was above the optimum pH for growing

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[1]Former Graduate Research Assistant. Currently Assistant Professor, Department of Horticultural Science, North Carolina State University, Raleigh, NC.
[2]Professor.
[3]Former Visiting Research Scientist.
[4]To whom reprint requests should be addressed; e-mail brian_jackson@ncsu.edu.

annual vinca (*Catharanthus roseus* L.) which was the plant species used in the study. There was no treatment in their study without limestone. Other work with 100% PTS by Saunders et al. (2005) showed no advantage to amending 100% PTS with limestone for the growth of marigold.

More recent work (Jackson et al., 2009c; Wright et al., 2008a) has shown an advantage of grinding PTS coarsely (less expensive to grind) and adding peatmoss or aged PB to increase the amount of fine particles (less than 0.5 mm) to provide adequate container capacity (amount of water held by the substrate in a container after drainage; container capacity is equivalent to waterholding capacity of a substrate). The additions of peatmoss or PB to PTS would likely necessitate limestone incorporation as a result of the low pH of those materials. Therefore, in the absence of well-defined recommendations for lime additions to PTS for pH adjustment and optimal plant growth—especially if peatmoss is incorporated—studies were conducted to evaluate the effect of limestone additions to 100% PTS and PTS amended with peatmoss on pH and the growth of two pH-sensitive greenhouse crops.

Materials and Methods

Pine tree substrate was produced from trees harvested and delimbed on 19 Feb. 2007, chipped on 20 Feb. to 2.5 cm × 2.5 cm × 0.25-cm wood chips, and reduced further with a hammermill (Meadows Mills, Inc., North Wilkesboro, NC) passing through a 4.76-mm screen. From this material, three substrates were prepared: 100% PTS and PTS incorporated by volume with either 25% (PTS-25P) or 50% (PTS-50P) peatmoss. Peat-lite (4 peat:1 perlite v/v; Premier Tech, Quebec, Canada) was also used as a control. Each of the four substrates was amended with pulverized dolomitic limestone (89% calcium $CO_3{\cdot}MgCO_3$, Pro pulverized Limestone; Old Castle Stone Products, Atlanta, GA) at the following rates: 0, 1.78, 3.56, 5.35, or 7.12 $kg{\cdot}m^{-3}$. Particle distribution of the limestone was as follows: 100% passed an 841-μm (#20) screen, 90% passed a 297-μm (#50) screen, and 80% passed a 150-μm (#100) screen. Substrates were also amended with calcium sulfate ($CaSO_4$) at 0.6 $kg{\cdot}m^{-3}$. On 4 June 2007, marigold plugs (144-tray, 2-week-old seedings) were potted in 10-cm square (l-L) containers filled with the substrates. Plants were glasshouse grown in Blacksburg, VA, with average day and night temperatures of 26 and 22 °C, respectively. Plants in each substrate were overhead watered together as needed depending on need and weather conditions and never showed any symptoms of water stress. Blacksburg, VA, municipal water with an alkalinity of 36 $mg{\cdot}L^{-1}$ was used. Plants were fertilized at each watering with 250 mL of a 300 $mg{\cdot}L^{-1}$ nitrogen (N) fertilizer solution from Peters 20N-4.4P-16.6K Peat-lite special (The Scotts Co., Marysville, OH) containing 12% nitrate (NO_3-N) and 8% ammonium (NH_4-N). Substrate solution was extracted weekly using the pourthrough method (Wright, 1986) and analyzed for pH and electrical conductivity (EC) using a Hanna HI 9811 instrument (Hanna Instruments, Woonsocket, RI). On 22 June, a growth index [(height + widest width + perpendicular width)/3] of each plant was taken, stems were severed at the substrate surface, fresh weight determined, dried for 5 d at 65 °C, and dry weights were then recorded.

A similar experiment was initiated when plugs as described previously were transplanted on 17 July into the previously described substrates with the following pulverized dolomitic limestone additions: 0, 0.89, 1.78, 3.56, and 5.34 $kg{\cdot}m^{-3}$. Plant culture and data taken were as described previously, and the experiment was ended 3 Aug.

