Poultry Litter Ash Rate and Placement Affect Phosphorus Dissolution in a Horticultural Substrate[1]

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Abstract

Poultry litter ash (PLA) is a byproduct of bioenergy production and an effective P source for horticultural crops since it reduces P losses from container production due to its low P solubility. Experiments were conducted to determine effects of rate and placement of PLA on P loss from greenhouse crop production and growth and quality of two commonly-grown greenhouse crops, *Verbena canadensis* Britton 'Homestead Purple' and *Lantana camara* L. 'New Gold', by comparing two rates (140 and 280 g·m^{-3} P or 0.4 and 0.8 lb·yd^{-3}) and two application methods (post-plant topdressed and pre-plant incorporated). Leachate-dissolved reactive phosphorus (DRP) concentrations were reduced by an average of 24% as P rate was reduced from 280 to 140 g·m^{-3}, but were 134% less on average when PLA was topdressed instead of incorporated. Foliar P concentrations were less 33% and 44% for verbena and lantana, respectively when plants were topdressed compared to incorporated. Shoot biomass of verbena and lantana was 9% and 24% greater, respectively, when incorporating instead of topdressing PLA. As a P source, PLA should be pre-plant incorporated within the substrate at a total P rate between 140 g·m^{-3} (0.4 lb·yd^{-3}) and 280 g·m^{-3} (0.8 lb·yd^{-3}).

Index words: phosphorus, poultry litter ash, *Verbena canadensis* Britton 'Homestead Purple', *Lantana camara* L. 'New Gold', dissolved reactive phosphorus.

Species used in this study: 'Homestead Purple' verbena (*Verbena canadensis* Britton); 'New Gold' lantana (*Lantana camara* L.).

Significance to the Horticulture Industry

The decline in domestic and global phosphate rock ore reserves may necessitate the adoption of alternative, environmentally-sustainable phosphorus (P) sources for nursery and greenhouse crop production. Previous experiments have shown that poultry litter ash (PLA) supplies adequate concentrations of P to short-term greenhouse crops, improves substrate pH, and reduces P losses compared to a highly water-soluble P source. In the current experiment, application of PLA as a topdressing did not result in lower plant growth parameters in every case, but did result in less flowering and plant P uptake compared with incorporated application of PLA as a substrate amendment. Reduction in plant P uptake resulting from application of PLA as a topdressing compared to application of PLA as a substrate amendment was most likely the result of limited interaction between plant roots and PLA. It is believed the interaction of plant roots is one of the primary mechanisms for P release form PLA. Reductions in P loss concentrations of 5.0 mg·L^{-1} (5 ppm) P, achieved through PLA topdressing, are negligible compared to previously reported reductions in P losses when replacing water-soluble P sources with PLA. Therefore, topdressing is not recommended as the primary application method of PLA due to lower plant growth and quality. For greenhouse crop container production, PLA should be pre-plant incorporated within the substrate at rates (as total P) between 140 g·m^{-3} (0.4 lb·yd^{-3}) and 280 g·m^{-3} (0.8 lb·yd^{-3}).

Introduction

Poultry litter is a biomass source consisting mostly of bird manure and bedding materials (Robinson and Sharpley 1996) and is a waste product from poultry production that is in great abundance in several areas of the United States. It contains higher amounts of phosphorus (P) than ruminant manures since fowls lack the ability to extract organically-bound P from feeds (Woyengo and Nyachoti 2011). Poultry litter has been used as a fertilizer source for many agricultural commodities but its usage has been limited due to associated transportation costs (Bernhart et al. 2010) and environmental concerns for surface and ground water impairment (Sharpley et al. 1994, Sharpley et al. 1998). Repeated land applications of poultry litter based on desired nitrogen application rates has led to P accumulation in soils of poultry-producing regions (Maguire and Mullins 2008) and accelerated eutrophication of adjacent water bodies (White et al. 2010).

Several processes that seek to concentrate nutrients in poultry litter, thereby reducing transportation costs, have been studied. The ultimate goal of each of these processes is to increase geographical areas to which it is economical to transport and spread poultry litter, thereby reducing potential water impairment due to elevated P concentrations in surface waters which often lead to accelerated eutrophication of such waters (Sharpley et al. 1994). Strategies include compaction (Bernhart et al. 2010), pelletization (McMullen 2005), composting (Brodie et al. 2000), P removal (Szogi et al. 2008), gasification (Priyadarsan et al. 2004), and combustion (Codling et al. 2002, Schiemenz and Eichler-Lobermann 2010).

Combusting poultry litter may be the most efficient means to concentrate P and reduce environmental concerns associated with raw poultry litter application because it

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leads to a greater reduction in mass than other processes and renders P less water-soluble, hence less prone to surface runoff when land applied. The combustion process is more complicated for poultry litter than for traditional fuel sources due to inconsistency of litter composition, moisture content, and a relatively high ash content (Jia and Anthony 2011). Combustion has become feasible due to technological advances in incinerator configurations (Habetz and Echols 2006). For example, Fibrominn is a power plant located in Benson, Minnesota that is currently producing 55 MW of energy per year through the co-combustion of poultry litter and wood, with poultry litter constituting more that 60% of the furnace feedstock. The resultant ash is utilized as a nutrient-rich fertilizer for agronomic crops. The majority of the ash content from the furnace feedstock is generated from the poultry litter (IPEP 2006, Jia and Anthony 2011) since wood has a low ash content (Misra et al. 1993).

Few experiments have investigated the potential of poultry litter ash (PLA) as a fertilizer amendment. In a laboratory experiment, Codling (2006) reported that PLA contained high concentrations of P, but that most PLA-P was water-insoluble. However, PLA was a successful P source for wheat (*Triticum aestivum* L) in a previous experiment (Codling et al. 2002). Faridullah et al. (2009) reported chicken and duck litter ashes to be suitable nutrient sources for Japanese mustard spinach (*Brassica rapa* L.) grown on a sandy soil. Bachmann and Eichler-Lobermann (2010) reported that PLA supplied adequate amounts of P to buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), and Westerwolths ryegrass (*Lolium multiflorum westerwoldicum* Gordo) while also enriching soil-P pools. More recently, PLA has been utilized as a P source for verbena (*Verberna canadensis* Britton 'Homestead Purple') and lantana (*Lantana camara* L. 'New Gold') (Wells et al. 2013) and has been shown to reduce total-P mass loss and leachate-dissolved reactive phosphorus (DRP) concentrations when compared to a highly water-soluble P source during greenhouse production (Wells et al. 2017).

