# POULTRY LITTER ASH AS A PHOSPHORUS SOURCE FOR GREENHOUSE CROP PRODUCTION

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# Effects of Phosphorus Source, Phosphorus Rate, and Liming Rate on Growth and Quality of *Verbena canadensis* Britton 'Homestead Purple' and *Lantana camara* L. 'New Gold'[1]

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## Abstract

Phosphate rock ores, rich in phosphorus (P), are mined in great quantities around the world for the production of P fertilizers. However, availability of phosphate reserves is in question due to decreasing global supplies. Therefore, application of alternative, renewable P sources is of interest. Poultry litter ash (PLA), a byproduct of bioenergy production, contains P concentrations comparable to conventional fertilizers. In this experiment, two P sources, PLA and superphosphate (SP), were compared at two P application rates and two liming rates as fertilizer sources for the production of two commonly-grown greenhouse crops (*Verbena canadensis* Britton 'Homestead Purple' and *Lantana camara* L.'New Gold'). Application of PLA produced plants of comparable biomass and quality to those fertilized with SP. Increasing P application rate, across both P sources, increased total flower numbers 42 and 26% for verbena and lantana, respectively. Foliar P concentrations of verbena and lantana increased 27 and 62% for PLA-fertilized plants compared to SP. In addition, substrate pH increased 25% using PLA versus SP. Overall, PLA supplies adequate P fertility and does not reduce pH compared to the more water-soluble, rock phosphate based SP fertilizer.

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

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

## Significance to the Nursery Industry

Due to declining global and domestic phosphate rock ore reserves, application of alternative, renewable phosphorus (P) fertilizers is of great importance. Poultry litter ash (PLA) performed as well as or better than superphosphate (SP) in terms of growth, biomass, quality, and P-fertilization of greenhouse-grown, containerized verbena and lantana. Substrate pH was increased 25% when PLA was used instead of SP, while substrate EC was comparable. Foliar P concentrations were higher for plants fertilized with PLA than those fertilized with SP. Foliar Mn concentrations were greatly reduced through PLA application compared with SP, while foliar Ca concentrations were slightly increased. Results indicate that PLA is a suitable alternative to SP, a phosphate rock ore-based fertilizer. In addition, PLA incorporation increases substrate pH, potentially reducing dependency on commonly used liming amendments. Poultry litter ash may reduce costs associated with P fertilization and substrate liming, while also reducing dependency on mined phosphate rock ore-based fertilizers. Future research should address P dissolution rates from PLA in soilless substrates.

## Introduction

Phosphorus (P) is the eleventh most abundant element in the earth's crust and is essential for most life forms, including plants (36). Phosphorus fertilizers commonly used in plant production systems, are mined and processed from phosphate-rich ore deposits in the earth's crust (25). However, future availability of phosphate rock ore reserves is in jeopardy (12). According to Roberts and Stewart (30), the United States' phosphate rock ore reserves, at current production, are estimated at less than 20 years. Current global commercial phosphate reserves are estimated to be depleted within 50 to 100 years (12). While expected durations of global and domestic phosphate reserves and resources are only estimates, a decline in phosphare rock ore quality is a consensus among speculators and scientists (12, 30, 36, 39). Therefore, development of renewable, high quality P fertilizer sources is of paramount importance.

Historically, animal manures have been utilized as fertilizers in production of many agricultural commodities. Given concerns regarding phosphate rock ore for P fertilizers, manures have gained interest as potential recycled P sources (13). The rise in poultry production has resulted in significant amounts of waste being produced from these facilities in many areas of the United States, particularly in the southeastern U.S. Poultry litter is a biomass source consisting predominantly of bird manure and bedding materials (31). Bedding materials typically consist of straw, sawdust, wood shavings, shredded paper, peanut hulls, and/or rice hulls, depending on location and availability of materials (22). Poultry litter contains comparable amounts of nitrogen to ruminant wastes, but higher concentrations of P, since fowls are unable to extract organically bound-P from feeds with the addition of phytase (38). Like most manures, poultry litter application as a fertilizer source is limited due to high transportation costs (7) and environmental concerns associated with surface water impairment (35).

To alleviate environmental concerns due to geographically-concentrated poultry litter applications as well as expand

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the use of poultry litter as a recyclable fertilizer source, several methods have been employed to reduce weight of, or concentrate P within, poultry litter including, compaction (7), pelletization (24), composting (9), P removal (40), gasification (27), and combustion (10, 34). Of all these methods, combustion of poultry litter may be the most efficient means available because the ash contains inorganic P while energy released during combustion could be used for electricity or heat production (19). Although the combustion process can be more complicated for poultry litter compared to traditional fuel sources due to inconsistent composition, moisture content, and high ash content (6), combustion of poultry litter is technologically feasible (16). For example, Fibrominn power plant in Benson, MN, an alternative energy plant, co-combusts poultry litter and wood to provide energy to approximately 40,000 homes. Ash from the combustion process is sold as a commercial fertilizer (26) with the majority of ash a product of combusted poultry litter (19, 21).