A third study was initiated 11 May 2007 with rooted cuttings of zonal geranium (*Pelargonium ×hortorum* 'Rocky Mountain White') potted in round 15-cm, 1.25-L containers with the same substrates as described previously. Limestone rates were 0, 1.75, and 3.5 $kg{\cdot}m^{-3}$ and plants were irrigated and fertilized as described previously. The experiment was ended on 27 June.

All studies were arranged in a completely randomized design with six replications for the two marigold studies and eight for the geranium experiment. Data were subjected to analysis of variance with mean separation by Duncan's multiple range test using SAS (Version 9.1; SAS Institute, Cary NC) and regression analysis using SigmaPlot (Version 9.01; SPSS, Chicago, IL.).

Results and Discussion

The pH of all substrates in all studies was highest for 100% PTS and generally decreased as the proportion of peat increased (PTS-25P, PTS-50P, and PL) regardless of limestone rate (Table 1). The pH also increased with limestone additions, but the increase in pH was less responsive as the amount of peatmoss in the substrate increased from 25% to 50%. For example, in the July marigold experiment (Table 1), the addition of 0.89 $kg{\cdot}m^{-3}$ limestone resulted in a pH increase of 1.3 units for 100% PTS, 0.8 for PTS-25P, 0.6 for PTS-50P, and 0.4 for PL. This is an indication that the buffering capacity of PTS is lower than for peatmoss requiring more limestone—as the percent peat in PTS increases—to adjust the pH of PTS to 5.4 to 6.5, a suitable range for most greenhouse crops (Nelson, 2003). For example, the amount of limestone required to reach this range, using the July pH data (Table 1), was 0.89 $kg{\cdot}m^{-3}$ (pH 6.0) for 100% PTS, 3.56 $kg{\cdot}m^{-3}$ (pH 5.9) for PTS-25P, 5.35 $kg{\cdot}m^{-3}$ (pH 5.9) for PTS-50P, and 5.35 $kg{\cdot}m^{-3}$ (pH 5.5) for PL. The same trend was observed with the June marigold and the geranium data, although the pH range of 5.4 to 6.5 was not reached with geranium except for the 100% PTS and PTS-25P (at the 3.56-$kg{\cdot}m^{-3}$ rate) because limestone levels did not go above 3.56 $kg{\cdot}m^{-3}$. In addition, adding even more limestone (7.12 $kg{\cdot}m^{-3}$) in the June marigold study increased pH very little above the 5.34-$kg{\cdot}m^{-3}$ rate. The pH for PL and PTS-50P did not reach the desired pH in some cases, which could be the result of low water alkalinity (36 $mg{\cdot}L^{-1}$) and the acidic reaction of the fertilizer (200 g acidity/kg fertilizer). The apparent low buffering capacity of PTS observed in this study is in contrast to peatmoss and PB substrates that have been shown to have high buffering capacities (Daniels and Wright, 1988; Nash et al., 1983).

Marigold growth. For the June experiment, at the 0-$kg{\cdot}m^{-3}$ lime rate, 100% PTS-grown plants had higher shoot dry mass than the other treatments; PTS-25P was intermediate in shoot dry mass and PTS-50P and PL were lowest (Table 2). The lower pH (Table 1) of the substrates containing peat likely accounts for these plant growth differences. Applying limestone at the 1.78 $kg{\cdot}m^{-3}$ rate and above resulted in no differences in shoot dry mass between the substrate treatments showing that limestone improved the growth of PL and PTS when amended with peatmoss (25% or 50%), especially at the 50% level, although pH with the peat-amended substrates was still lower than the 6.0 to 6.6 recommended for marigold culture (Argo and Fisher, 2002). Regression analysis validated a significant increase in shoot dry mass as lime rate increased for only PTS-50P. With the July experiment, 100% PTS and PTS-25P, but not PTS-50P, had a higher shoot dry mass at the 0 and 0.89-$kg{\cdot}m^{-3}$ lime rates than PL (Table 2). A limestone rate of 3.56 $kg{\cdot}m^{-3}$ was required to attain an equivalent plant dry weight in PL like in the PTS substrates. Also, only with PL and PTS-50P was there an overall growth response (regression analysis) to lime rate (Table 2). These data indicate that 100% PTS does not require limestone for the growth of marigold, but as the percent of peatmoss increases in PTS, there is a greater need for limestone additions to increase pH and optimize plant growth.