While PLA application reduces P losses from a soilless substrate compared with a water-soluble P source when incorporated within the substrate, no studies have characterized the effect PLA placement has on plant growth and P leaching losses. In a related experiment, Warren et al. (1997) reported reductions of more than 80% of total phosphorus in leachate (leachate-TP) when controlled release fertilizers (CRFs) were surface applied to a soilless substrate, as opposed to incorporated within the substrate. In 2001, Warren et al. (2001) concluded increases in P-leaching, due to increased P solubility, was a result of either more uniform dispersal of, or increased moisture surrounding incorporated fertilizer prills, compared with those that were surface-applied. Therefore, the objective of this experiment was to characterize the effects of PLA application rate and placement have on plant growth, quality, and leachate-P concentrations during greenhouse crop production.

Materials and Methods

Experiment setup. Forty *Lantana camara* L. 'New Gold' and *Verbena canadensis* Britton 'Homestead Purple' plants growing in 105-cell trays were selected for uniform quality and size prior to the initiation of experiments on September 6, 2011 and February 29, 2012. For each species, two plants were transplanted into 20 1.6-L (6-in azalea) containers for a total of 40 containers. Substrate was composed of amended pine bark, screened to <0.95 cm (<3/8 in), and peat moss (4:1 v:v). Pre-plant incorporated amendments, common to all treatments, were 0.89 kg·m^{-3} (1.5 lb·yd^{-3}) of a micronutrient package (Micromax, Scotts Company, Marysville, OH), 0.25 kg·m^{-3} (0.8 lb·yd^{-3})K (0-0-43; 0N-0P-35.7K), and 1.5 kg·m^{-3} (5 lb·yd^{-3}) pulverized dolomitic limestone. Phosphorus treatment source was PLA (10% total P), obtained courtesy of North American Fertilizer, LLC (Benson, MN), which was either pre-plant incorporated or post-plant topdressed uniformly on the substrate surface, at either 140 or 280 g·m^{-3} P (0.4 or 0.8 lb·yd^{-3})). Containers were arranged in a 2 (P rate) by 2 (PLA placement) factorial experiment in a completely randomized design with five single container replications. Treatments were: (1) pre-plant incorporated PLA at 280 g·m^{-3} P (2) pre-plant incorporated PLA at 140 g·m^{-3} P (3) post-plant topdressed PLA at 280 g·m^{-3} P (4) post-plant topdressed PLA at 140 g·m^{-3} P. All plants were maintained under greenhouse conditions at averages of 24 C (75 F) and 28 C (82 F) in 2011 and 2012, respectively, with no supplemental irradiance, for 42 and 70 d for verbena and lantana, respectively. During the experiment, plants were supplied with 350 ml·d^{-1} water including 120 ml·container^{-1} aliquots of NH_4NO_3 (aq.) at 250 mg·L^{-1} (250 ppm) N.

Plant response. Growth was measured bi-weekly using a growth index [(height + widest width + perpendicular width) / 3]. Flowers were quantified bi-weekly in 2012 by counting flower buds showing color. At the end of each experimental period, shoots and roots were harvested, separated with roots washed to remove substrate, dried at 60 C (140 F) for 72 hours, and biomass recorded. Leaf samples of 0.5 g (0.02 oz), composed of the most recently matured leaves, were milled to <0.5 mm (<0.02 in) (Thomas Wiley® Mini-Mill; Thomas Scientific, Swedesboro, NJ) and digested in concentrated nitric acid at an average temperature of 120 C (248 F). Samples were then diluted to 20 ml with deionized water, vortexed, and filtered before being analyzed for plant-essential elements, excluding C, N, and O, using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Spectro ArCos; SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA).

Leachate collection and P analyses. Leachate from three replicates per treatment of *Lantana camara* L. 'New Gold' was collected weekly following the Virginia Tech Pour-Thru Method (Wright 1986). Leachate samples were cooled to room temperature (21 C; 69.8 F) and leachate-pH and EC measured (Orion Star A215 solution analyzer,

Table 1. Effects of poultry litter ash rate and placement on growth index of container-grown *Verbena canadensis* 'Homestead Purple' over a 42-d experimental period in 2011.

Rate ($g\ m^{-3}$)	Placement[z]	Growth Index 2011[y] 14 DAP[x]	28 DAP	42 DAP	Average
140	-	14.78	16.80	27.70	19.76
280	-	13.13	14.84	26.58	18.18
		0.0483[w]	*NS*	*NS*	*NS*
-	Topdressed	12.41	13.93	25.55	17.30
-	Incorporated	15.50	17.71	28.73	20.65
		0.0011	*0.0013*	*NS*	*0.019*
140	Topdressed	13.65	15.63	27.10	18.79
280	Topdressed	11.17	12.23	24.00	15.80
140	Incorporated	15.92	17.97	28.30	20.73
280	Incorporated	15.08	17.45	29.17	20.57
		NS	*NS*	*NS*	*NS*
Rate ($g\ m^{-3}$)	**Placement**	**Growth Index 2012 14 DAP**	**28 DAP**	**42 DAP**	**Average**
140	-	17.93	33.00	38.35	29.76
280	-	18.46	35.94	44.76	33.06
		NS	-	-	*NS*
-	Topdressed	14.15	33.67	41.78	29.87
-	Incorporated	22.24	35.28	41.33	32.95
		0.0007	-	-	*NS*
140	Topdressed	14.61	36.47ab[v]	41.36b	30.81
280	Topdressed	13.69	30.86b	42.19ab	28.92
140	Incorporated	21.25	29.53b	35.33c	28.70
280	Incorporated	23.22	41.03a	47.33a	37.19
		NS	*0.0006*	*0.0027*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Growth index was measured in cm as: [(Height + widest width + perpendicular width) / 3].

[x]Days after potting.

[w]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[v]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

Thermo Scientific Inc., Beverly, MA). In the laboratory, a 15 ml aliquot from each leachate sample was filtered through a 0.45 μm disposable nylon filter (22 mm diameter, Whatman™; GE Healthcare UK Limited, Buckinghamshire) in preparation for dissolved reactive phosphorus (DRP) analysis. Samples were then analyzed for DRP using the molybdate colorimetric method developed by Murphy and Riley (1962) and modified by Pote and Daniel (2000).

Statistical analysis. Lantana and verbena were arranged separately in completely randomized designs with five replicates on raised benches in a greenhouse. Growth index, flower counts, plant dry weights, leachate-pH and EC, leachate-DRP, and tissue nutrient concentrations were subjected to analysis of variance in SAS (SAS Institute Inc. 2011) by year using PROC MIXED. Means for each measurement at each collection date, and for the total experiments, were separated using Tukey's Honest Significant Difference Test at a significance level of 0.05. If interactions between factors occurred for a particular response at a measurement date, simple effects are described. If interactions did not occur, main effects are described.

Table 2. Effects of poultry litter ash rate and placement on flower counts of container-grown *Verbena canadensis* 'Homestead Purple' over a 42-d experimental period in 2012.

