Poultry Litter Ash Reduces Phosphorus Losses during Greenhouse Production of *Lantana camara* L. ‘New Gold’

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Abstract. Phosphorus (P) fertilizers with high water-solubility are often applied in excessive amounts to porous horticultural substrates to produce high-quality plants. As a result, high P losses during containerized plant production have presented an environmental challenge to responsible growers. Poultry litter ash (PLA), a byproduct of bioenergy production, contains P concentrations comparable to conventional P fertilizers but is characterized as having lower water-solubility. Therefore, a series of experiments were conducted to characterize effects of PLA on container-plant growth and P leaching. PLA was compared with superphosphate (SP), a highly water-soluble P source, in ratios of 0:100, 25:75, 50:50, 75:25, and 100:0 (SP:PLA) in the production of *Lantana camara* L. ‘New Gold’. In 2011, lantana fertilized with higher ratios of PLA exhibited slower growth with lower shoot and root biomasses compared with 100% SP-fertilized lantana. However, in 2012, differences in fertilizer treatments lessened, with 100% PLA-fertilized lantana exhibiting 14% less shoot biomass and no differences in root biomass compared with 100% SP-fertilized lantana. Measurement of shoot:root biomass, a common indicator of P deficiency, was not different between any P treatments in 2011 or 2012. This indicates root growth was most likely the driving factor in P-treatment effects on shoot biomass in each year of the experiment. During a post-production field trial, no differences in growth or biomass were observed between lantana previously fertilized with P, regardless of source. However, application of PLA as the single P source reduced dissolved reactive P (DRP) concentrations in leachate >90% and total P (TP) mass losses 69% compared with 100% SP-fertilized lantana during container production, with P treatments reducing DRP and TP losses as PLA ratios increased. Therefore, the benefit of P-loss reduction during container production achieved through PLA application may warrant the acceptance of slightly smaller plants or extending production cycles.

Soilless substrates common to nursery and greenhouse production are often characterized as having high percolation rates (Zhu et al., 2007) and low P-sorption capacities (Bilderback, 2001; Yeager and Barrett, 1984). Many growers compensate for low P retention of soilless substrates by applying higher fertilizer rates more frequently (Silber et al., 2005). However, fertility practices that rely on high, frequent fertility rates have been correlated to increased nutrient leaching (Zhu et al., 2007). As a result, nursery and greenhouse operations have been identified as potential contributors to nonpoint-source nutrient pollution (Mangiafico et al., 2008), especially

with regards to P-acceleration of eutrophication in adjacent surface waters.

Research has shown that P leaching in soilless substrates is highly influenced by water solubility of the P source applied during container production (Yeager and Wright, 1982). Therefore, utilization of more controlled-release fertilizers (CRFs), which release nutrients slowly over time somewhat in accordance with plant growth and uptake, is a strategy currently implemented by many producers to reduce nutrient losses from soilless substrates in container production (Lea-Cox and Ristvey, 2003). However, CRFs are generally more expensive compared with many highly water-soluble fertilizers and vary in efficacy with regard to stemming nutrient-leaching losses depending on environmental conditions (Bilderback, 2001; Ristvey et al., 2007; Shaviv, 2001; Tyler et al., 1996).

Given the high costs associated with CRFs and increasing concern for P leaching, recycling nutrients, mainly in the form of manures, have been researched as a means to mitigate P losses during crop production cycles (Bachmann and Eichler-Lobermann,

2010; Dawson and Hilton, 2011). One recycled P source in great abundance in the southeastern United States is poultry litter. Poultry litter contains comparable amounts of nitrogen to ruminant wastes, but higher concentrations of P because fowl are unable to extract organically-bound P from feeds without the addition of phytase (Woyengo and Nyachoti, 2011). Poultry litter has been primarily used as a fertilizer on pastures and other agricultural commodities. However, continuous application of poultry litter has led to increased incidence of surface-water impairment because of concentrated land applications (Sharpley et al., 1994). Processes to concentrate poultry litter P to reduce associated transportation costs to expand the area of application have included compaction (Bernhart et al., 2010), pelletization (McMullen et al., 2005), composting (Brodie et al., 2000), P extraction (Szogi et al., 2008), gasification (Priyadarsan et al., 2004), or combustion (Codling et al., 2002; Schiemenz and Eicler-Lobermann, 2010). However, many of the concentration processes listed have not been widely adopted to date.