Geranium growth. At the 0-$kg{\cdot}m^{-3}$ limestone rate, there was no difference in growth of geranium regardless of substrate (Table 2). Adding 1.78 $kg{\cdot}m^{-3}$ and 3.56 $kg{\cdot}m^{-3}$ limestone increased dry weight of geranium in substrates containing peatmoss, but not in 100% PTS, resulting in smaller plants for 100% PTS compared with plants grown in PTS-25P, PTS-50P, or in PL. The highest dry weight occurred at the 1.78-$kg{\cdot}m^{-3}$ rate of limestone for PTS-25P, but 3.6 $kg{\cdot}m^{-3}$ of limestone was required for PTS-50P and PL (Table 2). These growth responses reflected changes in pH as a result of limestone additions (Table 1) because more limestone is required to increase substrate pH relative to the amount of peat present in the substrate. At any given limestone rate, pH decreases relative to the amount of peatmoss in the substrate. Higher limestone application rates for treatments containing peatmoss may have resulted in increased growth because pH (Table 1) for geranium did not reach the 6.0

Table 1. Effect of dolomitic limestone rate on substrate pH of marigold and geranium grown in peat-lite (PL) and pine tree substrate (PTS) amended with peatmoss.

	Substrate pH[z]			
	Marigold (June)			
Lime rate (kg·m^{-3})	PL[y]	PTS[x]	PTS-25P[w]	PTS-50P[v]
0	3.8 b[u]	5.1 a	4.0 b	3.9 b
1.78	4.5 d	6.6 a	5.5 b	5.0 c
3.56	5.2 d	6.8 a	6.1 b	5.7 c
5.35	5.5 d	7.0 a	6.3 b	6.1 c
7.12	5.8 c	7.1 a	6.4 b	6.5 b
Significance[t]	L***	L***	L***	L***
	Q***	Q***	Q***	Q***
P values[s]	Substrate (S) ≤ 0.0001; Lime rate (L) ≤ 0.0001; S*L ≤ 0.0001			
	Marigold (July)			
0	3.5 c	4.7 a	3.8 b	3.6 c
0.89	3.9 d	6.0 a	4.6 b	4.2 c
1.78	4.3 d	6.2 a	5.3 b	4.7 c
3.56	4.8 d	6.5 a	5.9 b	5.4 c
5.35	5.5 d	6.6 a	6.2 b	5.8 c
Significance	L***	L***	L***	L***
	Q***	Q***	Q***	Q***
P values	Substrate (S) = 0.0015; Lime rate (L) = ≤ 0.0001; S*L = 0.0117			
	Geranium			
0	3.5 c	4.9 a	3.8 b	3.6 c
1.78	4.1 d	5.9 a	5.2 b	4.4 c
3.56	4.8 d	6.1 a	5.7 b	5.2 c
Significance	L***	L***	L***	L***
	Q***	Q***	Q***	Q***
P values	Substrate (S) = ≤ 0.0001; Lime rate (L) ≤ 0.0001; S*L ≤ 0.0001			

[z]pH of substrate solution determined on pourthrough extracts (Wright, 1986).
[y]PL composed of 80% peatmoss/20% perlite (v/v).
[x]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammermilled to pass through a 4.76-mm screen.
[w]PTS-25P produced by amending PTS with 25% peatmoss (v/v).
[v]PTS-50P produced by amending PTS with 50% peatmoss (v/v).
[u]Mean separated within row by Duncan's multiple range test ($P \leq 0.05$).
[t]L = linear; Q = quadratic response for pH at *, **, or ***.
[s]Nonsignificant or significant at *$P \leq 0.05$, **0.01, or ***0.001, respectively.

Table 2. Effect of dolomitic limestone rate on shoot dry weight (g) of marigold and geranium grown in peat-lite (PL) and pine tree substrate (PTS) amended with peatmoss.