Rate ($g\ m^{-3}$)	Placement[z]	Flower Counts[y] 14 DAP[x]	28 DAP	42 DAP	Total
140	-	9	16	21	46
280	-	8	17	24	49
		-	*NS*[w]	*NS*	*NS*
-	Topdressed	8	15	19	42
-	Incorporated	10	18	25	53
		-	*NS*	*0.0212*	*0.0026*
140	Topdressed	9a[v]	15	19	43
280	Topdressed	6b	16	19	41
140	Incorporated	9a	18	22	49
280	Incorporated	11a	19	28	57
		0.0033	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Flower buds showing color.

[x]Days after potting.

[w]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[v]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

Results and Discussion

Plant response of verbena. In general, growth index of verbena was not affected by P rate in 2011 (Table 1). Over the 42-day experiment, average growth index was 19% greater when verbena were fertilized with incorporated PLA (20.65) compared with PLA applied as a topdressing (17.3). While individual factors did not generally affect growth index of verbena in 2012, an interesting interaction occurred in which increasing PLA application rate increased growth index of verbena fertilized with incorporated PLA from 29.53 to 41.03 at 28 DAP and from 35.33 to 47.33 at 42 DAP, but did not increase growth of verbena fertilized with PLA as a topdressing. In 2012, verbena flower count was not affected by PLA application rate but was 53.33 when PLA was incorporated, 26% greater than that seen with topdressing (42.17) (Table 2).

In 2011, shoot biomass was slightly increased, from 15.45 to 16.85 g when PLA application rate was decreased from 280 to 140 $g \cdot m^{-3}$ P (Table 3). It is not clear from the data why a lower P rate led to greater plant growth, but it is interesting that an identical increase in biomass was observed when PLA was incorporated into the substrate, as opposed to applied as a topdressing. Root biomass followed the same trends almost exactly, but an interaction was observed in which verbena root biomass increased 74% from 2.86 to 4.99 g when PLA application rate decreased from 280 to 140 $g \cdot m^{-3}$ P and PLA was applied as a topdressing, but was unaffected by PLA application rate when PLA was incorporated into the substrate (Table 3). While this is an interesting interaction, it is not abundantly clear from the data we collected why this trend was observed. We suspect that high salt concentrations at the substrate surface, due to topdressing PLA, limited root

Table 3. Effects of poultry litter ash rate and placement on biomass accumulation of container-grown *Verbena canadensis* 'Homestead Purple' over a 42-d experimental period.

Rate ($g\ m^{-3}$)	Placement[z]	2011 Shoot[y] (g)	Root (g)	Shoot:Root
140	-	16.85	5.27	3.23
280	-	15.45	3.91	4.14
		0.005[x]	-	-
-	Topdressed	15.45	3.92	4.11
-	Incorporated	16.85	5.26	3.25
		0.005	-	-
140	Topdressed	16.30	4.99a[w]	3.28b
280	Topdressed	14.60	2.86b	4.95a
140	Incorporated	17.40	5.56a	3.18b
280	Incorporated	16.30	4.96a	3.32b
		NS	*0.0067*	*<0.0001*
Rate ($g\ m^{-3}$)	**Placement**	**2012 Shoot**	**Root**	**Shoot:Root**
140	-	24.10	10.43	2.32
280	-	25.17	8.92	2.82
		-	*0.0122*	*0.0088*
-	Topdressed	23.53	9.38	2.54
-	Incorporated	25.74	9.98	2.60
		-	*NS*	*NS*
140	Topdressed	24.02b	10.33	2.34
280	Topdressed	23.04b	8.43	2.74
140	Incorporated	24.18b	10.53	2.30
280	Incorporated	27.30a	9.42	2.90
		0.0038	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Shoot and root dried biomasses were measured in grams while Shoot:Root ratio is unitless.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

Table 4. Effects of poultry litter ash rate and placement on foliar nutrient concentrations of container-grown *Verbena canadensis* 'Homestead Purple' grown in an experiment lasting 42 days.

Rate ($g\ m^{-3}$)	Placement[z]	2011 Ca[y] %	Mg %	Mn $mg \cdot kg^{-1}$	P %	K %
140	-	1.41	0.68	149.27	0.23	1.97
280	-	1.12	0.63	132.07	0.29	2.66
		0.0084[x]	*0.0103*	*0.0285*	*0.0192*	*0.0025*
-	Topdressed	1.10	0.66	208.09	0.23	2.71
-	Incorporated	1.42	0.65	73.25	0.29	1.92
		0.0054	*NS*	*<0.0001*	*0.0093*	*0.0012*
140	Topdressed	1.18	0.66	214.38	0.20	2.35
280	Topdressed	1.04	0.64	201.80	0.25	3.07
140	Incorporated	1.63	0.71	84.17	0.26	1.59
280	Incorporated	1.20	0.62	62.34	0.32	2.25
		NS	*NS*	*NS*	*NS*	*NS*
		2012 Ca %	**Mg %**	**Mn $mg \cdot kg^{-1}$**	**P %**	**K %**
140	-	0.74	0.45	102.58	0.27	1.67
280	-	0.67	0.45	87.34	0.29	1.85
		NS	*NS*	*NS*	*NS*	-
-	Topdressed	0.83	0.41	118.61	0.23	1.76
-	Incorporated	0.58	0.49	71.32	0.32	1.76
		NS	*NS*	*0.0003*	*0.0001*	-
140	Topdressed	0.67	0.39	117.57	0.21	1.50b[w]
280	Topdressed	0.50	0.43	119.65	0.25	2.03a
140	Incorporated	0.82	0.52	87.59	0.32	1.84ab
280	Incorporated	0.84	0.46	55.04	0.33	1.67ab
		NS	*NS*	*NS*	*NS*	*0.0022*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Macronutrients reported as percentage of dry matter. Mn reported in $mg \cdot kg^{-1}$ dry matter.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

growth in the early stages of growth. As salts were leached through watering, root growth increased, but those roots that were exposed to the highest topdressed P rate were not able to catch up in growth to other treatments. Phosphorus rate did not affect root growth when PLA was incorporated likely because incorporation lessened the initial high salt concentrations on young roots by spreading the PLA throughout the entire substrate volume.

Shoot:root biomass ratio can be used as an indicator of P stress in many species (Mengel and Kirkby 1987). In 2011, there was an interaction for verbena shoot:root ratio in which an increase in P rate increased shoot:root ratio from 3.28 to 4.95 when PLA was topdressed, but there was not a significant increase in shoot:root ratio when PLA was incorporated into the substrate (Table 3). In 2012, shoot:root ratio increased slightly, from 2.32 to 2.82, when P rate was increased from 140 to 280 $g \cdot m^{-3}$ P. No interaction between P rate and application method was observed in 2012. In the case of verbena in this experiment, root:shoot ratio was not a good indicator of plant P status. The interaction observed in 2011 can be explained by the low root biomass observed at the highest P rate when PLA was topdressed. As previously discussed, it is likely that high salt concentrations near the surface of the substrate, encountered by young verbena roots in the highest topdressed P rate treatment, limited early root growth. The shoot growth was not limited as much, so while there was not an observed statistical interaction for shoot biomass, identical interactions were observed for root biomass and shoot:root biomass ratio.

