Liming Requirements of Greenhouse Peat-based Substrates Amended with Pine Wood Chips as a Perlite Alternative

W. Garrett Owen[1,2], Brian E. Jackson[3], William C. Fonteno[3], and Brian E. Whipker[3]

ADDITIONAL INDEX WORDS. aggregate, dolomitic limestone, horticultural substrate, loblolly pine, potting media

SUMMARY. Processed loblolly pine (*Pinus taeda*) wood has been investigated as a component in greenhouse and nursery substrates for many years. Specifically, pine wood chips (PWCs) have been uniquely engineered/processed into a nonfibrous blockular particle size suitable for use as a substrate aggregate. The objective of this research was to compare the dolomitic limestone requirements of plants grown in peat-based substrates amended with perlite or PWC. In a growth trial with 'Mildred Yellow' chrysanthemum (*Chrysanthemum* ×*morifolium*), peat-based substrates were amended to contain 0%, 10%, 20%, 30%, 40%, or 50% (by volume) perlite or PWC for a total of 11 substrates. Substrates were amended with dolomitic limestone at rates of 0, 3, 6, 9, or 12 lb/yard^3, for a total of 55 substrate treatments. Results indicate that pH of substrates amended with ≥30% perlite or PWC need to be adjusted to similar rates of 9 to 12 lb/yard^3 dolomitic limestone to produce similar-quality chrysanthemum plants. In a repeated study, 'Moonsong Deep Orange' african marigold (*Tagetes erecta*) plants were grown in the same substrates previously formulated (with the exclusion of the 50% ratio) and amended with dolomitic limestone at rates of 0, 3, 6, 9, 12, or 15 lb/yard^3, for a total of 54 substrate treatments. Results indicate a similar dolomitic limestone rate of 15 lb/yard^3 is required to adjust substrate pH of 100% peatmoss and peat-based substrates amended with 10% to 40% perlite or PWC aggregates to the recommended pH range for african marigold and to produce visually similar plants. The specific particle shape and surface characteristics of the engineered PWC may not be similar to other wood products (fiber) currently commercialized in the greenhouse industry, therefore the lime requirements and resulting substrate pH may not be similar for those materials.

In production of greenhouse crops, including most all bedding, green/foliage, and potted flowering plants, managing container substrate pH is a major nutritional challenge (Argo and Fisher, 2002; Nelson, 2012). Recent increases in the production of controlled environment container crops, including vegetables, leafy greens, soft fruits, and cannabis (*Cannabis sativa*), have furthered the need for soilless substrates (Caplan, 2018; Jackson, 2018; Kingston et al., 2017). Incorporating limestone into horticultural substrates is common practice of substrate manufacturers and growers to adjust substrate pH to the recommended pH 5.4 to 6.4, for most all bedding plants (Nelson, 2012). When determining how much limestone to incorporate into substrates, other variables, including chemical composition, particle size, and hardness (Argo and Fisher, 2002), should be considered.

Increased interest in using substrates containing pine wood components has led to many unanswered questions about their performance during crop production. Among these unknown issues are those relating to the requirements of limestone addition to substrates for pH adjustment for optimal plant growth. In previous studies, substrates containing wood components were evaluated; however, no indication of initial (pre-plant) substrate pH testing or changes to lime applications to the substrates were reported (Bohne, 2004; Starr et al., 2011). Boyer et al. (2008) incorporated 5 lb/yard^3 dolomitic limestone to substrates produced from clean chip residuals (forestry materials left over from in-field chipping operations) and reported substrate pH of 6.7 (34 d after planting) to be above the optimal pH range (5.5 to 6.0) for 'Blue Hawaii' ageratum (*Ageratum houstonianum*).

In other studies, initial testing of substrates indicated the need to amend substrates with limestone; however, the rates of limestone addition resulted in pH of substrates above the recommended range for greenhouse crops. Fain et al. (2008a) processed loblolly pine (*Pinus taeda*), slash pine (*Pinus elliottii*), and longleaf pine trees (*Pinus palustris*) to produce three pine wood substrates (one from each species) and reported initial substrate pH of 5.3, 4.5, and 4.6, respectively. Substrates were amended with 3 lb/yard^3 dolomitic limestone to adjust the pH. Substrate testing (30 d after planting) indicated pH of substrates were 7.1, 6.9, and 7.2, respectively, above the recommended pH range (5.4 to 6.2) for growing annual vinca (*Catharanthus roseus*). In addition, Fain et al. (2008b) amended a pine wood substrate [WholeTree, containing bark, wood, limbs, and needles (Fain et al., 2006)] with dolomitic limestone at a rate of 1.78 kg·m^{-3} and reported pH of all substrates to be higher than the recommended pH range (5.4 to 6.2) for petunia (*Petunia* ×*hybrida*), with the exception of the peat-lite

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
0.7457	horsepower	kJ·s^{-1}	1.3410
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.0277	lb/inch^3	kg·cm^{-3}	36.1273
0.5933	lb/yard^3	kg·m^{-3}	1.6856
1	micron(s)	µm	1
1	mmho/cm	mS·cm^{-1}	1
28.3495	oz	g	0.0353
1.7300	oz/inch^3	g·cm^{-3}	0.5780
1	ppm	mg·L^{-1}	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

(control), which was at the upper limit of the recommended pH range.

Some authors have reported that no lime addition was needed for 100% wood substrates because substrate pH was inherently within the range of 5.5 to 6.4 (Gruda and Schnitzler, 2006). Saunders et al. (2005) reported no advantage of amending 100% pine tree substrate (PTS) with limestone for african marigold (*Tagetes erecta*) growth. They found the addition of peatmoss or pine bark to PTS would require limestone incorporation as a result of the acidic nature of those materials.

Jackson et al. (2009) evaluated the effect of limestone addition of 0, 1.78, 3.56, 5.35, or 7.12 $kg \cdot m^{-3}$ on substrate pH and growth of 'Inca Gold' african marigold and 'Rocky Mountain White' zonal geranium (*Pelargonium ×hortorum*), two pH-sensitive greenhouse crops grown in 100% PTS and PTS amended with 25% or 50% peatmoss. They reported substrate pH of marigold and geranium to be highest for 100% PTS and pH generally decreased as the amount of peatmoss increased, regardless of lime rate. They also reported that pH 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% (Jackson et al., 2009). In the study, 100% PTS did not require limestone for growth of marigold (pH 5.1), but they found as the percentage of peatmoss amended to PTS increased, there was an increased need for limestone to increase substrate pH and optimize plant growth. For zonal geranium, there were no growth differences when plants were grown in any substrate amended with 0 $kg \cdot m^{-3}$; however, the addition of lime increased plant dry weight when plants were grown in substrates amended with peatmoss compared with 100% PTS.

No information is available regarding lime requirements for sphagnum peat-based substrates amended with PWC aggregates as an alternative for perlite. Therefore, the objectives of this study were to determine lime requirements for pre-plant substrate pH modification and optimal plant growth in sphagnum peat-based substrates amended with aggregates of PWC or perlite.

Materials and methods

Preparation of substrates. On 2 June 2011, 9-year-old loblolly pine trees were harvested [Apex, NC (lat. 36°N)] at ground level, delimbed, and subsequently stored under shelter for protection from the weather. On 4 June, logs were chipped (with their bark intact) with an 18-horsepower chipper (model 356447; DR Power Equipment, Vergennes, VT) resulting in large wood chips [1.0 × 0.2 × 1.0-cm (length × width × height); n = 20 (Fig. 1A)]. Wood chips were then spread out (1-inch deep) on a concrete pad under shelter, turned periodically, and allowed to air dry for 2 d to reduce moisture content, which has been shown in unpublished studies to aid in the efficient processing of wood through hammer mills. In this experiment, the moisture content of the fresh wood chips was 45% after chipping and 36% after air drying for 2 d, resulting in 9% moisture loss. Wood chips were then hammer-milled through a 0.25-inch screen (Meadows Mills, North Wilkesboro, NC), resulting in smaller PWCs [0.11 × 0.4 × 0.2-cm (length × width × height); n = 20 (Fig. 1B)].

On 11 June, sphagnum peatmoss (Pro-Moss Sphagnum Peat, Quakertown, PA) was taken from a compressed bale, loosened/fluffed, and moistened (by hand) to a moisture content of 50% (by weight). Peatmoss was amended with 10%, 20%, 30%, 40%, or 50% (by volume) perlite (Carolina Perlite Co., Gold Hill, NC) or PWC plus a 100% peatmoss (0% aggregate) to produce a total of 11 substrate treatments. Substrate physical properties, including air space [AS (percent by volume)], total porosity [TP (percent

Fig. 1. Depiction of large loblolly pine wood chips (PWCs) produced by processing delimbed logs (with bark intact) through a chipper (A) and after 2 d, wood chips were hammer-milled through a 0.25-inch (6.350-mm) screen resulting in smaller PWCs (B).

Received for publication 16 Sept. 2019. Accepted for publication 27 Jan. 2020.

Published online 24 February 2020.