	Substrate			
	Marigold shoot dry wt (June)			
Lime rate (kg·m^{-3})	PL[z]	PTS[y]	PTS-25P[x]	PTS-50P[w]
0	1.7 b[v]	2.0 a	1.8 ab	1.5 b
1.78	2.0 a	2.2 a	2.1 a	2.0 a
3.56	2.0 a	2.1 a	2.0 a	1.9 a
5.35	1.9 a	2.0 a	2.1 a	1.9 a
7.12	1.9 a	2.1 a	1.9 a	1.9 a
Significance[u]	NS	NS	NS	NS
	NS	NS	NS	Q*
P values[t]	Substrate (S) = 0.0102; Lime rate (L) = 0.0023; S*L = 0.8882			
	Marigold shoot dry wt (July)			
0	3.0 b	3.7 a	3.5 a	3.4 ab
0.89	3.5 b	4.0 a	4.0 a	3.6 ab
1.78	3.4 b	3.9 ab	4.1 a	3.7 b
3.56	3.7 b	3.6 b	3.8 b	4.2 a
5.35	4.0 a	3.9 a	3.9a	4.3 a
Significance	L***	NS	NS	L***
	Q***	NS	NS	Q***
P values	Substrate (S) = 0.0015; Lime rate (L) ≤ 0.0001; S*L = 0.0117			
	Geranium shoot dry wt			
0	9.9 a	10.4 a	9.6 a	9.3 a
1.78	12.1 ab	11.0 b	13.7 a	13.1 ab
3.56	14.3 a	9.4 b	12.8 a	13.9 a
Significance	L***	NS	L*	L**
	Q***	NS	Q**	Q*
P values	Substrate (S) = 0.0198; Lime rate (L) ≤ 0.0001; S*L = 0.0157			

[z]PL composed of 80% peatmoss/20% perlite (v/v).
[y]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammermilled to pass through a 4.76-mm screen.
[x]PTS-25P produced by amending PTS with 25% peatmoss (v/v).
[w]PTS-50P produced by amending PTS with 50% peatmoss (v/v).
[v]Mean separated within row by Duncan's multiple range test ($P \leq 0.05$).
[u]L = linear; Q = quadratic response for dry weight at *, **, or ***.
[t]Nonsignificant or significant at *$P \leq 0.05$, **0.01, or ***0.001, respectively.

to 6.6 recommended by Argo and Fisher (2002) or 6.4 to 6.5 suggested by Andrew and Hammer (2006) for optimal growth of geranium. However, the fact that more limestone is required for PTS for pH adjustment as the level of peatmoss is increased is clearly demonstrated. One difference between marigold and geranium response to substrates and limestone additions was that geranium growth was not higher in the 100% PTS at 0 limestone compared with the other substrates that contained peatmoss, although pH was higher in 100% PTS than in the other substrates. There appear to be factors affecting geranium growth in 100% PTS other than pH, and these factors are ameliorated to some extent by the additions of peatmoss to PTS because growth in PTS was increased by adding peatmoss and limestone and not by increasing the pH of 100% PTS by adding limestone alone. It has been shown in several studies using wood-based substrates that fresh wood contains phytotoxins that affect the growth of plants (Gruda et al., 2009; Maas and Adamson, 1982; Rau et al., 2006; Worrall, 1976, 1981). Gruda et al. (2009) demonstrated that aqueous extracts from 100% PTS reduced the germination rate and radicle growth of tomato and lettuce. Improved growth of geraniums with the additions of peatmoss and limestone suggest that peatmoss added to PTS in some way reduces its toxic properties, which seemingly only affect certain crop species. Thus, additions of peatmoss or some other organic material (compost, aged PB, and so on) to PTS may be necessary for the production of geranium in PTS with corresponding limestone additions for pH adjustment.

The EC was slightly higher for substrates containing peatmoss (Table 3), likely the result of higher amounts of N immobilization in 100% PTS (Jackson and Wright, 2007; Jackson et al., 2009a) and other wood-based substrates (Gruda, 2005; Gruda et al., 2000) and higher nutrient retention in peatmoss as a result of higher cation exchange capacity of peat (15 $cmol\cdot L^{-1}$) compared with PTS (2 $cmol\cdot L^{-1}$). Higher EC levels for PL compared with 100% PTS have been demonstrated in other studies (Gruda et al., 2009; Jackson, 2008; Jackson et al., 2008; Wright et al., 2008b).