Tissue nutrient accumulation of verbena. A better indicator of P uptake than shoot:root ratio is foliar P concentration. Phosphorus uptake was increased, from 0.23% to 0.29%, by both increasing P rate and by incorporating PLA within the substrate in 2011 (Table 4). In 2012, foliar P concentration was increased, from 0.23% to 0.32%, by incorporating PLA within the substrate instead of topdressing PLA. It is likely that increased root interaction with PLA within the substrate led to the increased P uptake observed in both years.

When PLA was incorporated, foliar Mn was 73.25 $mg \cdot kg^{-1}$ in 2011 and 71.32 in 2012, 65% and 40% lower, respectively, than when PLA was topdressed. According to

Table 5. Effects of poultry litter ash rate and placement on root nutrient concentrations of container-grown *Verbena canadensis* 'Homestead Purple' grown in an experiment lasting 42 days.

Rate ($g\ m^{-3}$)	Placement[z]	Ca[y] %	Mg %	Mn $mg{\cdot}kg^{-1}$	P %	K %
140	-	0.25	0.20	103.43	0.16	1.42
280	-	0.24	0.19	136.01	0.24	2.01
		NS[w]	*NS*	*NS*	*0.0197*	*0.0117*
-	Topdressed	0.26	0.20	209.00	0.15	1.99
-	Incorporated	0.23	0.19	30.44	0.25	1.44
		NS	*NS*	*0.0007*	*0.0047*	*0.0161*
140	Topdressed	0.26	0.20	172.91	0.12	1.74
280	Topdressed	0.27	0.20	245.07	0.18	2.25
140	Incorporated	0.24	0.20	33.94	0.20	1.11
280	Incorporated	0.22	0.18	26.95	0.29	1.78
		NS	*NS*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Macronutrients reported as percentage of dry matter. Mn reported in $mg{\cdot}kg^{-1}$ dry matter.

[w]P-value derived from analysis of variance; NS = not significant.

Mills and Jones (2014), the optimum range for foliar Mn in 'Homestead Purple' verbena is 59 – 124 $mg{\cdot}kg^{-1}$ so this decrease in foliar Mn when PLA was incorporated was not problematic. On the other hand, foliar Mn was higher than optimal in 2011 (208.09 $mg{\cdot}kg^{-1}$). High concentrations of Mn are sometimes accompanied by foliar symptoms and reduced plant quality (Mills and Jones 2014), but such symptoms were not observed in this experiment. Foliar Ca concentration was decreased with increasing P rate, from 1.41% to 1.12%, and increased by incorporation, from 1.10% to 1.42%, in 2011, but was not affected by P rate or application method in 2012. Increased calcium uptake often corresponds with decreased Mn uptake (Mills and Jones, 2014), which is most often due to the effect of calcium-containing compounds on substrate pH. As pH increases, Mn uptake decreases. In this experiment, this was true due to PLA application method in 2011. When PLA was incorporated within the substrate foliar Ca concentration increased by 29% while foliar Mn concentration decreased by 65%. This trend was not observed in 2012. Potassium uptake often antagonizes Ca and Mg uptake in plants (Mills and Jones 2014). In 2011, foliar K increased 35% as P rate increased which corresponded to a 21% decrease in foliar Ca. Similarly in 2011, foliar K decreased 29% when PLA was incorporated, corresponding to a 29% increase in foliar Ca. In 2012, an interaction in which foliar K increased as P rate increased when PLA was topdressed, but foliar K concentration did not increase with increasing P rate when PLA was incorporated. Similar trends were not observed for foliar Ca or Mg in 2012.

Root nutrient concentrations in 2012 followed similar patterns to foliar nutrients (Table 5). Root P concentrations increased 50% and 67% when P rate was increased and when PLA was incorporated into the substrate, respectively. Root Mn concentration was decreased 85% when PLA was incorporated into the substrate. This is an interesting finding that translated somewhat to foliar Mn, a more important indicator of Mn uptake; however it is unclear to what extent these data should be cause for concern. Root K concentrations were affected by both P rate and PLA application method in 2012. Root K increased 41% and 33% when P rate was increased and PLA was topdressed, respectively.

Plant response of lantana. Increasing PLA application rate from 140 to 280 $g{\cdot}m^{-3}$ P reduced the lantana growth index from 15.7 to 11.95 at 28 DAP and from 17.43 to 13.35 at 42 DAP in 2011, but generally did not elicit the same response in 2012 (Table 6). The reason for the smaller growth index at 28 and 42 DAP in 2011 is unclear from these data, but may be due to high salt concentrations at the highest P rate. As salts were leached over time, growth differences based on P rate and application method disappeared. In 2012, at 14, 28, and 42 DAP, the growth index of lantana increased as P rate increased when PLA was incorporated, but did not increase when P rate was increased and PLA was topdressed. Although PLA placement did not affect growth index of lantana in 2011, lantana growth index was 18.6% greater when PLA was incorporated (34.48) instead of topdressed (29.06). For the experiment, total flower number increased 10% from 419 to 461 when P rate increased and PLA was incorporated, but did not increase with increasing P rate when PLA was topdressed (Table 7).

Shoot biomass of lantana was not affected by P rate in 2011 or 2012 (Table 8). However, shoot biomass of lantana was 32% and 16% greater when PLA was incorporated instead of topdressed in 2011 and 2012, respectively. Root biomass of lantana was decreased from 4.48 to 3.17 g in 2011 when PLA application rate increased from 140 to 280 $g{\cdot}m^{-3}$ P, but no differences in root biomass were observed between PLA application rates in 2012. However, in 2012 lantana root biomass was slightly greater (9.95 g) when PLA was topdressed as opposed to incorporated (8.78). No consistent trend was observed for shoot:root biomass between years.

Tissue nutrient accumulation of lantana. In this case, growth differences may be explained by nutrient uptake. Similar to verbena nutrient uptake results, lantana foliar Mn and P concentrations were affected by PLA rate and placement (Table 9). As PLA application rate increased from 140 to 280 $g{\cdot}m^{-3}$ P, lantana foliar Mn concentrations decreased 26% to 155.84 $mg{\cdot}kg^{-1}$ and 27% to 137.25 $mg{\cdot}kg^{-1}$ in 2011 and 2012, respectively. Similarly, and more markedly, foliar Mn concentration decreased 41% to 134.97 $mg{\cdot}kg^{-1}$ and 120.45 $mg{\cdot}kg^{-1}$ in 2011 and 2012, respectively when PLA was incorporated into the substrate as opposed to topdressed.