Unlike many processes used to concentrate P, combustion of poultry litter has been reported to reduce manure biomass by >80%, decrease P water-solubility, and produce energy (Habetz and Echols, 2006). For example, Fibrominn, a power plant in Benson, MN, is an alternative energy plant that cocombusts poultry litter and wood to provide ≈55 MW of energy for 40,000 homes. Combustion of poultry litter converts P from 50% to 60% water-soluble forms in raw poultry litter to 1.5% water-soluble P in PLA. More than 80% of PLA-P is soluble only in hydrochloric acid (Codling, 2006), suggesting that P will be less prone to offsite movement than from more water-soluble sources. Although PLA-P is present as low-soluble compounds, PLA has been reported to be a suitable P source for wheat [*Triticum aestivum* L.] (Codling et al., 2002), Japanese mustard spinach [*Brassica rapa* L.] (Faridullah et al., 2009), buckwheat (*Fagopyrum esculentum* L.) (Lifago), oil radish (*Raphanus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), ryegrass [*Lolium multiflorum westerwoldicum* Gordo] (Bachmann and Eichler-Lobermann, 2010), and ornamental crops (Wells et al., 2013). To date, no published research on the effect of PLA to reduce P leaching from soilless substrates is available. Therefore, experiments were conducted to determine if PLA application is suitable for plant growth and reduces P leaching within a soilless substrate in container-grown plant production.

Materials and Methods

Plant response and leachate-DRP in a greenhouse experiment. On 6 Sept. 2011 and 2 Mar. 2012, 60 lantana plants (*Lantana camara* L. ‘New Gold’) were transplanted from 105-cell trays to 30 1.6-L containers, with two plants per container. The substrate was composed of pine bark (particle size

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<0.38 cm) and peatmoss at a 4:1 ratio (by volume), and amended with 0.89 kg·m⁻³ micronutrient package (Micromax; Scotts Company, Marysville, OH), potassium (K) (Meister 0-0-43; Graco Fertilizer Company, Cairo, GA) at 0.25 kg·m⁻³ K (0N-0P-35.7K), and 2.97 kg·m⁻³ pulverized dolomitic limestone. Preplant-incorporated P treatment sources were either SP or PLA (260 g·m⁻³ P), with the latter being a product of commercial energy production via combustion of poultry litter and obtained courtesy of North American Fertilizer, LLC (Benson, MN). Total P, available P, and water-soluble P of SP and PLA were determined using the spectrophotometric molybdovanadophosphate method for determining TP in fertilizers (AOAC INTERNATIONAL, 2005b), direct extraction method for determining available P in fertilizers (AOAC INTERNATIONAL, 2005c), and the spectrophotometric molybdovanadophosphate method for determining water-soluble P in fertilizers (AOAC INTERNATIONAL, 2005a), respectively. Total P and water-soluble P were determined at Louisiana State University's Agricultural Chemistry Department (Baton Rouge, LA), and available P was determined at Brookside Laboratories, Inc. (New Bremen, OH). PLA was 10% TP and 6.7% available P, 1% of which was water-soluble for a total analysis of 0N-3.1P-4.2K. Superphosphate was 20% TP and 18% available P, 85% of which was water-soluble for a total analysis of 0N-8.7P-0K. Superphosphate and PLA were incorporated as single P sources or in ratios (by % available P) of 25:75, 50:50 or 75:25 SP:PLA at 260 g·m⁻³ P (Yeager and Barrett, 1985) with controls receiving no P fertilizer.

Plants were maintained in a greenhouse under natural light for 84 d at temperatures between 23 and 29 °C. Temperature was recorded using a datalogger (HOBO H08-004-02; Onset Computer Corporation, Bourne, MA) and averaged 23.7 and 28.4 °C in 2011 and 2012, respectively. During the experiment, plants were supplied with 350 mL water including 120 mL aliquots of NH₄NO₃ (aq.) at a rate of 250 mg·L⁻¹ N per container per day.

Lantana growth was measured biweekly using a growth index [(height + widest width + perpendicular width)/3]. Flowers showing color were quantified biweekly. At 84 d after planting (DAP), lantana shoots and roots were harvested and separated. Roots were washed with a gentle stream of water to remove adhering substrate. Lantana leaf and root tissue samples were collected and rinsed with deionized water to remove exterior salts or contaminants. Shoots and roots, including tissue samples, were dried at 60 °C for 72 h before determining biomass gravimetrically. Leaf-tissue samples, in amounts of 0.5 g, were ground in a stainless-steel mill (Thomas Wiley® Mini-Mill; Thomas Scientific, Swedesboro, NJ) to a particle size of <0.5 mm and digested according to procedures for wet acid digestion using nitric and perchloric acids described by Mills and Jones (1996). Concentrated samples were diluted with 20 mL

deionized water and analyzed for elemental concentrations using inductively coupled plasma optical emission spectroscopy (ICP-OES; SPECTRO Analytical Instruments, Kleve, Germany).