[1]Department of Horticulture, Michigan State University, 1066 Bogue Street, East Lansing, MI 48824

[2]Michigan State University Extension, Tollgate Farm and Education Center, 28115 Meadowbrook Road, Novi, MI 48377

[3]Department of Horticultural Science, North Carolina State University, 2721 Founders Drive, Raleigh, NC 27695

We gratefully acknowledge Lesley Judd, Jeb Fields, Kole Andrews, Ian Harris, and Diane Mays for greenhouse and laboratory assistance. We thank Raker-Roberta's Young Plants for plant material.

The use of trade names in this publication does not imply endorsement by Michigan State University, Michigan State University Extension, or North Carolina State University of products named or criticism of similar ones not mentioned.

W.G.O. is a former Graduate Research Assistant.

B.E.J. is an Associate Professor.

W.C.F. and B.E.W. are Professors.

W.G.O. is the corresponding author. E-mail: wgowen@msu.edu.

https://doi.org/10.21273/HORTTECH04506-19

Table 1. Physical properties of 100% sphagnum peatmoss (PM) or sphagnum peat-based substrates amended (by volume) with 10%, 20%, 30%, 40%, or 50% perlite or pine wood chip (PWC) aggregates.[z]

Substrate	Total porosity (% vol)[y]	Air space (% vol)[x]	Container capacity (% vol)[w]	Bulk density ($g \cdot cm^{-3}$)[v]
100 PM	91.3 a[u]	14.1 b	77.2 a	0.10 h
10 Perlite[t]	90.1 ab	15.7 b	74.4 ab	0.11 fg
20 Perlite	87.2 abc	14.0 b	73.2 ab	0.13 d
30 Perlite	87.7 ab	14.2 b	73.5 ab	0.11 f
40 Perlite	82.5 d	14.4 b	68.1 cd	0.11 fg
50 Perlite	82.4 d	17.1 ab	65.3 d	0.11 gh
10 PWC[s]	91.6 a	16.5 ab	75.1 ab	0.12 e
20 PWC	91.4 a	18.0 ab	73.4 ab	0.13 d
30 PWC	86.6 bcd	15.5 b	71.1 bc	0.14 c
40 PWC	82.1 d	18.0 ab	64.2 de	0.15 b
50 PWC	83.0 cd	22.0 a	61.0 e	0.17 a

[z]Data were collected from three samples per substrate and represented as means. Analysis performed using the North Carolina State University Porometer method (Fonteno et al., 1995).
[y]Total porosity is equal to container capacity + air space.
[x]Air space is the volume of water drained from the sample ÷ volume of the sample.
[w]Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.
[v]Bulk density after forced-air drying at 105 °C (221.0 °F) for 48 h; 1 $g \cdot cm^{-3}$ = 0.5780 $oz/inch^3$.
[u]Means were separated within-column by Duncan's least significant difference test at $P \leq 0.05$.
[t]Substrates were formulated with sphagnum peat and amended with either 10%, 20%, 30%, 40%, or 50% perlite or PWC.
[s]PWCs were produced from 9-year-old loblolly pine trees, delimbed, chipped, and hammer-milled to pass through 0.25-inch (6.350 mm) screen.

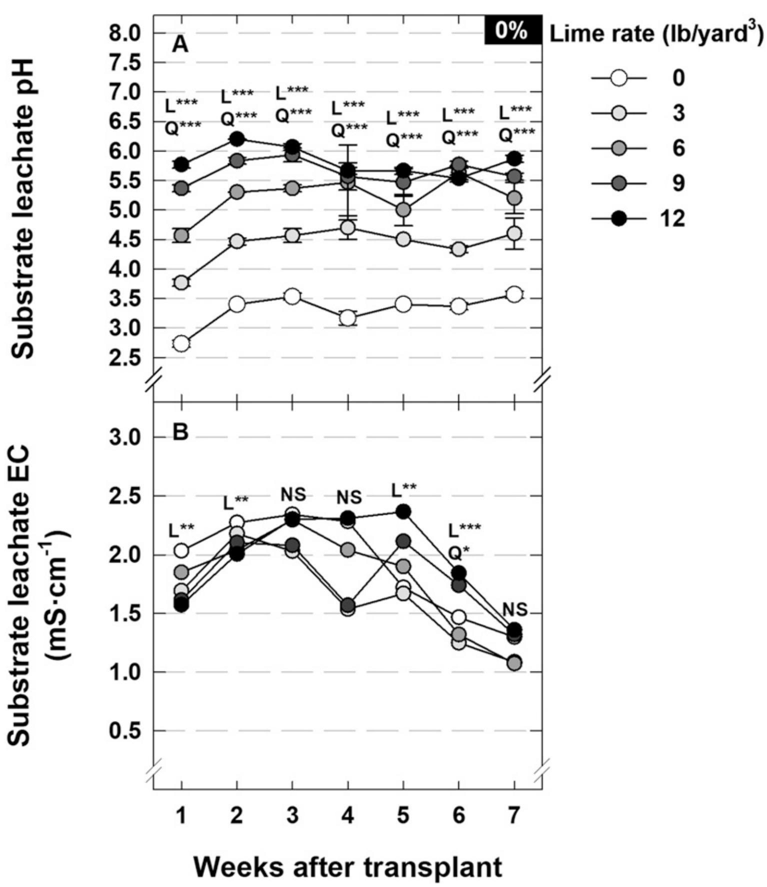

Fig. 2. Substrate leachate pH (A) and electrical conductivity [EC (B)] of 'Mildred Yellow' chrysanthemum grown in 100% sphagnum peatmoss amended with 0% perlite or pine wood chips and incorporated with 0, 3, 6, 9, or 12 $lb/yard^3$ pulverized dolomitic carbonate limestone. Substrate solution was extracted 1 h after irrigation using the pour-through method and determined at 1, 2, 3, 4, 5, 6, and 7 weeks after transplant. Each symbol represents a mean of three samples, and error bars represent SE. Linear (L) and/or quadratic (Q) regression response within each week is indicated and nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***); 1 $lb/yard^3$ = 0.5933 $kg \cdot m^{-3}$, 1 $mS \cdot cm^{-1}$ = 1 mmho/cm.

by volume)], container capacity [CC (percent by volume)], and bulk density [BD (grams per cubic centimeter)] were determined using three representative samples of each substrate, analyzed using the North Carolina State University Porometer (Fonteno et al., 1995), and are reported in Table 1.

After formulation of the substrates, initial substrate pH was determined by the 2:1 saturated media extraction method [2 parts deionized water: 1 part substrate (Argo and Fisher, 2002)] using a hand-held pH and electrical conductivity (EC) meter (HI 9813-6; Hanna Instruments, Woonsocket, RI). After determining initial substrate pH, a pulverized dolomitic carbonate limestone (85% $CaCO_3 \cdot MgCO_3$; Rockyardale Quarries Corp., Roanoke, VA) was incorporated at rates of 0, 3, 6, 9, or 12 $lb/yard^3$, yielding a total of 55 treatments (11 substrates × 5 lime rates). A screening of the pulverized dolomitic carbonate limestone showed 100% of the liming material passed through a 2000-µm (#10) screen, 90% passed through a 84-µm (#20) screen, 60% passed through a 250-µm (#60) screen, and 35% passed through a 149-µm (#100) screen. Substrates were incubated for 2 d in sealed plastic bags to allow for lime/pH equilibration.

CHRYSANTHEMUM GROWTH TRIAL. On 8 July, rooted cuttings of 'Mildred Yellow' chrysanthemum