Similar, yet opposite trends were observed for lantana foliar P concentrations. Lantana foliar P concentrations were 0.28% and 0.32% (Table 9), increases of 12% and 23% in 2011 and 2012, respectively as P application rate increased from 140 to 280 $g{\cdot}m^{-3}$. When PLA was incorporated into the substrate foliar P concentrations were 0.32% and 0.34%, increases of 45% and 42% in 2011 and 2012, respectively compared to topdressed PLA. Incorporating PLA into the substrate also decreased root Mn

Table 6. **Effects of poultry litter ash rate and placement on growth index of container-grown *Lantana camara* 'New Gold' over a 70-d experimental period.**

Rate ($g\ m^{-3}$)	Placement[z]	Growth Index[y] 2011 14 DAP[x]	28 DAP	42 DAP	56 DAP	70 DAP	Average
140	-	13.65	15.70	17.43	32.10	36.00	22.98
280	-	10.50	11.95	13.35	26.70	29.53	18.41
		NS[w]	*0.045*	*0.039*	*NS*	*NS*	*NS*
-	Topdressed	10.93	12.50	14.0	26.93	30.63	19.00
-	Incorporated	13.22	15.15	16.78	31.87	34.90	22.38
		NS	*NS*	*NS*	*NS*	*NS*	*NS*
140	Topdressed	12.93	15.47	17.27	31.07	34.47	22.24
280	Topdressed	8.93	9.53	10.73	22.80	26.80	15.76
140	Incorporated	14.37	15.93	17.60	33.13	37.53	23.71
280	Incorporated	12.07	14.37	15.97	30.60	32.27	21.05
		NS	*NS*	*NS*	*NS*	*NS*	*NS*
Rate ($g\ m^{-3}$)	**Placement**	**Growth Index 2012 14 DAP**	**28 DAP**	**42 DAP**	**56 DAP**	**70 DAP**	**Average**
140	-	10.82	19.5	31.53	45.39	50.53	31.55
280	-	12.35	21.85	30.61	45.25	49.89	31.99
		-	-	-	*NS*	*NS*	*NS*
-	Topdressed	9.79	18.74	29.52	42.68	44.58	29.06
-	Incorporated	13.38	22.61	32.62	47.96	55.83	34.48
		-	-	-	*0.03*	*0.0228*	*0.0275*
140	Topdressed	9.78b[v]	19.86b	32.9a	44.92	47.50	30.87
280	Topdressed	9.81b	17.61b	26.75b	40.44	41.67	27.26
140	Incorporated	11.86b	19.14b	30.78ab	45.86	53.56	32.24
280	Incorporated	14.89a	26.08a	34.46a	50.06	58.11	36.72
		0.0444	*0.0008*	*0.0051*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Growth index was measured in cm as: [(Height + widest width + perpendicular width) / 3].

[x]Days after potting.

[w]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[v]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test (α = 0.05).

concentrations and increased root P concentrations by 50% in 2012 (Table 10).

Substrate leachate-pH and EC. An interaction was observed in average substrate pH over the entirety of the experiments in both 2011 and 2012 in which pH increased as P rate increased when PLA was incorporated, but did not increase with increasing P rate when PLA was topdressed (Table 11). The same type of interaction was not observed for substrate leachate-EC (Table 12). Over the entirety of the experiments in 2011 and 2012 EC increased as P rate increased and decreased as PLA was incorporated. It was

Table 7. **Effects of poultry litter ash rate and placement on flower counts of container-grown *Lantana camara* 'New Gold' over a 70-d experimental period.**

Rate ($g\ m^{-3}$)	Placement[z]	Flower Counts[y] 14 DAP[x]	28 DAP	42 DAP	56 DAP	70 DAP	Total
140	-	24	47	131	98	107	407
280	-	26	43	131	96	116	412
		NS[w]	-	*NS*	-	-	-
-	Topdressed	24	36	122	90	106	378
-	Incorporated	26	53	141	103	117	440
		NS	-	*0.002*	-	-	-
140	Topdressed	24	43b[v]	123	97ab	108b	394bc
280	Topdressed	24	30c	121	83b	103b	361c
140	Incorporated	24	51ab	140	99ab	106b	419b
280	Incorporated	28	55a	141	108a	128a	461a
		NS	*0.0064*	*NS*	*0.0176*	*0.0024*	*0.0069*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Flower buds showing color.

[x]Days after potting.

[w]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[v]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test (α = 0.05).

Table 8. **Effects of poultry litter ash rate and placement on biomass accumulation of container-grown *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.**

Rate ($g\ m^{-3}$)	Placement[z]	Shoot[y] (g)	Root (g)	Shoot:Root
		2011		
140	-	10.19	4.48	3.21
280	-	8.76	3.17	2.31
		NS[x]	*0.0194*	*0.0092*
-	Topdressed	8.18	3.40	2.86
-	Incorporated	10.78	4.24	2.66
		0.0239	*NS*	*NS*
140	Topdressed	9.36	4.00	2.45
280	Topdressed	6.99	2.79	3.27
140	Incorporated	11.03	4.95	2.17
280	Incorporated	110.53	3.54	3.16
		NS	*NS*	*NS*
		2012		
Rate ($g\ m^{-3}$)	**Placement**	**Shoot (g)**	**Root (g)**	**Shoot:Root**
140	-	25.99	9.62	2.59
280	-	24.79	9.11	2.62
		NS	*NS*	*NS*
-	Topdressed	23.50	9.95	2.31
-	Incorporated	27.23	8.78	2.90
		0.0357	*0.0368*	*0.0004*
140	Topdressed	25.01	10.21	2.40
280	Topdressed	21.90	9.70	2.22
140	Incorporated	26.88	9.02	2.78
280	Incorporated	27.57	8.53	3.02
		NS	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Shoot and root dried biomasses were measured in grams while Shoot:Root ratio is unitless.

[x]P-value derived from analysis of variance; NS = not significant.