Conclusion

This research shows that the growth of marigold, a plant noted for its sensitivity to low pH, can be effectively grown in 100% PTS with no limestone additions as a result of the higher pH of PTS. This result is support by earlier work by Saunders et al. (2005). The pH of PTS without limestone was 5.1 for the June study and 4.7 for the July study. This difference in pH could be attributed to substrate storage time: 3.5 months for the June study and 4.5 months for the July study. Recent unpublished results by these authors (Brian Jackson and Robert Wright) have shown that the pH of 100% PTS will drop during storage of the substrate to levels observed at the initiation of these present studies. However, the lower pH for 100% PTS used in these studies was not detrimental to growth. Pine tree substrate produced from freshly harvested pine trees and used immediately (stored for less than 1 month) with no lime additions has been reported in numerous articles as having a higher pH than observed in the studies discussed in this article. For example, pH of 100% PTS has been reported at 6.6 (Jackson et al., 2008), 6.3 (Jackson et al., 2009b; Wright et al., 2008b), and 5.8 (Gruda et al., 2009). It is unclear why the pH of pine wood from freshly harvested trees is so variable in these reports, but one possibility may be related to the season (time of year) of tree harvest.

Different from marigold, geranium required the addition of both peatmoss and limestone for best growth. The different growth response of marigold and geranium in 100% PTS associated with peatmoss and limestone additions indicates a need to evaluate how other commercial greenhouse taxa respond to limestone and peatmoss additions to PTS taking into account irrigation water

Table 3. Effect of dolomitic limestone rate on electrical conductivity (EC) of marigold and geranium grown in peat-lite (PL) and pine tree substrate (PTS) amended with peatmoss.

	Substrate EC ($dS\cdot m^{-1}$)[zy]			
	Marigold (June)			
Lime rate ($kg\cdot m^{-3}$)	PL[x]	PTS[w]	PTS-25P[v]	PTS-50P[u]
0	2.23 a[t]	1.85 b	2.28 a	2.28 a
1.78	2.21 a	1.73 c	1.96 b	2.24 a
3.56	2.19 a	1.82 b	1.97 ab	2.02 ab
5.35	2.20 a	1.79 b	2.03 a	2.09 a
7.12	2.26 a	1.72 b	2.11 a	2.08 a
Significance[s]	NS	NS	NS	L**
	NS	NS	Q**	Q*
P values[r]	Substrate (S) ≤ 0.0001; Lime rate (L) = 0.0156; S*L = 0.2446			
	Marigold (July)			
0	2.08 ab	1.92 b	2.06 ab	2.15 a
0.89	2.04 a	1.84 b	1.91 ab	2.04 a
1.78	2.02 a	1.82 b	1.93 ab	1.95 ab
3.56	2.04 a	1.86 b	1.99 ab	1.96 ab
5.35	2.07 a	1.83 b	1.96 a	1.98 a
Significance	NS	NS	NS	L*
	NS	NS	NS	Q**
P values	Substrate (S) ≤ 0.0001; Lime rate (L) = 0.0129; S*L = 0.9230			
	Geranium			
0	2.72 b	3.17 a	2.62 b	2.39 b
1.78	3.04 a	3.01 a	2.7 a	2.89 a
3.56	3.06 a	2.9 a	2.69 a	2.85 a
Significance	NS	NS	NS	L**
	NS	NS	NS	Q*
P values	Substrate (S) = 0.0100; Lime rate (L) = 0.1981; S*L = 0.2173			

[z]EC of substrate solution determined on pourthrough extracts (Wright, 1986).
[y]1 $dS\cdot m^{-1}$ = 1 mmho/cm.
[x]PL composed of 80% peatmoss/20% perlite (v/v).
[w]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammermilled to pass through a 4.76-mm screen.
[v]PTS-25P produced by amending PTS with 25% peatmoss (v/v).
[u]PTS-50P produced by amending PTS with 50% peatmoss (v/v).
[t]Mean separated within row by Duncan's multiple range test ($P \leq 0.05$).
[s]L = linear; Q = quadratic response for concentration at *, **, or ***.
[r]Nonsignificant or significant at *$P \leq 0.05$, **0.01, or ***0.001, respectively.

alkalinity and the acidic or basic reaction of the fertilizer used. The effect of storage method and time on PTS as it relates to a drop in pH and limestone requirements to adjust those anticipated changes needs further investigation. Use of aged PTS for crop production may require different management in regard to pH than when using PTS produced from freshly harvested trees.

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