Leachate from three containers per treatment was collected weekly after the Virginia Tech Pour Through method (Wright, 1986). In the laboratory, 15-mL aliquots of leachate were filtered through 0.45 µm disposable nylon filters (22 mm diameter, Whatman™; GE Healthcare UK Limited, Buckinghamshire, UK) in preparation for DRP analysis using the molybdate colorimetric method developed by Murphy and Riley (1962) and modified by Pote and Daniel (2000a).

Quantification of TP losses. In 2012, lantana were grown following the same previously outlined procedures. However, these plants were used to quantify effluent-total P (effluent-TP) by continuously collecting effluent from containers using 18.9-L polypropylene buckets during the 84-d experimental period. To capture total container effluent and minimize evaporative losses, a 15-cm diameter opening was fashioned in each bucket's lid to allow leachate to drain directly from the growing container into the collection bucket. A silicone caulk sealant was applied to seal the container-bucket junction. Bucket lids were placed on top of buckets, but were not fastened to avoid creation of a vacuum and to allow water to move through substrates and into collection buckets.

Total leachate volume was quantified biweekly, and 120-mL aliquots were collected for TP analysis. Total P was analyzed using the sulfuric acid-nitric acid digestion method for determining TP in water samples (Pote and Daniel, 2000b). Samples (25 mL) were digested in concentrated sulfuric and nitric acids (1 mL + 5 mL, respectively), at 200 °C for 6 h on a digestion block (Bran + Luebbe BD-40) controlled with a BD-20/40 controller (Bran + Luebbe, Vallejo, CA) to hydrolyze polyphosphates, organically bound phosphates, and particulate P to orthophosphate. After digestion, samples were neutralized using NaOH and diluted with distilled water before determination of orthophosphate concentrations using the molybdate colorimetric method for determining orthophosphate concentrations in water samples developed by Murphy and Riley (1962) and modified by Pote and Daniel (2008a). At 84 DAP, lantana shoots and roots were harvested and processed for biomass and leaf/root tissue elemental concentrations were determined as previously described.

Postproduction field evaluation. In 2012, 30 lantana plants were grown concurrently with and under the same treatments and conditions as previously described plants. After an 84-d period in the greenhouse, plants were transplanted into a raised bed to simulate posttransplant field conditions. A linear bed measuring 120 m long and 1 m wide composed of native soil (Oliver silt loam; fine-silty, mixed, thermic, typic fragiudalf) and amended via rototillage with a 7.5 cm

layer of pine bark, milled to <0.95 cm (Phillips Bark Processing Co., Brookhaven, MS), was established at the Burden Research Center located in Baton Rouge, LA. Granular fertilizer (Sta-Green, 12N-2.6P-4.9K; Spectrum Brands Holdings, Atlanta, GA) was applied to the surface of the bed at 0.97 kg·100 m⁻² N before transplanting. Plants were transplanted into the bed 1.2 m apart in a linear row, watered in thoroughly, and were irrigated daily for the duration of the experiment.

Lantana plants were measured weekly to calculate growth index [(height + widest width + perpendicular width)/3] and quantify flowers showing color for the first 4 weeks after transplanting. At 49 DAP, shoots were harvested, dried at 60 °C for 96 h, and biomass was recorded.

Experimental designs and statistical analyses. An experimental unit was defined as an individual container in greenhouse experiments and as plants removed from individual containers and planted into the landscape in the field experiment. Experimental units were arranged in completely randomized designs with five replications in greenhouse experiments and as a randomized complete block design with five blocks in the field experiment. Growth index, flower count, plant dry weight, tissue nutrient concentration, leachate-DRP and effluent-TP data were analyzed using PROC MIXED (SAS version 9.3; SAS Institute, Cary, NC) and the block was treated as a RANDOM effect in the field experiment. Where appropriate, means for each measurement at each sample date were separated using Tukey's Honest Significant Difference test at a significance level of 0.05.

Results

Plant response in greenhouse experiments. Application of P, regardless of P-treatment combination, increased growth index of lantana compared with control at 42, 56, and 70 d after potting (DAP) in 2011, and at all measurement dates in 2012 (Table 1). When applied as a singular P source, PLA increased growth compared with the control by 75%, 157%, and 178% at 42, 56, and 70 DAP in 2011 and 72% at 84 DAP in 2012. As PLA composition of the fertilizer treatment increased, lantana exhibited a pattern of slower growth in 2011 between 28 and 70 DAP. However, less treatment effect was observed in 2012.