Table 9. **Effects of poultry litter ash rate and placement on foliar nutrient concentrations of container-grown *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.**

Rate ($g\ m^{-3}$)	Placement[z]	Ca[y] %	Mg %	Mn $mg{\cdot}kg^{-1}$	P %	K %
		2011				
140	-	0.74	0.41	209.62	0.25	2.23
280	-	0.78	0.39	155.84	0.28	2.29
		NS[x]	*NS*	*<0.0001*	*0.0006*	*NS*
-	Topdressed	0.65	0.41	230.49	0.22	2.31
-	Incorporated	0.86	0.39	134.97	0.32	2.21
		0.0139	*NS*	*<0.0001*	*<0.0001*	*NS*
140	Topdressed	0.67	0.42	258.79	0.20	2.34
280	Topdressed	0.63	0.41	202.20	0.23	2.28
140	Incorporated	0.80	0.41	160.45	0.30	2.12
280	Incorporated	0.92	0.37	109.48	0.33	2.31
		NS	*NS*	*NS*	*NS*	*NS*
		2012				
		Ca %	**Mg %**	**Mn $mg{\cdot}kg^{-1}$**	**P %**	**K %**
140	-	0.69	0.30	188.30	0.26	1.40
280	-	0.71	0.33	137.25	0.32	1.44
		-	-	*0.0003*	*0.0035*	*NS*
-	Topdressed	0.62	0.27	205.10	0.24	1.47
-	Incorporated	0.78	0.37	120.45	0.34	1.37
		-	-	<0.0001	0.0002	NS
140	Topdressed	0.66b[w]	0.27c	237.90a	0.22	1.48
280	Topdressed	0.57c	0.27c	172.29	0.26	1.46
140	Incorporated	0.71b	0.33b	138.70	0.29	1.32
280	Incorporated	0.85a	0.40a	102.20	0.39	1.41
		<0.0001	*0.0188*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Macronutrients reported as percentage of dry matter. Mn reported in $mg{\cdot}kg^{-1}$ dry matter.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

not surprising that EC increased as P rate increased, since EC typically increases with increased fertilizer application rate (Fain et al. 2008). Increased EC topdressed treatments were unexpected but may be the result of increased interaction of PLA with irrigation water. Direct contact with irrigation water would have increased solubility of ancillary salts that could have limited substrate and root interactions, resulting in greater EC measurements compared to incorporated PLA treatments.

Leachate-DRP. As P rate increased from 140 to 280 $g{\cdot}m^{-3}$, leachate-DRP leachate concentrations were 7.14 $mg{\cdot}L^{-1}$ P and 6.69 $mg{\cdot}L^{-1}$ P, increases of 30% and 18%, in 2011 and 2012, respectively (Tables 13 and 14, respectively). Leachate-DRP losses were not proportionate to PLA application rate increases. Although both main effects of P rate and PLA placement were significant for leachate-DRP concentration, PLA placement method had a more pronounced effect in both years compared to P application rate. On average, leachate-DRP concentration was increased 127% and 141% in 2011 and 2012, respectively, when PLA was incorporated into the substrate as opposed to topdressed. While the percent increase is large, actual concentrations of leachate-DRP were lower than what is typically measured from more water-soluble P forms. From

Table 10. **Effects of poultry litter ash rate and placement on root nutrient concentrations of container-grown *Lantana camara* 'New Gold' grown in an experiment lasting 70 days in 2011.**

Rate ($g\ m^{-3}$)	Placement[z]	Ca[y] %	Mg %	Mn $mg{\cdot}kg^{-1}$	P %	K %
140	-	0.25	0.23	79.34	0.11	0.21
280	-	0.26	0.25	55.27	0.13	0.25
		NS[w]	*NS*	*0.008*	*0.0015*	*0.0174*
-	Topdressed	0.23	0.23	89.45	0.10	0.22
-	Incorporated	0.28	0.25	45.16	0.15	0.24
		NS	*NS*	*0.0002*	*<0.0001*	*NS*
140	Topdressed	0.23	0.24	99.46	0.09	0.20
280	Topdressed	0.23	0.23	79.45	0.10	0.24
140	Incorporated	0.28	0.23	59.23	0.13	0.22
280	Incorporated	0.29	0.27	31.10	0.16	0.26
		NS	*NS*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Macronutrients reported as percentage of dry matter. Mn reported in $mg{\cdot}kg^{-1}$ dry matter.

[w]P-value derived from analysis of variance; NS = not significant.

Table 11. **Effects of poultry litter ash rate and placement on substrate leachate-pH measured from container-grown *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.**

Rate ($g\ m^{-3}$)	Placement[z]	Substrate Leachate-pH									
		2011									
		7 DAP[y]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	Average
140	-	6.01	6.02	6.48	6.74	6.54	6.26	6.32	6.44	6.26	6.34
280	-	6.00	6.06	6.56	6.81	6.81	6.39	6.48	6.45	6.42	6.44
		-	*NS*[x]	*NS*	-	*0.0086*	*NS*	*0.0122*	-	-	-
-	Topdressed	5.83	5.71	6.36	6.68	6.55	6.26	6.37	6.37	6.21	6.26
-	Incorporated	6.19	6.37	6.68	6.88	6.80	6.39	6.43	6.2	6.48	6.53
		-	*0.0005*	*0.0019*	-	*0.0128*	*NS*	*NS*	-	-	-
140	Topdressed	6.05ab[w]	5.78	6.38	6.77ab	6.46	6.19	6.28	6.50b	6.21b	6.29b
280	Topdressed	5.60c	5.63	6.33	6.58b	6.65	6.32	6.45	6.23b	6.20b	6.22b
140	Incorporated	5.98bc	6.26	6.57	6.71ab	6.63	6.32	6.36	6.39b	6.31b	6.39b
280	Incorporated	6.40a	6.48	6.79	7.05a	6.96	6.47	6.51	6.66a	6.64a	6.66a
		0.0014	*NS*	*NS*	*0.0322*	*NS*	*NS*	*NS*	*0.0484*	*0.0154*	*0.0181*
		2012									
140	-	5.68	6.02	6.21	6.32	6.54	6.58	6.51	6.42	6.31	6.29
280	-	5.82	6.00	6.36	6.50	6.67	6.77	6.73	6.60	6.58	6.50
		-	-	-	*0.0007*	*0.0265*	-	-	*0.0007*	-	-
-	Topdressed	5.59	5.84	6.12	6.28	6.41	6.42	6.57	6.35	6.25	6.20
-	Incorporated	5.92	6.18	6.46	6.53	6.80	6.79	6.66	6.67	6.58	6.58
		-	-	-	*<0.0001*	*<0.0001*	-	-	*<0.0001*	-	-
140	Topdressed	5.75b	6.01b	6.09c	6.21	6.32	6.31c	6.35b	6.25	6.08c	6.15b
280	Topdressed	5.42b	5.67c	6.15c	6.35	6.51	6.53bc	6.80a	6.44	6.42b	6.25b
140	Incorporated	5.62b	6.03b	6.33b	6.42	6.77	6.85a	6.67a	6.58	6.55b	6.42b
280	Incorporated	6.22a	6.32a	6.58a	6.64	6.82	6.74ab	6.65a	6.77	6.61a	6.74a
		0.0007	*0.0005*	*0.0454*	*NS*	*NS*	*0.0213*	*<0.0001*	*NS*	*0.0031*	*0.0025*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Days after potting.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

a previous experiment, we reported that PLA decreased average leachate-DRP concentrations by more than 90% when compared to a more water-soluble P source (Wells et al. 2017).