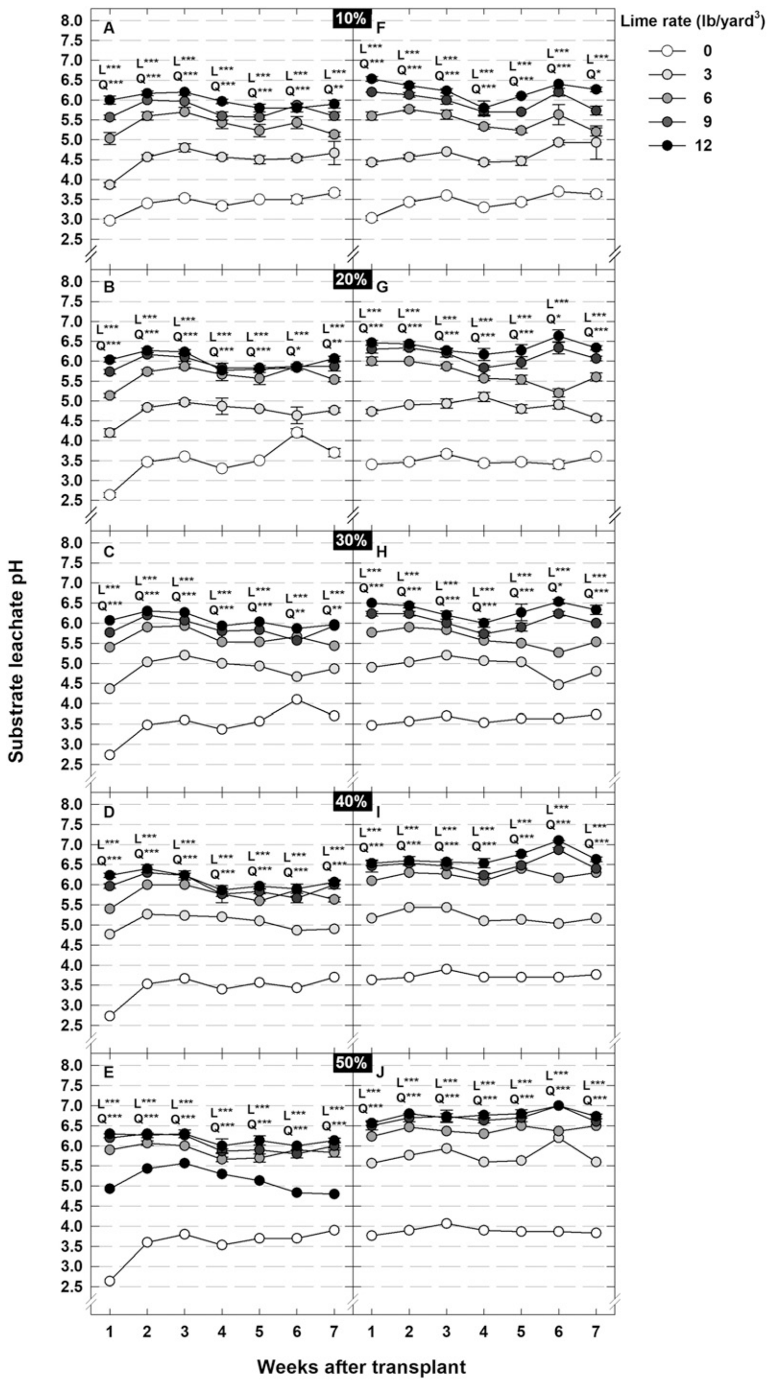

Fig. 3. Substrate leachate pH of 'Mildred Yellow' chrysanthemum grown in sphagnum peatmoss amended with perlite (by volume) at 10% (A), 20% (B), 30% (C), 40% (D), or 50% (E) or pine wood chips (by volume) at 10% (F), 20% (G), 30% (H), 40% (I), or 50% (J) and incorporated with 0, 3, 6, 9, or 12 lb/yard³ pulverized dolomitic carbonate limestone. Substrate solution was extracted 1 h after irrigation using the pour-through method and determined at 1, 2, 3, 4, 5, 6, and 7 weeks after transplant. Each symbol represents a mean of three samples, and error bars represent SE. Linear (L) and/or quadratic (Q) regression response within each week is indicated and significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***); 1 lb/yard³ = 0.5933 kg·m⁻³.

(*Chrysanthemum ×morifolium*) in 51-cell liner trays (27.2 mL individual cell volume; Raker-Roberta's Young Plants, Litchfield, MI) with similar heights were selected and transplanted one plant per 6-inch-diameter (1.3 L) container (ITML Horticultural Products, Middlefield, OH) filled with each substrate treatment resulting in a total of 330 containers/plants (55 treatments × 6 single plant replications). All plants were irrigated as needed (when the substrate surface began to dry) depending on weather conditions. Plants were fertilized at each irrigation with 200 mg·L^{-1} nitrogen (N) delivered by a water-soluble fertilizer injector (MiniDos; Hydro Systems Co., Cincinnati, OH) providing 20N–4.4P–16.6K (Peters Professional; Scotts Co., Marysville, OH), containing 8.1% ammonium (NH_4-N) and 11.9% nitrate-nitrogen (NO_3-N). Plants were grown in a glass-glazed greenhouse [North Carolina State University, Marye Anne Fox Science Teaching Laboratory Greenhouse, Raleigh (lat. 36°N)] at 23/17 °C (day/night) air temperature and under ambient daylight (light intensity not monitored during growth trial).

Data were collected weekly for 7 weeks after transplant (WAT). At each collection date, substrate solution was extracted 1 h after irrigation using the pour-through method (Wright, 1986) and analyzed for pH and EC using a hand-held pH meter (Hanna Instruments). At 7 WAT, all plants were destructively harvested by severing the stem at the substrate surface, individually bagged, and oven dried at 70 °C for 7 d before plant dry weight (PDW) was determined.

Marigold growth trial. Except where indicated, procedures for the african marigold growth trial were as described for the chrysanthemum growth trial. On 28 May 2012, 'Moonsong Deep Orange' african marigold seeds were sown into 288-cell (5 mL individual cell volume) plug trays containing moistened (50% moisture) propagation substrate (Fafard Super Fine Germination Mix; Sun Gro Horticulture, Agawam, MA) consisting of (by volume) 65% peat, 20% perlite, and 15% vermiculite.

On 17 June, 9-year-old loblolly pine trees were harvested and processed as previously described. Substrates were formulated with moistened peatmoss amended with 10%, 20%, 30%, or 40% (by volume) perlite or PWC plus a 100% peatmoss (0% aggregate) to produce a total of nine substrate treatments. In this experiment, the 50% substrate treatments (for both perlite and PWC aggregates) were excluded based on poor growth performance observed in the

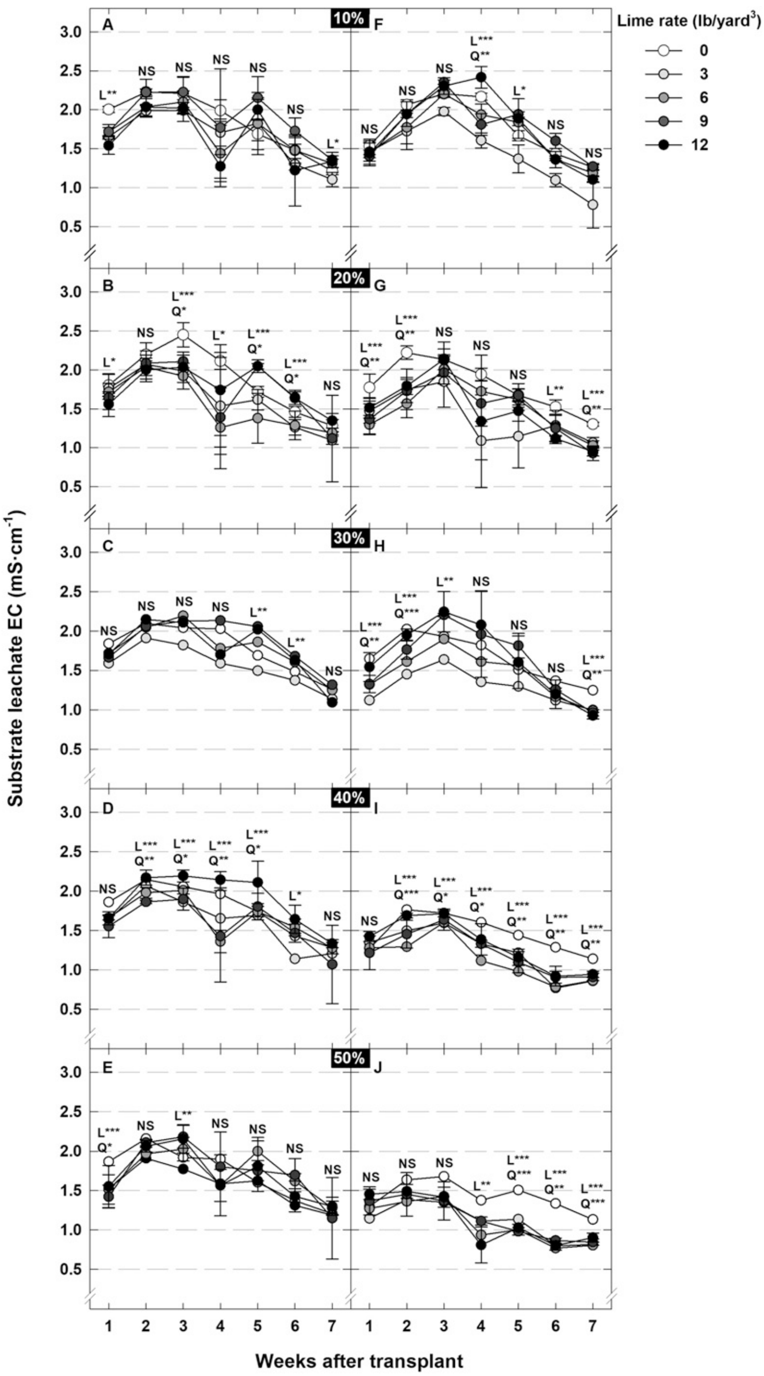

Fig. 4. Substrate electrical conductivity (EC) of 'Mildred Yellow' chrysanthemum grown in sphagnum peatmoss amended with perlite (by volume) at 10% (A), 20% (B), 30% (C), 40% (D), or 50% (E) or pine wood chips (by volume) at 10% (F), 20% (G), 30% (H), 40% (I), or 50% (J) and incorporated with 0, 3, 6, 9, or 12 lb/yard^3 pulverized dolomitic carbonate limestone. Substrate solution was extracted 1 h after irrigation using the pour-through method and determined at 1, 2, 3, 4, 5, 6, and 7 weeks after transplant. Each symbol represents a mean of three samples, and error bars represent SE. Linear (L) and/or quadratic (Q) regression response within each week is indicated and significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***); 1 lb/yard^3 = 0.5933 kg·m^{-3}, 1 mS·cm^{-1} = 1 mmho/cm.

chrysanthemum growth trial. Dolomitic limestone was amended at rates of 0, 3, 6, 9, 12, or 15 lb/yard^3, making for a total of 54 treatments (9 substrates × 6 lime rates). A higher rate (15 lb/yard^3) of limestone was amended to substrates as a result of observations in the chrysanthemum growth trial, where pH levels never plateaued (stopped rising) at the highest (12 lb/yard^3) limestone rate.