Similar to growth indices, shoot dry weight slightly decreased to 17.4, 14.6, 12.0, and 10.8 g as the percentage of PLA increased in 2011 compared with 18.2 g for 100% SP-fertilized lantana (Table 2). Fertilization with 100% PLA decreased shoot dry weight by 41% compared with lantana fertilized with 100% SP. However, a similar trend was not observed in 2012 as shoot dry weight was reduced only 14% through fertilization with 100% PLA, compared with 100% SP.

In 2011, root dry weight decreased 28%, from 5.55 to 4.00 g, when plants were fertilized with 100% PLA compared with

Table 1. Effect of SP, PLA, and combinations thereof as P sources on growth index of *Lantana camara* 'New Gold' throughout an 84-d experimental period.

Treatment ^z	Growth index ^y					
	14 DAP ^x	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP
2011						
Control	9.5 a ^w	9.7 c	9.9 d	9.4 c	8.9 c	—
100:0 SP:PLA	11.1 a	14.6 ab	25.6 a	30.4 a	32.8 a	—
75:25 SP:PLA	11.2 a	15.9 a	26.1 a	30.4 a	32.3 a	—
50:50 SP:PLA	11.2 a	14.7 ab	22.7 ab	27.2 ab	28.9 ab	—
25:75 SP:PLA	10.6 a	13.3 ab	18.6 bc	25.2 ab	26.7 ab	—
0:100 SP:PLA	10.5 a	11.8 bc	17.3 c	24.1 b	25.0 b	—
	NS ^v	<0.0001	<0.0001	<0.0001	<0.0001	—
2012						
Control	7.5 c	12.3 b	15.1 b	18.8 c	22.4 b	24.9 b
100:0 SP:PLA	16.5 a	27.4 a	31.9 a	36.9 ab	44.8 a	47.9 a
75:25 SP:PLA	17.4 a	26.6 a	32.7 a	42.5 a	46.5 a	48.1 a
50:50 SP:PLA	16.7 a	24.2 a	28.9 a	37.7 ab	46.0 a	49.1 a
25:75 SP:PLA	12.5 b	24.3 a	27.4 a	33.2 ab	40.9 a	43.5 a
0:100 SP:PLA	13.1 b	21.1 a	26.0 a	31.9 b	39.7 a	42.7 a
	<0.0001	0.0002	<0.0001	0.0001	<0.0001	<0.0001

^zControl = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.^yGrowth index was measured in centimeters as: [(height + widest width + perpendicular width)/3].^xDAP = days after potting.^wValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).^vP value derived from analysis of variance; NS = not significant.Table 2. Effect of SP, PLA, and combinations thereof as P sources on biomass accumulation of *Lantana camara* 'New Gold' during an 84-d experimental period.

Treatment ^z	2011			2012		
	Shoot DW ^y (g)	Root DW (g)	Shoot:root	Shoot DW (g)	Root DW (g)	Shoot:root
Control	2.1 d ^c	2.2 d	0.9 b	8.5 c	5.6 c	1.5 b
100:0 SP:PLA	18.2 a	5.6 b	3.1 a	25.2 a	8.3 ab	2.9 a
75:25 SP:PLA	17.4 a	6.9 a	2.6 a	27.4 a	9.9 a	2.8 a
50:50 SP:PLA	14.6 b	5.8 ab	2.4 a	26.2 a	9.4 ab	2.8 a
25:75 SP:PLA	11.9 c	4.7 bc	2.7 a	21.9 b	7.7 b	2.7 a
0:100 SP:PLA	10.8 c	4.0 c	2.7 a	21.8 b	7.9 b	2.7 a
	<0.0001 ^w	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^zControl = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.^yShoot and root biomasses (DW) were measured at 84 DAP.^wValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).^vP value derived from analysis of variance; NS = not significant.

100% SP. However, shoot:root biomass ratios did not differ between any P treatments. In 2012, when shoot growth responses between 100% SP- or PLA-fertilized plants were lessened, no differences in root growth were observed. As in 2011, no differences between shoot:root biomass ratios existed between P treatments in 2012. Shoot:root biomass was increased by P application, regardless of source or combination of sources in both years, illustrating a larger disparity in shoot mass than root mass based on P application.

Tissue nutrient accumulation. All P sources increased lantana foliar P concentrations compared with controls in 2011 (Table 3). As the percentage of PLA increased, foliar P concentrations decreased slightly from 0.37% to 0.33% in 100% SP- and 100% PLA-fertilized lantana, respectively. Lantana fertilized with 100% PLA had foliar Mn concentrations reduced by 49%, from 226 to 116 mg·kg⁻¹ and foliar K concentrations increased 52% from 1.81% to 2.76% compared with 100% SP-fertilized lantana.