In general, placement of PLA had a greater effect on P uptake than did P rate. In verbena, there was a significant increase in growth as P rate decreased from 140 to 280 in 2011, but rate was not a significant factor in lantana growth in either year. Placement was significant for both species in 2011 and for lantana in 2012 as incorporated PLA increased growth compared to topdress applications. The growth differences may be best explained by foliar P concentrations and leachate-DRP concentrations. Incorporation of PLA within the substrate increased foliar P concentrations of verbena by 26% and 39% in 2011 and 2012, respectively, and in lantana by and 45% and 42% in 2011 and 2012, respectively. Incorporation of PLA also increased average leachate-DRP 127% and 141% in 2011 and 2012, respectively, compared to topdressed PLA. Leachate-DRP concentration is a good estimate of P availability within the substrate, hence the increase in P uptake when more P was available in the substrate. As reported from a previous experiment, PLA decreased average leachate-DRP concentrations by more than 90% when compared to a more water-soluble P source (Wells et al. 2017) so utilization of PLA as a P source would greatly reduce P losses from greenhouse crop production.

In the current study, given the nature of P uptake by plants, it is likely that root system-PLA interactions accelerated P dissolution and plant uptake. According to Dias and others (2000) phosphorus uptake was increased through root system interaction with low soluble rock phosphates in a multi-year experiment evaluating P source and placement on eucalyptus growth in an acidic soil. Processes, including ion release, gaseous flux, and organic ligand exudation, can alter rhizospheric chemical conditions in order to enhance P solubility and uptake from soils (Hinsinger 2001). While rhizospheric chemical parameters were not measured directly in this experiment, based on plant tissue analyses, greater uptake was most likely a result of increased root and P interaction from PLA incorporated within the substrate. In addition to root-P interactions, organic acids within the substrate, not originating from plant roots, may have also affected P solubility (Bolan et al. 1994).

In either case, P concentrations in plant biomass were greater when PLA was incorporated into the substrate compared to topdressed. In contrast, topdressed PLA likely remained at or near the substrate surface during the experiment and limited PLA-root interactions. Consequently, leachate-DRP and biomass P concentrations were reduced when PLA was topdressed as opposed to incorporated within the substrate. In a previous related experiment, tissue nutrient concentrations, including shoot and root P, were increased when controlled-release

Table 12. Effects of poultry litter ash rate and placement on substrate leachate-EC measured in container-grown *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.

Rate ($g\ m^{-3}$)	Placement[z]	Substrate Leachate-EC									
		2011									
		7 DAP[y]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	Average
140	-	2.00	1.97	1.79	1.56	1.70	1.83	1.13	0.75	0.42	1.46
280	-	2.81	2.54	2.40	2.22	1.97	2.15	1.13	0.89	0.58	1.85
		0.0001[x]	*<0.0001*	-	-	*NS*	*0.0091*	*NS*	*NS*	*NS*	*0.0183*
-	Topdressed	2.60	2.49	2.37	2.20	2.18	2.37	1.19	0.83	0.48	1.86
-	Incorporated	2.21	2.02	1.82	1.58	1.49	1.61	1.06	0.81	0.52	1.46
		0.0091	*0.0001*	-	-	*0.014*	*<0.0001*	*NS*	*NS*	*NS*	*0.0172*
140	Topdressed	2.18	2.14	1.97bc[w]	1.73b	2.03	2.20	1.25	0.79	0.46	1.63
280	Topdressed	3.02	2.84	2.78a	2.67a	2.32	2.53	1.12	0.87	0.57	2.08
140	Incorporated	1.81	1.80	1.62c	1.39b	1.36	1.46	0.99	0.71	0.38	1.29
280	Incorporated	2.60	2.23	2.02b	1.77b	1.62	1.76	1.14	0.91	0.59	1.63
		NS	*NS*	*0.0456*	*0.0169*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
		2012									
140	-	1.94	1.88	1.87	1.57	1.21	1.20	0.98	0.83	0.57	1.34
280	-	2.55	2.33	2.35	2.18	1.59	1.45	1.27	1.30	0.76	1.72
		-	-	*<0.0001*	*<0.0001*	*0.0005*	*0.0036*	*0.012*	*0.0063*	*0.0062*	*0.008*
-	Topdressed	2.34	2.30	2.35	2.07	1.62	1.63	1.39	1.14	0.78	1.73
-	Incorporated	2.15	1.92	1.87	1.68	1.18	1.01	0.86	0.71	0.55	1.33
		-	-	*<0.0001*	*0.0004*	*0.0002*	*<0.0001*	*<0.0001*	*<0.0001*	*0.002*	*0.0059*
140	Topdressed	2.14b	2.18a	2.15	1.74	1.44	1.51	1.20	1.08	0.69	1.57
280	Topdressed	2.53a	2.42a	2.56	2.41	1.79	1.74	1.58	1.20	0.87	1.90
140	Incorporated	1.74c	1.59b	1.59	1.41	0.98	0.88	0.75	0.57	0.44	1.11
280	Incorporated	2.56a	2.25a	2.15	1.95	1.38	1.15	0.96	0.86	0.65	1.55
		0.0077	*0.0421*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Days after potting.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

fertilizers (CRF) were incorporated into the substrate, as opposed to topdressed (Warren et al. 2001). In fact, total plant P content was reduced >70%, regardless of CRF formulation, when the fertilizer was topdressed rather than incorporated into the substrate. Leachate-TP was also increased up to 88% (Warren et al. 2001) and 83% (Warren et al. 1997) when CRF was incorporated into the substrate instead of topdressed. Researchers concluded increased P solubility resulting from CRF incorporation was due to uniform dispersal of fertilizer prills throughout the substrate and/or increased moisture content within the substrate. Broschat (2005) reported release rates of P from CRFs were slowed when CRFs were topdressed as opposed to incorporated within the substrate.

In this experiment, substrate leachate-DRP was affected by both P rate and PLA placement with PLA placement

Table 13. Effect of poultry litter ash rate and placement on leachate dissolved reactive phosphorus measured in container-grown *Lantana camara* 'New Gold' over the course of a 70-d experiment in 2011.