On 21 June, germinated african marigold seedlings were transplanted one plant per 6-inch-diameter (1.3 L) plastic container filled with each substrate, resulting in a total of 324 plants (54 treatments × 6 single plant replications). Substrate solution was extracted from three representative plants/containers, using the pour-through method each week for 4 WAT and was analyzed for pH and EC. On 18 July, plant height was determined by measuring from the substrate surface to the apical meristem. Plant diameter was determined by measuring the widest dimension and the axis perpendicular to the widest dimension and averaged. Growth index [GI = (height + widest diameter + perpendicular widest diameter) ÷ 3] was calculated for each plant. Following GI assessment, shoots were severed at the substrate surface, dried in an oven at 70 °C for 1 week, and weighed to determine PDW. Root balls of plants grown in substrates amended with either 0%, 20%, or 40% perlite or PWC and amended with any limestone rate were washed. Roots were bagged and oven dried at 70 °C, and after 1 week, root dry weight (RDW) was determined.

Both growth trials used a completely randomized design. On each sampling date, data were collected on three experimental units (individual plants) for pour-through (pH and EC) data. For chrysanthemum PDW, data were collected on six experimental units. For african marigold, GI, PDW, and RDW data were collected on six experimental units per substrate per limestone rate. Data were analyzed using SAS (version 9.4; SAS Institute, Cary, NC) general linear model (PROC GLM) for analysis of variance. For substrate physical properties, means were separated by Duncan's least significant differences (LSD). For GI, PDW, and RDW, where significant differences occurred, regression analysis using regression procedure (PROC REG) was conducted and means were separated by Duncan's LSD. Within each growth trial, pour-through data for aggregate type (perlite or PWC) × dolomitic limestone rates were reported across WAT. Regression

Table 2. Plant dry weight (PDW) of 'Mildred Yellow' chrysanthemum plants grown for 7 weeks in 100% sphagnum peatmoss (PM) or peat-based substrates amended (by volume) with 10%, 20%, 30%, 40%, or 50% perlite or pine wood chips (PWCs) and incorporated with 0, 3, 6, 9, or 12 lb/yard³ pulverized dolomitic carbonate limestone.

	Dolomitic limestone rate (lb/yard³)[y]					
	0	3	6	9	12	
Substrate[z]	PDW (g)[y]					Significance[x]
100 PM	9.58 ab[w]	17.18 a	18.03 abc	19.05 ab	18.15 a	L***, Q***
10 Perlite[v]	6.82 e	16.07 ab	18.32 abc	16.38 bcd	15.55 c	L***, Q***
20 Perlite	7.68 de	16.88 a	17.98 abc	18.62 ab	15.30 cd	L**, Q***
30 Perlite	8.03 cde	17.55 a	19.48 a	15.42 cd	16.93 abc	L**, Q***
40 Perlite	8.27 bcd	16.42 ab	17.40 abc	16.60 bcd	15.85 bc	L***, Q***
50 Perlite	9.10 abc	17.68 a	16.02 bcd	17.83 bc	18.22 ab	L***, Q**
10 PWC[u]	8.53 abcd	17.47 a	18.82 a	21.45 a	15.33 cd	L**, Q***
20 PWC	8.60 abcd	18.77 a	19.65 a	18.15 bc	18.62 a	L***, Q***
30 PWC	9.37 abc	17.85 a	14.95 de	16.23 bcd	18.40 a	L***, Q[NS]
40 PWC	9.15 abc	15.93 ab	15.83 cd	16.37 bcd	14.83 cd	L**, Q***
50 PWC	9.65 a	13.70 b	13.53 e	13.88 d	13.00 d	L*, Q***

[z]Substrates were formulated with sphagnum peat and amended with either 10%, 20%, 30%, 40%, or 50% perlite or PWC.
[y]1 lb/yard³ = 0.5933 kg·m⁻³, 1 g = 0.0353 oz.
[x]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***); L = linear; Q = quadratic response across measurement dates (7 weeks) at *, **, or ***.
[w]Means were separated within-column using Duncan's least significant differences test at $P \leq 0.05$.
[v]Substrates were formulated with sphagnum peat and amended with either 10%, 20%, 30%, 40%, or 50% perlite or PWC.
[u]PWCs were produced from 9-year-old loblolly pine trees, delimbed, chipped, and hammer-milled to pass through 0.25-inch (6.350-mm) screen.

analysis within WAT with dolomitic limestone rate as the independent variable were performed using SAS (version 9.4) PROC REG. For all analyses, a $P \leq 0.05$ was used to determine significant effects.

Results and discussion

Substrate physical properties. TP was highest in peatmoss (91.3%) and similar in substrates amended with 10% or 20% PWC and 10%, 20%, or 30% perlite (Table 1). The TP of 30% PWC-amended substrate was similar to 10% to 30% perlite-amended substrates and similar to those amended with 40% or 50% PWC. The addition of aggregates to peatmoss does not always change TP. Evans (2011) reported the TP of peatmoss amended with perlite at 10%, 15%, 20%, 25%, and 30% to be in the range of 83.3 to 85.8, respectively. The greatest AS (22.0%) occurred when substrates were formulated with 50% PWC aggregates (Table 1). AS of substrates amended with 10%, 20%, and 40% PWC and 50% perlite were similar. All other formulated substrates were similar in AS, with 100% peatmoss resulting in the lowest of 14.1%. Previous work by Smith (2018) amended peatmoss with 15%, 30%, and 45% perlite and reported no effect on the AS values compared with 100% peatmoss by itself. Evans and Gachukia (2007) reported the physical properties of peatmoss amended with perlite at rates of 20%, 30%, 40%, and 50% (by volume) to have AS that only increased from 9.5% to 12.7%. The resulting change in TP or AS of peatmoss when amended with perlite (or other aggregates) is likely influenced by the particle size of the aggregate material, not just the percentage of amendment. CC for 100% peatmoss was 77.2% (Table 1) and similar among substrates formulated with 10% and 20% PWC and 10% to 30% perlite. However, similar CC was observed when the proportion of peat replaced was not more than 30% for both aggregate types. For instance, the CC of the 30% PWC-amended substrate was similar to substrates amended with 10% and 20% PWC and 10% to 30% perlite. CC of substrates amended with 30% and 40% PWC were similar to substrates amended with 40% and 50% perlite, respectively, and substrates amended with 40% and 50% PWC were similar. Compared with 100% peatmoss, substrates containing 30% to 50% PWC, and 40% and 50% perlite decreased the CC to 16.2%, 9.1%, and 11.9%, respectively. Therefore, substrates with similar CC would likely provide similar water and aeration to plants, resulting in similar plant growth. Substrate BD was greatest when substrates were amended with 50% PWC and decreased with increasing proportion of peat compared with those amended with perlite (Table 1). The BD of perlite-amended substrates did not change with increasing percentage of perlite. Compared with substrates amended with PWC or perlite aggregates, 100% peatmoss had the lowest BD of 0.10 g·cm⁻³.

Chrysanthemum growth trial. Before dolomitic limestone incorporation, initial substrate pH of PWC-amended substrates averaged a pH of 4.4, compared with an average pH of 4.0 for perlite-amended substrates and pH of 3.4 for 100% peatmoss (data not shown). Of all the substrates formulated, the pH of those containing PWC aggregates were generally higher than perlite-amended substrates, and pH among all substrates generally decreased with increasing proportion of peatmoss. This is consistent with work by Evans and Gachukia (2008), who reported increasing parboiled rice hulls or perlite resulted in an increase in substrate pH. Similarly, substrate EC levels before limestone amendment were highest in PWC-amended substrates compared with perlite-amended substrates, and generally decreased with increasing peatmoss proportion (data not shown).