In 2012, when differences in plant growth between P treatments were muted, shoot P concentrations were lower for plants fertilized with 100% SP than they were for lantana

fertilized with PLA (Table 3). Shoot P concentrations increased from 0.17% for 100% SP-fertilized lantana to 0.2% for 100% PLA-fertilized lantana, whereas control plants were 0.05% P.

Dissolved reactive P. Lantana fertilized with 100% PLA had lower concentrations of leachate DRP for the first 6 weeks of experimental periods in 2011 and 2012, compared with plants fertilized with 100% SP. Lantana fertilized with 100% PLA resulted in an average decrease in DRP concentrations of 91% and 94% in 2011 and 2012, respectively, throughout the 84-d experimental periods compared with lantana fertilized with 100% SP (Table 4). Increasing the percentage of PLA as a component of P fertilizer treatments in 25% gradations reduced average leachate-DRP concentrations by 40%, 67%, and 88% in 2011 and 42%, 68%, and 87% in 2012 compared with 100% SP-fertilized lantana. All lantana fertilized with treatments containing SP exhibited higher initial leachate-DRP concentrations at 0 DAP with 499, 288, 96, and 42 mg·L⁻¹ in 2011 and 513, 296, 150, and 51 mg·L⁻¹ in 2012 with subsequent DRP leachate losses declining over time. Lantana fertilized with 100% PLA resulted in leachate-DRP concentrations

reaching maxima of 14 mg·L⁻¹ in each year of the experiment.

Total P effluent mass loss collected in an effluent collection system. Effluent-TP mass loss was higher for all P treatments at 14, 28, 42, 56, and 70 DAP compared with the control (Table 5). Similar to leachate-DRP concentrations, cumulative effluent-TP mass loss was reduced 69%, from 348.5 to 106.5 mg/container, when PLA was applied as a single P source. For the experiment, 77% of applied P, from 100% SP, was collected in effluent compared with only 24% from PLA. At 14 DAP, 76% of cumulative TP was collected from SP, compared with 25% from PLA (Table 4). Whereas 76%, 92%, 98%, and 99% of cumulative TP was collected from the 100% SP treatment by 14, 28, 42, and 56 DAP, respectively, TP was released from the 100% PLA treatment more slowly as 25%, 48%, 72%, 86%, and 95% of cumulative effluent-TP was collected from PLA on the same respective collection dates.

Application of P, regardless of source, increased shoot dry weight of lantana grown in a closed system compared with control plants (Table 6), but there were no differences between P treatments. Similarly, root dry weights did not differ between P

Table 3. Effect of SP, PLA, and combinations thereof, as P sources on tissue nutrient concentrations of *Lantana camara* 'New Gold' grown in drain-to-waste and effluent collection systems in 2011 and 2012, respectively.

Treatment ^z	Foliar ^y (2011)					Entire shoots ^x (2012)				
	Ca (%)	Mg (%)	Mn (mg·kg ⁻¹)	P (%)	K (%)	Ca (%)	Mg (%)	Mn (mg·kg ⁻¹)	P (%)	K (%)
Control	0.83 a ^w	0.49 a	226.5 a	0.03 d	3.24 a	0.67 c	0.28 c	355.4 b	0.05 c	1.32 a
100:0 SP:PLA	1.04 a	0.42 abc	225.5 a	0.37 ab	1.81 d	0.70 bc	0.62 a	463.1 a	0.17 b	0.48 d
75:25 SP:PLA	0.97 a	0.45 ab	187.9 b	0.39 a	1.98 cd	0.73 bc	0.49 ab	435.8 ab	0.19 a	0.59 cd
50:50 SP:PLA	0.94 a	0.42 abc	158.2 bc	0.36 abc	2.29 bcd	0.83 ab	0.50 b	370.9 b	0.20 a	0.57 cd
25:75 SP:PLA	0.85 a	0.40 bc	147.1 cd	0.34 bc	2.57 abc	0.92 a	0.49 b	242.2 c	0.21 a	0.76 c
0:100 SP:PLA	0.86 a	0.35 c	115.9 d	0.33 c	2.76 ab	0.89 a	0.44 b	168.7 c	0.20 a	0.84 b
	NS ^v	0.0066	<0.0001	<0.0001	0.0003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^zControl = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.

^yMost recently matured and fully opened leaves.

^xEntire top portion of plant including stems, leaves, and flowers.

^wValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).

^vP value derived from analysis of variance; NS = not significant.

Table 4. Effect of SP, PLA, and combinations thereof as P sources on concentrations of dissolved reactive phosphorus in leachates collected via the Virginia Tech pour through method in 84-d experiments in 2011 and 2012.

Treatment ^z	Dissolved reactive P ^y (mg·L ⁻¹ P)							
	0 DAP ^x	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Avg
2011								
Control	0.36 e ^w	0.23 d	0.28 d	0.36 c	0.30 b	0.22 b	0.19 c	0.28 d
100:0 SP:PLA	499.9 a	178.9 a	134.9 a	34.2 a	6.2 a	3.8 a	1.6 b	122.8 a
75:25 SP:PLA	287.7 b	108.6 b	83.7b	23.7 ab	6.9 a	4.0 a	2.1 ab	73.8 b
50:50 SP:PLA	96.1 c	61.5 bc	56.9 b	15.8 ab	5.5 a	4.4 a	4.7 a	40.6 bc
25:75 SP:PLA	41.8 cd	26.5 c	16.9 c	8.6 b	5.0 a	4.8 a	2.6 ab	15.2 c
0:100 SP:PLA	3.8 d	14.1 c	12.1 c	8.9 b	6.8 a	4.5 a	2.9 ab	11.2 c
	<0.0001 ^v	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
2012								
Control	0.41 f	0.20 e	0.28 e	0.28 e	0.25 b	0.23 b	0.20 b	0.26 d
100:0 SP:PLA	513.4 a	159.4 a	113.4 a	20.3 a	4.9 a	3.2 a	2.1 a	116.7 a
75:25 SP:PLA	295.6 b	107.1 b	49.9 b	12.4 b	4.4 a	2.9 a	1.5 a	67.7 b
50:50 SP:PLA	150.4 c	57.1 c	33.5 bc	10.7 bc	4.7 a	3.5 a	1.6 a	37.3 bc
25:75 SP:PLA	50.8 d	25.1 cd	16.9 cd	7.1 d	3.9 a	3.6 a	1.6 a	15.6 c
0:100 SP:PLA	3.5 e	14.5 d	12.9 d	8.0 cd	6.1 a	4.2 a	2.3 a	7.4 c
	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^zControl = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.

^yConcentration of soluble orthophosphate collected in leachate.

^xDAP = days after potting.

^wValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).

^vP value derived from analysis of variance.

Table 5. Effects of SP, PLA, and combinations thereof as P sources on total P in effluent from *Lantana camara* 'New Gold' grown in an effluent collection system over an 84-d experimental period in 2012.

Treatment ^z	Effluent-total P (mg) ^y						
	14 DAP ^x	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Total
Control	0.7 f ^w	0.3 c	0.6 c	0.8 d	0.5 d	0.8 e	3.8 e
100:0 SP:PLA	265.3 a	55.2 a	19.6 ab	3.8 bc	3.4 bc	1.1 de	348.5 a
75:25 SP:PLA	186.5 b	54.8 a	11.5 b	2.7 c	2.1 c	1.7 bc	259.5 b
50:50 SP:PLA	117.4 c	33.5 b	12.1 b	4.9 b	3.4 bc	1.4 cd	172.9 c
25:75 SP:PLA	68.7 d	25.1 b	11.5 b	4.1 bc	4.5 b	2.1 b	116.2 d
0:100 SP:PLA	26.6 e	25.0 b	25.0 a	15.3 a	8.8 a	5.6 a	106.5 d
	<0.0001 ^v	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^zTreatments were the following: control = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.

^yA total of 450 mg P was added to system at experiment initiation.

^xDays after potting.

^wValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).

^vP value derived from analysis of variance; NS = not significant.

treatments, and shoot:root biomass increased because of P application, regardless of source.

Effects of P source on posttransplant growth in field. During production, P source only affected landscape performance of *lantana* during the initial weeks after planting. *Lantana* fertilized with P during production, regardless of treatment, had a greater growth index than control plants at 0, 7, and 14 DAP.

From 21 DAP onwards, plants in the control group were as large as plants that were fertilized with P during container production, with the exception of the 100% SP treatment group, which remained larger than control plants for the duration of the field experiment (Table 7). At the end of the 49-d experimental period, *lantana* shoot biomass did not differ among production treatments, including the control group.