Rate ($g\ m^{-3}$)	Placement[z]	Dissolved Reactive Phosphorus ($mg{\cdot}L^{-1}$)										
		7 DAP[y]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	70 DAP	Average
140	-	7.73	8.38	7.33	6.06	5.86	4.58	5.23	3.23	3.44	3.20	5.51
280	-	8.03	9.03	9.11	8.38	8.69	8.16	7.21	5.36	4.16	3.24	7.14
		NS[x]	*NS*	-	-	-	*0.0003*	*0.0075*	-	*NS*	*NS*	*0.0083*
-	Topdressed	3.07	4.60	4.48	3.97	4.93	3.89	4.56	3.03	3.19	3.01	3.87
-	Incorporated	12.70	12.82	11.96	10.47	9.63	8.85	7.88	5.56	4.41	3.44	8.77
		<0.0001	*<0.0001*	-	-	-	*<0.0001*	*0.0003*	-	*0.0083*	*NS*	*<0.0001*
140	Topdressed	3.06	4.49	4.38c[w]	3.60c	3.96d	2.76	3.90	2.77b	3.02	2.76	3.47
280	Topdressed	3.08	4.70	4.59c	4.34c	5.89c	5.02	5.21	3.28b	3.37	3.26	4.28
140	Incorporated	12.42	12.27	10.29b	8.52b	7.76b	6.40	6.56	3.68b	3.87	3.66	7.54
280	Incorporated	12.98	13.37	13.62a	12.42a	11.49a	11.29	9.21	7.44a	4.95	3.22	10.00
		NS	*NS*	*0.001*	*0.0495*	*0.0117*	*NS*	*NS*	*0.0092*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Days after potting.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

Table 14. **Effect of poultry litter ash rate and placement on leachate dissolved reactive phosphorus measured in container-grown *Lantana camara* 'New Gold' over the course of a 70-d experiment in 2012.**

Rate ($g\ m^{-3}$)	Placement[z]	Dissolved Reactive Phosphorus ($mg{\cdot}L^{-1}$) 7 DAP[y]	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP	Average
140	-	6.80	8.43	7.40	4.88	3.81	2.56	5.65a
280	-	7.32	9.45	8.58	6.55	4.64	3.60	6.69a
		-	*0.0352*[x]	*0.0146*	*0.029*	*0.0295*	*0.0143*	*0.0322*
-	Topdressed	3.19	4.87	4.46	3.64	3.11	2.43	3.62
-	Incorporated	10.93	13.01	11.52	7.80	5.34	3.73	8.72
		-	*<0.0001*	*<0.0001*	*0.0002*	*0.0001*	*0.0047*	*<0.0001*
140	Topdressed	3.22c[w]	4.32	4.24	3.44	2.76	2.00	3.33
280	Topdressed	3.15c	5.43	4.69	3.83	3.46	2.86	3.90
140	Incorporated	10.37b	12.54	10.56	6.32	4.86	3.11	7.96
280	Incorporated	11.50a	13.47	12.48	9.27	5.82	4.35	9.48
		0.005	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

[z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[y]Days after potting.

[x]P-value derived from analysis of variance; NS = not significant. If interaction was significant, P-values for main effects are not reported.

[w]Values in columns followed by the same letters were not significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

being the more substantial factor. Subsequently, both shoot and root P concentrations were affected to a greater extent by PLA placement than PLA application rate. For example, when PLA application rate was reduced from 280 to 140 g P m^{-3}, leachate-DRP concentrations were not reduced proportionally. In fact, during the first two weeks of the experiment, leachate-DRP concentration was not reduced by lowering PLA application rate in 2011 and was only slightly reduced in 2012. Losses of P from container production have previously been shown to be unaffected by P rate even when CRFs were used as P sources. In an experiment spanning 100 days, Tyler et al. (1996) reported cumulative effluent-DRP was reduced 57% by reducing the leaching fraction by 50%, but was not affected by fertilizer application rate. Similarly, in an experiment focused on reducing P losses from container-grown plants by amending substrates with calcined clay, Owen et al. (2008) reported cumulative effluent-DRP was unaffected by P application rate, but was dependent on irrigation rate and substrate amendment. Given the results of current and previous experiments, P dissolution rate in a soilless substrate may not be a function of P application rate but rather PLA-P solubility is controlled by root interactions.

In addition to influencing PLA-P dissolution, PLA application rate and placement also affected substrate pH and EC and thus nutrient uptake. Since solution pH strongly affects Mn solubility in soilless substrates (Handreck and Black 2010), the effect of PLA placement on substrate leachate-pH led to decreased foliar and root Mn concentrations in verbena and lantana when PLA was incorporated instead of topdressed. In general, substrate leachate-pH was within the range at which inorganic P is most available to plants (5.0 – 6.5) (Schachtman et al. 1998). This indicates P plant uptake was not likely limited due to substrate pH effects on P solubility. Leachate-DRP concentrations were within the recommended range of 5 to 60 $mg{\cdot}L^{-1}$ P (Raviv and Lieth 2008) for greenhouse crops throughout the experiment when PLA was incorporated within the substrate.

During a 47-week experiment evaluating nutrient release patterns from commonly-used CRFs incorporated in a substrate composed of peat moss, pine bark, and sand (5:4:1 v:v:v) used to fill fallow containers, Merhaut et al. (2006) reported that TP concentrations ranged from 15 to 60 $mg{\cdot}L^{-1}$ P for the first 10 weeks, but averaged below 10 $mg{\cdot}L^{-1}$ for the final 27 weeks. According to the authors, nutrient release would have been expected to accelerate if plants were grown in the substrate. They concluded commonly-used water-soluble fertilizers and CRFs may supply excessive nutrients early in the growing cycle of a plant, leading to shortages of nutrients in the later weeks of the production cycle. Although, pre-plant incorporation of water-soluble P fertilizers within the growing substrate is a common practice for container-grown plant production, this practice should be questioned given the high nutrient leaching losses (Altland and Buamscha 2008). Use of PLA as a P source may reduce unnecessary P losses from container-grown plant production with little to no deleterious effects to plant growth and quality, and may provide growers with an alternative to more costly fertilizers.

Application of PLA as a topdressing did not result in lower plant growth parameters in every case, but did result in lower flowering and plant P uptake compared with application of PLA as a substrate amendment. Reductions in plant P uptake when PLA was applied as a topdressing were most likely the result of limited interaction between plant roots and PLA. It is believed the interaction of plant roots is one of the primary mechanisms for P release form PLA. While topdressing PLA did reduce leachate-DRP compared incorporating PLA into the substrate, the reduction is minimal when compared to previously reported reductions of leachate-DRP of more than 90% when replacing a more water-soluble P source with PLA. Therefore, topdressing is not recommended as the primary application method of PLA due to lower plant growth and quality. For greenhouse crop container production, PLA should be pre-plant incorporated within the substrate at a rate (as total P) between 140 $g{\cdot}m^{-3}$ (0.4 $lb{\cdot}yd^{-3}$) and 280 $g{\cdot}m^{-3}$ (0.8 $lb{\cdot}yd^{-3}$)

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