Over the duration of this trial, substrate leachate pH (Figs. 2A and 3A–J) at all substrates increased quadratically with increasing dolomitic limestone incorporation rate at each sampling time, although to different magnitudes. At 1 WAT, the pH of substrates amended with the lime rate of 0 lb/yard³ decreased compared with the initial substrate pH values (data not shown). At 1 WAT, pH of PWC-amended substrates at the 0 lb/yard³ dolomitic limestone rate increased as the proportion of peatmoss decreased, compared with perlite-amended substrates. This is consistent to previous work by Jackson et al. (2008), who reported 100% PTS and PTS amended with 25% and 50% peatmoss at 0 kg·cm⁻³ to have a pH of 5.1, 4.0, and 3.9, respectively. Over the duration of 7 weeks, pH of PWC- and perlite-amended substrates increased as the proportion of

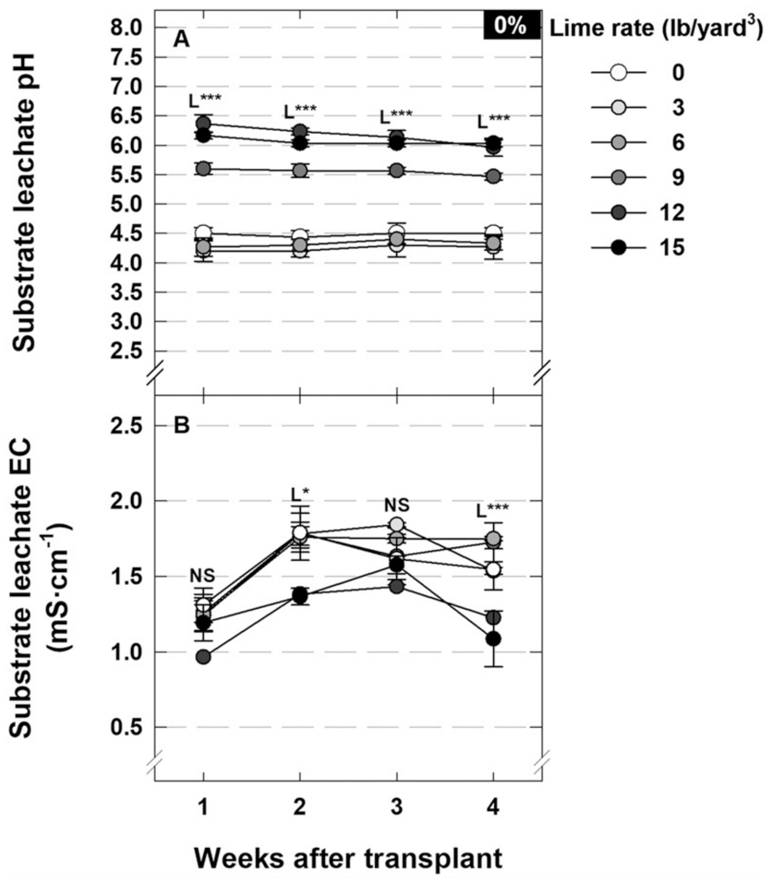

Fig. 5. Substrate leachate pH (A) and electrical conductivity [EC (B)] of 'Moonsong Deep Orange' african marigold plants grown in 100% sphagnum peatmoss amended with 0% perlite or pine wood chips and incorporated with 0, 3, 6, 9, 12, or 15 lb/yard³ pulverized dolomitic carbonate limestone. Substrate solution was extracted 1 h after irrigation using the pour-through method and determined at 1, 2, 3, and 4 weeks after transplant. Each symbol represents a mean of three samples, and error bars represent SE. Linear (L) regression response within each week is indicated and nonsignificant (NS) or significant at $P \leq 0.05$ (*) or 0.001 (***); 1 lb/yard³ = 0.5933 kg·m⁻³, 1 mS·cm⁻¹ = 1 mmho/cm.

peat decreased and pH increased with increasing dolomitic limestone rates. Analysis of substrate solution from 100% peatmoss (Fig. 2A) and 10% perlite-amended substrates (Fig. 3A) indicated the requirement of 12 lb/yard³ dolomitic limestone to adjust substrate pH to the recommended pH range of 5.5 to 6.3 for optimal chrysanthemum growth (Whipker et al., 2000). Substrates formulated to contain ≤40% perlite (by volume) aggregates (Fig. 3D and E) and amended with dolomitic limestone rates of 9 and 12 lb/yard³, adjusted substrate pH to the recommended pH range. In addition, substrates formulated to contain up to 50% perlite [by volume (Fig. 3E)] would require lime rates of 6 to 12 lb/yard³ to adjust substrate pH to the recommended range. From 1 to 3 WAT, the substrate containing 50% perlite (by volume) aggregates at dolomitic limestone rate 12 lb/yard³, achieved a pH of 6.3, the upper pH limit of the recommended pH range (Whipker et al., 2000).

Overall, increasing the proportion of PWC in a substrate resulted in an increase in substrate pH. This result is supported by the previous work of Jackson et al. (2009). Substrate amended with 10% PWC [by volume (Fig. 2F)] aggregates required dolomitic limestone rates of 9 and 12 lb/yard³ for pH adjustment to the recommended pH range for optimal chrysanthemum growth. Recommended pH range was determined in substrates containing ≤30% PWC aggregates (Fig. 3H) at dolomitic limestone rates of 6 to 12 lb/yard³. Substrates containing 40% (Fig. 3I) and 50% PWC [by volume (Fig. 3J)] aggregates achieved pH values above the recommended pH range at lime rates 6 to 12 lb/yard³. The increased pH levels reported in substrates containing higher percentages of pine wood may be due to wood having less pH buffering capacity than peatmoss. Therefore, as the percent wood increases and the percent peatmoss decreases, the change in pH can be more pronounced at lower lime rates. The pH buffering capacities of pine wood substrate materials has not been fully understood or reported. Among all substrates, there were no visual mineral deficiencies or toxicities related to substrate pH below or above the recommended pH range for chrysanthemum.

In general, substrate solution EC (Figs. 2B and 4A–J) varied with increasing dolomitic limestone incorporation rate throughout the trial, although to different magnitudes. The highest EC levels occurred in the 100% peatmoss (2.37 mS·cm⁻¹). In PWC-amended substrates, the lower CC may have contributed to decreased EC levels due to nutrient leaching or N immobilization. After 3 WAT, EC levels of all substrates decreased (Figs. 2B and 4A–J), with the lowest EC levels occurring at 7 WAT, which were similar among all substrates (data not shown).

Low substrate EC levels are consistent with previous research by Wright et al. (2008), who reported nutrient levels of 0.53 mS·cm⁻¹ in a 100% PTS compared with 1.58 mS·cm⁻¹ in a peat-lite substrate containing 45% peat, 15% perlite, 15% vermiculite, and 25% bark (by volume). They reported chrysanthemum grown in 100% PTS to require an additional 100 mg·L⁻¹ N compared with plants grown in the peat-lite substrate. Also, lower substrate nutrient levels in PTS compared with peat-lite may relate to increased microbial N immobilization (Tisdale et al., 1993). However, low nutrient levels were consistent among all substrates 7 WAT, therefore N immobilization most likely did not contribute to the decline of substrate nutrients. According to Nelson (2012), a constant fertigation of 200 mg·L⁻¹ N is sufficient for proper chrysanthemum growth, which was supplied to all plants in this experiment, although lower nutrient levels are likely related