Discussion

Poultry litter ash has been reported as a potentially-suitable P source for greenhouse crop production with liming potential to improve substrate pH (Wells et al., 2013). However, the most positive attribute of PLA as a P fertilizer for greenhouse crop production may be its potential to reduce P-leaching losses. In the current experiments, *lantana*

fertilized with 100% PLA exhibited reductions in DRP and TP losses by averages of 92% and 69%, respectively, compared with lantana fertilized with 100% SP. Reductions in initial DRP losses were disproportionate to the percentage of PLA applied. For example, replacement of the SP fraction of the P fertilizer with 25%, 50%, and 75% PLA resulted in initial DRP reductions of 45%, 70%, and 86%, respectively. Use of readily available nutrients early in crop production is questionable (Altland and Buamscha, 2008) from an environmental as well as a production standpoint. To concur with the work of Altland and Buamscha (2008), limited plant rooting associated with developing plants restricts exploitation of the substrate and thus necessity of soluble nutrients early in the production cycle.

Even though all experimental units received the same volume of water during daily irrigation, leachate-DRP concentrations decreased each subsequent week for all SP-containing fertilizer treatments, whereas lantana fertilized with 100% PLA remained relatively stable ranging from 3 to 14 mg·L⁻¹ for the first 10 WAP. These differences in leachate-DRP concentrations suggest that PLA-P solubility, a factor known to affect

P-leaching losses, is less affected by water usage compared with more highly soluble P sources during crop production. According to Raviv and Lieth (2008), solution P concentrations for most greenhouse crops should fall between 5 and 60 mg·L⁻¹, whereas a narrower range of 5 to 10 mg·L⁻¹ is recommended for container-grown crops when employing CRFs (Yeager et al., 2007). However, over-application of P is often the result of target N fertilization rates of complete, water-soluble fertilizers commonly applied to greenhouse crops (Smith et al., 2004).

Monocalcium phosphate, with a water solubility of 20,000 mg·L⁻¹ water (Van Wazer, 1958), is the primary P-containing compound within SP (Prochnow et al., 2003). Although TP content is somewhat similar for SP and PLA, on average 93% of SP-P is highly water-soluble (Gowariker, 2009), whereas a lower fraction of PLA-P is water-soluble (Codling, 2006). This is likely due to formation, during combustion, of highly water-insoluble di- and tricalcium phosphates having water solubilities of 200 and 20 mg·L⁻¹ water, respectively (Van Wazer, 1958).

Given the lack of P-sorption capacities of common substrate components (Bilderback, 2001; Khandan-Mirkohi and Schenk, 2008), P is lost from soilless substrates relatively quickly if applied in highly water-soluble forms. Yeager and Barrett (1984) reported up to 37% of P, applied as SP, leached within 1 d after application with up to 76% P losses within 21 d after application. In a subsequent experiment, Yeager and Barrett (1986) reported 80% of applied P leached within 21 d from a substrate composed of pine bark, peatmoss, and sand. Therefore, reductions in P losses through application of PLA during container production are mostly likely a direct result of reduced PLA-P water-solubility in comparison with the more highly water-soluble SP-P.

Given the positive environmental attributes of PLA as a P fertilizer source in container crop production, it is important to evaluate the effect of PLA on plant growth and quality. In these experiments, growth differences in lantana were inconsistent between years. In 2011, lantana fertilized with 100% PLA reduced growth indices 33%, 21%, and 24% at 42, 56, and 70 DAP, respectively, compared with those fertilized

with 100% SP. These reductions in growth of PLA-fertilized lantana were accompanied with reduced shoot and root biomasses of 41% and 28% compared with 100% SP-fertilized lantana. As the portion of SP increased, lantana growth and shoot biomass increased. In 2012, shoot dry weight difference between 100%-SP fertilized plants and 100% PLA-fertilized plants declined to 14%, whereas no differences in root biomass were measured. This, along with the fact that shoot:root biomass ratios, which commonly indicate P-deficiency in crops (Mengel and Kirkby, 1987), did not differ between P treatments in either year suggests decreased root growth was the primary factor driving differences in shoot biomass.

More likely, the differences in lantana response to P-fertilization treatments in 2011 and 2012 may be the result of environmental conditions. During 2011, plants were grown at an average daily temperature of 23.7 °C with shorter daylengths compared with 28.4 °C and longer day lengths in 2012. Temperature has been shown to affect vigor and rooting of container grown plants (Mathers et al., 2007). Delayed lantana rooting would have limited root interaction with PLA. Interaction of lantana roots with less soluble P sources, such as PLA, is an important mechanism for releasing P in plant-available forms (Hinsinger, 2001). In a multiyear experiment comparing P fertilizer source and placement on P availability to eucalyptus in an acidic Brazilian oxisol, Dias et al. (2000) reported eucalyptus root systems increased P dissolution rates of low soluble rock phosphates for increased plant uptake. Rhizospheric chemical conditions differ significantly from the surrounding bulk soil or substrate environment because of processes involving ion release, gaseous flux, and exudation of organic ligands. Release of these chemicals around the root alters pH to affect P solubility, thus availability (Hinsinger, 2001). Therefore, environmental factors will greatly affect PLA-P plant availability as a function of root growth and interaction.