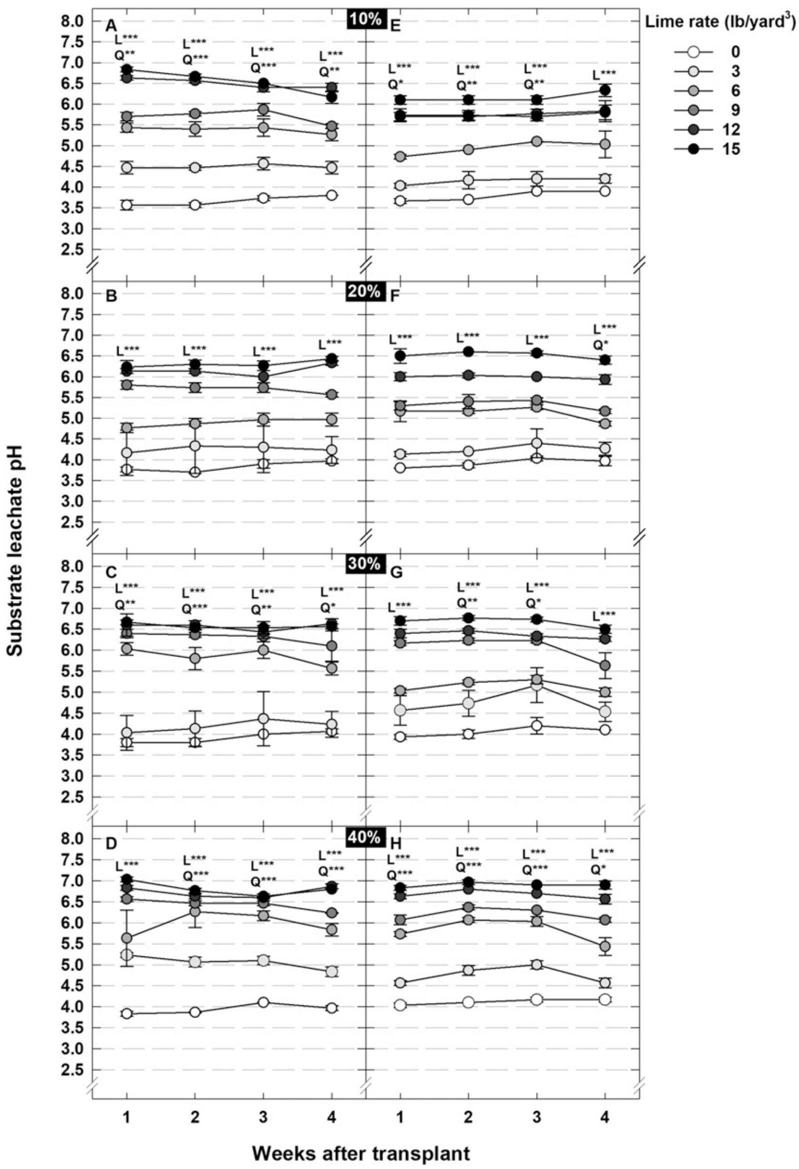

Fig. 6. Substrate leachate pH of 'Moonsong Deep Orange' african marigold plants grown in sphagnum peatmoss amended with perlite (by volume) at 10% (A), 20% (B), 30% (C), or 40% (D) or pine wood chips (by volume) at 10% (E), 20% (F), 30% (G), 40% (H) and incorporated with 0, 3, 6, 9, 12, or 15 lb/yard³ pulverized dolomitic carbonate limestone. Substrate solution was extracted 1 h after irrigation using the pour-through method and determined at 1, 2, 3, and 4 weeks after transplant. Each symbol represents a mean of three samples, and error bars represent SE. Linear (L) and/or quadratic (Q) regression response within each week is indicated and significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***); 1 lb/yard³ = 0.5933 kg·m⁻³.

to the increased growth stage of chrysanthemum plants occurring between 3 and 7 WAT. According to Whipker et al. (2000), nutrient concentrations (EC) between 0.0 and 1.0 $mS \cdot cm^{-1}$ may not be able to sustain rapid plant growth. For chrysanthemum production, increasing the rate of N would likely increase substrate EC levels to the recommended EC range of 2.60 to 4.60 $mS \cdot cm^{-1}$ (Whipker et al., 2000).

Comparable PDW of chrysanthemum plants occurred between substrates formulated to contain similar proportions of PWC and perlite aggregates. Chrysanthemum plants grown in 50% PWC-amended substrates at the 0-lb/yard³ lime rate were higher in PDW (Table 2). In general, and for both aggregate types, as the proportion of peatmoss increased from 50% to 90%, PDW of chrysanthemum plants decreased. Similar PDW occurred among all PWC-amended substrates and in substrates containing 50% perlite (by volume) aggregates and 100% peatmoss. Equivalent PDW occurred among all substrates at the 3-lb/yard³ lime rate, with the exception of plants grown in the 50% PWC-amended substrate, which were similar to plants grown in 40% PWC- and 10% and 40% perlite-amended substrates. At the 6-lb/yard³ dolomitic limestone rate, the greatest PDW occurred in plants grown in 10% to 20% PWC- and 30% perlite-amended substrates and similar to PDW of chrysanthemum plants grown in 100% peatmoss and 10% to 40% perlite-amended substrates. Plants grown in substrates containing 50% perlite aggregates were similar to those grown in substrates amended with 30% and 40% PWC aggregates, and similar to PDW of chrysanthemum plants grown in the 50% PWC-amended substrate. Maximum PDW occurred in 100% peatmoss, 10%, 40%, and 50% PWC- and 20% perlite-amended substrates at the 9-lb/yard³ dolomitic limestone rate. Increasing the dolomitic limestone rate up to 12 lb/yard³ resulted in maximum plant growth of chrysanthemum grown in 30% PWC- and 50% perlite-amended substrates. Increasing beyond the lime rate of 12 lb/yard³ is unknown, therefore maximum PDW of chrysanthemum grown in these substrates is likely correlated to the substrate pH within the recommended pH range for optimal chrysanthemum growth.

These data indicate that PWC aggregates can substitute for perlite in greenhouse substrates to grow chrysanthemum. Increasing dolomitic limestone rates and aggregate proportion of substrates affected substrate pH, EC, and plant growth. Substrates containing perlite or PWC aggregates require similar dolomitic limestone rates to adjust substrate pH. Lower substrate EC levels observed in substrates containing high proportions of both PWC or perlite aggregates can be overcome with an additional N supply. For most substrates, maximum chrysanthemum growth occurred between dolomitic limestone rates of 6 and 9 lb/yard³, which adjusted substrate pH to the recommended range for growing chrysanthemum.

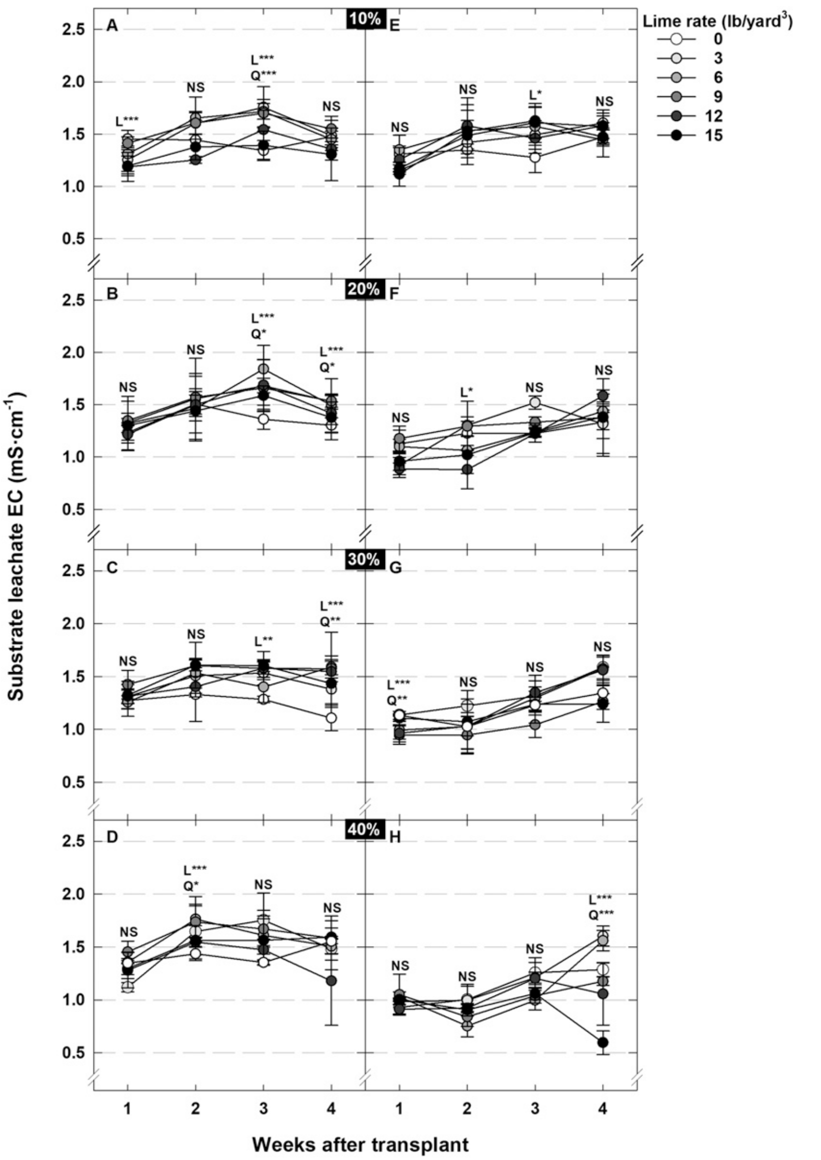

Fig. 7. Substrate electrical conductivity (EC) of 'Moonsong Deep Orange' african marigold plants grown in sphagnum peatmoss amended with perlite (by volume) at 10% (A), 20% (B), 30% (C), or 40% (D) or pine wood chips (by volume) at 10% (E), 20% (F), 30% (G), 40% (H) and incorporated with 0, 3, 6, 9, 12, or 15 lb/yard^3 pulverized dolomitic carbonate limestone. Substrate solution was extracted 1 h after irrigation using the pour-through method and determined at 1, 2, 3, and 4 weeks after transplant. Each symbol represents a mean of three samples, and error bars represent SE. Linear (L) and/or quadratic (Q) regression response within each week is indicated and nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***); 1 lb/yard^3 = 0.5933 kg·m^{-3}, 1 mS·cm^{-1} = 1 mmho/cm.

African marigold growth trial. Over the duration of this trial, substrate leachate pH (Figs. 5A and 6A–G) at all substrates was higher with increasing dolomitic limestone incorporation rate at each sampling time throughout the trial, although to different magnitudes. At 0 WAT, pH of substrates at the 0-lb/yard^3 dolomitic limestone rate were similar with the exception of 100% peatmoss with a pH of 4.4. Similar to the chrysanthemum trial, substrate pH response increased as dolomitic limestone rate increased and proportions of peatmoss decreased. For example, substrates amended with 10% PWC aggregates required a dolomitic limestone rate of 15 lb/yard^3 (Fig. 6D) to increase substrate pH compared with substrates amended with 40% PWC requiring a dolomitic limestone rate of 9 lb/yard^3 (Fig. 6G). Therefore, buffering capacity was greater in substrates amended with higher proportions of aggregates.

For all substrates (Figs. 5A and 6A–G), the addition of 0- and 3-lb/yard^3 dolomitic limestone rates did not adjust substrate pH to the recommended pH range of 6.0 to 6.6 for optimal african marigold growth (Whipker et al., 2000). As a result of low substrate pH, visual symptoms of low pH-induced iron/manganese toxicity were observed in this study at the 0- and 3-lb/yard^3 dolomitic limestone rates. To increase substrate pH to the recommended pH range for african marigold, dolomitic limestone rates of 9, 12, or 15 lb/yard^3 were required. Therefore, substrates containing 20%, 30%, and 40% PWC, 10% to 40% perlite aggregates, and 100% peatmoss required similar rates of dolomitic limestone between 15, 12, and 12 lb/yard^3, respectively, with the exception of 10% PWC-amended substrates, which required an additional 6 lb/yard^3 compared with 10% perlite-amended.

The interaction between increasing dolomitic limestone rate and substrates evaluated in the trial was not significant with regard to substrate solution EC. EC at 0 WAT was similar among all substrates and dolomitic limestone rates (data not shown). In general, substrate solution EC (Figs. 5B and 7A–G) at all substrates was either unaffected or significantly influenced with increasing dolomitic limestone incorporation rate throughout the trial, although to different magnitudes. For most substrates, EC levels at 1 to 4 WAT were similar and in the optimal EC range of 1.00 to 2.60 mS·cm^{-1} (Whipker et al., 2000). Over the duration of the study, the change in leachate color was observed (W.G. Owen, personal observation). Transparent leachates were observed at the 0 lb/yard^3 dolomitic limestone rate and darkened as limestone rate and proportion of aggregated increased. This occurred for both aggregates, but leachate color for PWC seem to be most prominent (W.G. Owen, personal observation). The correlation between leachate color and PWC-amended substrates may likely be a function of the chemical composition of the substrate component. It is postulated and supported by literature indicating the presence of phenolic compounds, terpenes, and organic acids (Morel and Guillemain, 2004; Ortega et al., 1996) contained in the bark and wood of softwood trees may be the result of the leachate color; however, further investigation is warranted.

Growth indices of african marigold plants were influenced by increasing dolomitic limestone rate to different magnitudes (Table 3). At dolomitic limestone rates of 0, 9, and 12 lb/yard³, GI of all african marigold plants were unaffected by increasing proportions of perlite, PWC, or 100% peatmoss. Smaller plants were observed when substrates were formulated with 10% or 30% perlite aggregates and amended with a dolomitic limestone rate of 3 lb/yard³. In general, for most substrates, the largest plants were observed when substrates were amended with 6 lb/yard³ dolomitic limestone, in which the substrate pH ranged from 5.4 to 5.8.

PDW of african marigold plants was significantly influenced by increasing dolomitic limestone rate to different magnitudes (Table 3). PDW was unaffected by substrate at the 0 lb/yard³ dolomitic limestone rate. Increased african marigold PDW occurred as a response to increased dolomitic limestone rate and adjusted pH. In general, the greatest PDW occurred when the 40% perlite substrate was amended with rates of 6 to 15 lb/yard³ dolomitic limestone. In contrast, Jackson et al. (2009) reported maximized PDW of african marigold and zonal geranium plants at the similar dolomitic limestone rate of 3.56 kg·cm⁻³ amended to a substrate containing 50% PTS (by volume). Greatest african marigold PDWs were those grown in substrates containing 10% PWC aggregates and occurred at the dolomitic limestone rate of 9 lb/yard³. Substrates amended with 10% (pH 5.8) and 40% (pH 5.4) PWC aggregates were not in the recommended pH range for african marigold plants, therefore lower substrate pH could account for the differences in PDW. At the 12-lb/yard³ lime rate, maximum african marigold PDW occurred when plants were grown in a substrate containing 40% perlite (by volume) aggregates. Similar to the 40% perlite-amended substrate, maximized PDW occurred when african marigold plants were grown in 100% peatmoss substrates and limed with 12 lb/yard³. A similar dolomitic limestone rate of 12 lb/yard³ was required to adjust pH of 20% (pH 5.9) and 30% (pH 6.3) PWC aggregates to achieve maximum

Table 3. Growth indices (GIs), plant dry weight (PDW), and root dry weight (RDW) of 'Moonsong Deep Orange' african marigold plants grown 4 weeks in 100% sphagnum peatmoss (PM) or peat-based substrates amended (by volume) with 10%, 20%, 30%, or 40% perlite or pine wood chips (PWCs) and incorporated with 0, 3, 6, 9, 12, or 15 lb/yard³ pulverized dolomitic carbonate limestone.

	Dolomitic limestone rate (lb/yard³)[y]						
	0	3	6	9	12	15	
Substrates[z]	GI (cm)[w]						Significance[x]
100 PM	18.9 a[v]	18.7 bc	19.7 b	21.2 a	20.6 a	22.2 a	L***, Q^NS
10 Perlite[u]	18.5 a	18.6 bc	21.3 a	21.6 a	21.0 a	21.0 ab	L***, Q**
20 Perlite	18.1 a	20.1 ab	19.3 b	21.0 a	21.7 a	21.4 ab	L***, Q^NS
30 Perlite	18.3 a	18.2 c	22.8 a	20.8 a	21.3 a	20.5 cb	L**, Q**
40 Perlite	19.5 a	20.0 ab	21.5 a	20.8 a	20.4 a	20.9 ab	L*, Q*
10 PWC[t]	19.7 a	19.5 bc	21.4 a	21.1 a	21.4 a	21.9 ab	L***, Q^NS
20 PWC	19.1 a	20.0 b	22.2 a	22.3 a	21.4 a	21.0 ab	L**, Q***
30 PWC	19.1 a	19.8 ab	21.4 a	20.9 a	20.5 a	20.7 ab	L*, Q*
40 PWC	19.4 a	21.3 a	22.1 a	20.7 a	20.4 a	19.2 c	L^NS, Q***
	PDW (g)[y]						
100 PM	2.15 a	2.44 abc	2.51 d	3.36 abc	3.82 ab	3.59 ab	L***, Q^NS
10 Perlite	1.98 a	2.33 abc	2.78 dc	3.35 abc	3.65 bc	3.47 ab	L***, Q*
20 Perlite	1.89 a	2.34 abc	2.34 d	3.11 bc	3.54 bc	3.74 ab	L***, Q^NS
30 Perlite	1.83 a	2.34 abc	3.50 ab	3.65 ab	3.67 bc	3.92 a	L***, Q**
40 Perlite	1.96 a	1.97 c	3.94 a	3.91 a	4.21 a	3.61 ab	L***, Q***
10 PWC	2.10 a	2.62 ab	3.12 bc	3.78 ab	3.27 c	3.68 ab	L***, Q^NS
20 PWC	1.96 a	2.43 abc	3.39 b	3.36 abc	3.62 bc	3.54 ab	L***, Q***
30 PWC	1.85 a	2.44 bc	3.10 bc	3.50 abc	3.67 bc	3.20 b	L***, Q***
40 PWC	2.03 a	2.22 abc	3.29 bc	2.84 c	2.74 d	2.67 c	L^NS, Q***
	RDW (g)						
100 PM	1.15 a	0.60 a	1.28 bc	0.60 cd	1.98 a	1.13 b	L^NS, Q^NS
20 Perlite	1.00 a	0.60 a	0.80 c	0.48 d	1.43 b	1.35 abc	L**, Q**
40 Perlite	0.80 a	0.52 a	1.80 ab	0.90 bc	1.65 ab	1.15 b	L*, Q^NS
20 PWC	0.88 a	0.62 a	1.65 ab	1.03 ab	1.48 b	1.58 a	L**, Q^NS
40 PWC	0.98 a	0.70 a	2.08 a	1.28 a	1.43 b	1.40 ab	L***, Q^NS

[z]Substrates were formulated with sphagnum peat and amended with either 10%, 20%, 30%, or 40% perlite or PWC.
[y]1 lb/yard³ = 0.5933 kg·m⁻³, 1 g = 0.0353 oz.
[x]Nonsignificant (NS) or significant at $P \le 0.05$ (*), 0.01 (**), or 0.001 (***); L = linear; Q = quadratic response across measurement dates (4 weeks) at *, **, or ***.
[w]Growth index (GI) = [(height + widest width + perpendicular width) ÷ 3]; 1 cm = 0.3937 inch.
[v]Means were separated within-column using Duncan's least significant differences test at $P \le 0.05$.
[u]Substrates were formulated with sphagnum peat and amended with either 10%, 20%, 30%, 40%, or 50% perlite or PWC.
[t]PWCs were produced from 9-year-old loblolly pine trees, delimbed, chipped, and hammer-milled to pass through 0.25-inch (6.350-mm) screen.