The lack of growth and quality differences observed in the postproduction field trial, between lantana fertilized with high- and low-soluble P sources, further highlights the benefits of using low soluble P sources for container plant production. The endpoints for

Table 6. Effects of SP, PLA, and combinations thereof as P sources on biomass accumulation of *Lantana camara* 'New Gold' grown in a closed system over an 84-d experimental period in 2012.

Treatment ^z	Dry wt ^y		
	Shoot (g)	Root (g)	Shoot:root
Control	9.68 b ^x	6.77 b	1.44 b
100:0 SP:PLA	32.56 a	8.88 ab	3.75 a
75:25 SP:PLA	32.59 a	10.19 a	3.22 a
50:50 SP:PLA	38.04 a	10.21 a	3.75 a
25:75 SP:PLA	27.74 a	8.15 ab	3.41 a
0:100 SP:PLA	32.14 a	8.75 ab	3.70 a
	<0.0001 ^w	0.0282	0.0027

^zTreatments were the following: control = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.

^yShoot and root dried biomasses were measured in grams while shoot:root ratio is unitless.

^xValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).

^wP value derived from analysis of variance; NS = not significant.

Table 7. Effects of SP, PLA, and combinations thereof as P sources during greenhouse production on postproduction growth index and shoot biomass dry weight under simulated landscape conditions of *Lantana camara* 'New Gold' in 2012.

Treatment ^z	Growth index ^y								Shoot DW (g)
	0 DAP ^x	7 DAP	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	49 DAP
Control	38.9 b ^w	39.1 b	42.6 b	48.9 b	82.3 b	88.9 b	90.6 b	93.8 b	421.8 a
100:0 SP:PLA	67.9 a	59.9 a	60.5 a	61.4 ab	99.7 a	101.3 a	104.2 a	109.0 a	571.0 a
75:25 SP:PLA	69.9 a	61.1 a	61.1 a	64.1 a	90.4 ab	94.8 ab	97.1 ab	101.3 ab	569.5 a
50:50 SP:PLA	65.1 a	59.2 a	59.2 a	63.4 a	95.4 a	97.6 ab	100.1 ab	103.7 ab	571.3 a
25:75 SP:PLA	68.2 a	58.9 a	59.6 a	63.2 a	93.8 ab	98.0 ab	100.7 ab	104.7 ab	524.7 a
0:100 SP:PLA	61.5 a	61.1 a	56.7 a	60.7 ab	93.9 ab	97.6 ab	100.2 ab	103.7 ab	521.8 a
	<0.0001 ^v	0.0003	0.0032	0.0215	0.0052	0.0434	0.0413	0.049	NS

^zTreatments were the following: control = no exogenous phosphorus (P) applied; SP = superphosphate; PLA = poultry litter ash.

^yGrowth index was measured in centimeters as: [(height + widest width + perpendicular width)/3].

^xDAP = days after potting.

^vValues in columns sharing a letter were not significantly different according to Tukey's Honest Significance Difference test ($\alpha = 0.05$).

^wP value derived from analysis of variance; NS = not significant.

greenhouse grown ornamental crops are either larger containers or constructed landscapes. In either case, postproduction fertilizers, including P, are used to further the crop's effective lifespan and can offset minor differences in growth or flowering observed during production.

Conclusions

Mitigating P losses from container-grown plant production sites poses a challenge to responsible growers in the nursery and greenhouse industries. Recycled P, in the form of low water-soluble biomass ash, such as PLA, has the potential to limit environmental impact of P. Use of PLA in lantana production reduced leachate-DRP concentrations and TP mass losses, by averages of 92% and 69%, respectively, compared with plants fertilized with 100% SP, a highly water-soluble P source. Application of PLA as a P-fertilizer amendment did limit lantana growth and extended the production duration under less-than-suitable environmental conditions. Plant availability of PLA-P, which is influenced by root rhizosphere reactions, may not be suitable for all crops and substrate combinations. However, from an environmental protection standpoint, the benefit of P-loss reduction during container production achieved through PLA application may warrant the acceptance of slight decreases in plant size observed during crop production especially when considering the offset of those slight decreases in postproduction landscapes.

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