PDW. At a similar dolomitic limestone rate of 15 lb/yard³, african marigold plants grown in 30% (pH 6.4) and 40% (pH 6.6) perlite-amended substrates achieved the maximum PDW.

RDWs were similar among all substrates at dolomitic limestone rates of 0 and 3 lb/yard³ (Table 3). In general, RDW followed the similar trend of GI. Maximum RDW occurred among 20% and 40% PWC- and 20% perlite-amended substrates at the dolomitic limestone rate of 6 lb/yard³, where the largest RDW occurred in substrates containing 40% PWC. The dolomitic limestone rate of 12 lb/yard³ amended to the 100% peatmoss and 20% perlite-amended substrates resulted in maximum RDW; however, the RDWs were significantly different. Decreased RDW of african marigold plants occurred when substrates were amended with the lime rate of 15 lb/yard³ and is consistent to previous work (Chrustic and Wright, 1983; Gillman et al., 1998).

Results indicate that similar rates of 9 and 12 lb/yard³ dolomitic limestone are required to adjust substrates amended with 20%, 30%, or 40% PWC or perlite aggregates, to the recommended range for african marigold growth. Substrate pH followed the similar trend, increasing with lime rate and with decreasing proportion of peatmoss. Substrate solution EC was generally similar for all substrates from 0 to 4 WAT.

Conclusion

Based on these results, PWC aggregates can be a suitable alternative for perlite in greenhouse substrates for the production of chrysanthemum and african marigold. Along with determining recommended lime rates for PWC-amended substrates, these studies have demonstrated the variation in substrate pH associated with lime rates and plant growth. Therefore, the importance of understanding greenhouse substrates, their components, and the proportion in which they are formulated, is vital with regard to limestone amendment and the increased interest in using alternatives. Acknowledging the initial pH of substrates and substrate components should be considered before formulating substrates for greenhouse crop production. The common practice of amending a standard rate of lime to a substrate can impact durability of substrate pH and crop performance. It is recommended to initially test substrates before amending with pre-plant limestone. This practice is especially true when growers adopt/use commercial wood products that may be different from the PWC reported in these works.

For chrysanthemum and african marigold production, changes in liming practices are often not needed when substituting perlite with PWC. Based on the growth trial of chrysanthemum, it is recommended that pH of substrates amended with ≥30% perlite or PWC aggregates to be adjusted using dolomitic limestone rates of 9 and 12 lb/yard³. Understanding plant requirements is vital in terms of plant quality. As observed in the african marigold growth trial, iron toxicity related to low substrate pH affected plant growth and visual quality. Based on the results of the african marigold growth trial, it is recommended that substrate pH be adjusted using limestone rates of 9 and 15 lb/yard³, for optimal african marigold growth and quality. Overall, PWC can be used in production of greenhouse crops without changing liming practices and offers greenhouse growers in the southeastern United States a more local/regional and organic alternative to perlite.

PWCs are engineered and processed to specific sizes and shapes to be functional as aggregates in a container substrate. Not all wood components are designed, or capable of improving/influencing the physical and chemical behavior of a substrate the same. The influence of particle size and surface area (internal and external) on microbial decomposition, nutrient immobilization, and pH buffering (among other things) is not well understood for wood substrate components, but it is hypothesized to be significant. For example, wood processed into fibers (increased surface area) and amended with peat may show different pH adjustments and plant growth response during cultivation, in addition to changing the substrate air and water relations much differently from PWC-sized particles. Based on the known variability of many wood components being developed, commercialized, and marketed, it is suggested that all substrate wood components be tested/trialed before large-scale use.

Literature cited

Argo, W.R. and P.R. Fisher. 2002. Understanding pH management for container-grown crops. Meister Publ., Willoughby, OH.

Bohne, H. 2004. Growth of nursery crops in peat-reduced and in peat free substrates. Acta Hort. 644:103–106.

Boyer, C.R., G.B. Fain, C.H. Gilliam, T.V. Gallagher, H.A. Torbert, and J.L. Sibley. 2008. Clean chip residual: A substrate component for growing annuals. HortTechnology 18:423–432.

Caplan, D.M. 2018. Propagation and root zone management for controlled environment *Cannabis* production. Univ. Guelph, Guelph, ON, Canada, Master's Thesis.

Chrustic, G.A. and R.D. Wright. 1983. Influence of liming rate on holly, azalea, and juniper growth in pine bark. HortScience 108:791–795.

Evans, M.R. 2011. Physical properties of and plant growth in peat-based root substrates containing class-based aggregate, perlite, and parboiled fresh rice hulls. HortTechnology 21:30–34.

Evans, M.R. and M. Gachukia. 2007. Physical properties of sphagnum peat-based root substrates amended with perlite or parboiled fresh rice hulls. HortTechnology 17:312–315.

Evans, M.R. and M. Gachukia. 2008. Root substrate pH, electrical conductivity, and macroelement concentration of sphagnum peat-based substrates amended with parboiled fresh rice hulls or perlite. HortTechnology 18:644–649.

Fain, G.B., C.H. Gilliam, J.L. Sibley, and C.R. Boyer. 2006. Evaluation of an alternative, sustainable substrate for use in greenhouse crops. Southern Nursery Assn. Res. Conf. 51:59–61.

Fain, G.B., C.H. Gilliam, J.L. Sibley, and C.R. Boyer. 2008a. *Wholetree* substrates derived from three species of pine in production of annual vinca. HortTechnology 18:13–17.

Fain, G.B., C.H. Gilliam, A.L. Witcher, J.L. Sibley, and C.R. Boyer. 2008b. WholeTree substrate and fertilizer rate in production of greenhouse-grown petunia (*Petunia ×hybrida*) and marigold (*Tagetes patula*). HortScience 43:700–705.

Fonteno, W.C., C.T. Harden, and J.P. Brewster. 1995. Procedures for determining physical properties of horticultural substrates using the North Carolina

State University porometer. North Carolina State Univ., Horticultural Substrates Lab., Raleigh.

Gillman, J.H., M.A. Dirr, and S.K. Braman. 1998. Effects of dolomitic lime on growth and nutrient uptake of *Buddleia davidii* 'Royal Red' grown in pine bark. J. Environ. Hort. 16:111–113.

Gruda, N. and W.H. Schnitzler. 2006. Wood fiber substrates as a peat alternative for vegetable production. Eur. J. Wood Prod. 64:347–350.

Jackson, B.E., R.D. Wright, and M.C. Barnes. 2008. Pine tree substrate, nitrogen rate, particle size, and peat amendment affects poinsettia growth and substrate physical properties. HortScience 43:2155–2161.

Jackson, B.E., R.D. Wright, and N. Gruda. 2009. Container medium pH in a pine tree substrate amended with peatmoss and dolomitic limestone affects plant growth. HortScience 44:1983–1987.

Jackson, B.E. 2018. Substrates on trial: Wood fiber in the spotlight. Greenhouse Mgt. 38(9):52–56.

Kingston, P.H., C.F. Scagel, and D.R. Bryla. 2017. Suitability of sphagnum moss, coir, and douglas fir bark as soilless substrates for container production of highbush blueberry. HortScience 52:1692–1699.

Morel, P. and G. Guillemain. 2004. Assessment of possible phytotoxicity of a substrate using an easy representative biotest. Acta Hort. 664:417–423.

Nelson, P.V. 2012. Greenhouse operation and management. 7th ed. Prentice Hall, Upper Saddle River, NJ.

Ortega, M.C., M.T. Moreno, J. Ordovas, and M.T. Agudo. 1996. Behavior of different horticultural species in phytotoxicity bioassays of bark substrates. HortScience 66:125–132.

Saunders, T.N., R.D. Wright, and J.F. Browder. 2005. Chipped pine logs: A potential substrate for nursery and greenhouse crops. Proc. Southern Nursery Assn. Res. Conf. 50:112–114.

Smith, J.T. 2018. Paclobutrazol drench efficacy in soilless substrates containing wood and pine bark, and vegetative hemp growth in peat and coir-based substrates. North Carolina State Univ., Raleigh, MS Thesis.

Starr, Z., C. Boyer, and J. Griffin. 2011. Cedar substrate particle size affects growth of container-grown *Rudbeckia*. Proc. Southern Nursery Assn. Res. Conf. 56:292–296.

Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil fertility and fertilizers. 5th ed. Macmillan, New York, NY.

Whipker, B.E., J.M. Dole, T.J. Cavins, J.L. Gibson, W.C. Fonteno, P.V. Nelson, D.S. Pitchey, and D.A. Bailey. 2000. Plant root zone management. North Carolina Comm. Flower Growers' Assn., Raleigh, NC.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227–229.

Wright, R.D., B.E. Jackson, J.F. Browder, and J.G. Latimer. 2008. Growth of chrysanthemum in a pine tree substrate requires additional fertilizer. HortTechnology 18:111–115.