With the increase in capability of using poultry litter for ashing or power production the potential of poultry litter ash (PLA) as a fertilizer source needs to be examined for a variety of cropping systems. Limited scientific experiments have reported PLA is a suitable nutrient source for several agronomic crops including wheat (*Triticum aestivum* L.) (10), Japanese mustard spinach (*Brassica rapa* L.) (14), buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), or ryegrass (*Lolium multiflorum westerwoldicum* Gordo) (5). In each of these experiments, researchers reported increased plant P accumulation for soils amended with PLA even though PLA-P is characterized as having low water solubility (11, 5). No experiments have examined PLA as a P source for containerized horticultural crops.

Given the uncertainty of future P ore based fertilizer availability and quality, low cost alternatives such as PLA may be highly desirable in nursery and greenhouse production systems that require high P fertilization additions with high water usage. Additionally, environmental concerns due to P losses from highly concentrated production sites may be reduced by utilizing less soluble, recycled P sources. Therefore, the objective of the experiment was to examine the use of PLA as an alternative P source during the production of two commonly-grown greenhouse crops (*Lantana camara* L. 'New Gold' and *Verbena canadensis* Britton 'Homestead Purple').

## Materials and Methods

*Experiment design*. Eighty *Lantana camara* L. 'New Gold' and *Verbena canadensis* Britton 'Homestead Purple' plants growing in 105-cell trays were selected for uniform quality and size for the experiment initiated February 3, 2012. For each species, two plants were transplanted into 1.6-liter containers for a total of 40 containers per species. Containers were filled with a substrate composed of pine bark (<0.38 cm) and peat moss (4:1 by vol ) and pre-plant incorporated with 0.89 kg·m$^{-3}$ of micronutrient package (Micromax, Scotts Company, Marysville, OH), and 0.25 kg K·m$^{-3}$ (0N-0P-35.7K). Remaining pre-plant amendments were superphosphate (SP; 18% $P_2O_5$) or poultry litter ash (PLA; 7% $P_2O_5$), incorporated at 140 or 280 g P·m$^{-3}$, in combination with pulverized dolomitic limestone (DL) at 1.5 or 3.0 g·m$^{-3}$. Poultry litter ash used in this experiment was the product of commercial energy production via combustion of poultry litter and was obtained courtesy of North American Fertilizer, LLC. Containers filled with the eight pre-plant incorporated combinations were arranged in a completely randomized design with five single-container replications. All plants were maintained under greenhouse conditions at an average temperature of 27.7C (82F), with no supplemental irradiance, for 42 and 70 days for *Verbena canadensis* and *Lantana camara*, respectively. During the experiment, plants were supplied with 350 ml water per day including 120 ml aliquots per container N at 250 mg $NH_4NO_3$ liter$^{-1}$·d$^{-1}$.

*Plant response*. Plant growth was measured bi-weekly using a growth index [(height + widest width + perpendicular width) / 3] and flower number was quantified for flower buds showing color. Leaf samples, composed of the most recently matured leaves, were removed, dried at 60C (140F) for 72 hours, and biomass recorded before tissue was milled to <0.5 mm using a Thomas Wiley® Mini-Mill (Thomas Scientific, Swedesboro, NJ). Tissue was digested in concentrated nitric acid at an average of 120C (250F), diluted to 20 ml with deionized water, and filtered prior to analysis of elemental Al, B, Ca, Cu, Fe, Mg, Mn, Mo, P, K, Na, S, and Zn concentrations using inductively coupled plasma optical emission spectroscopy (SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA). At 42 and 70 days, plant shoots were harvested at the substrate surface, dried at 60C (140F) for 72 hours, and biomass recorded.

*Leachate collection and analysis*. Leachate samples measuring 90 ml, from three containers per treatment for Lantana camara, were collected bi-weekly following the Virginia Tech extraction method (41). Leachate samples were transported to the laboratory and allowed to cool to room temperature [21C (70F)] prior to leachate-pH and EC measurement (Orion Star A215 solution analyzer; Thermo Scientific Inc., Beverly, MA).

*Statistical analysis*. The experiment was a completely randomized design with five replications. Growth index, flower counts, plant dry weight, leachate pH, EC, and tissue nutrient analyses data were analyzed following the mixed procedure in SAS/STAT® statistical software (32). Means for each measurement at each collection interval were separated using Tukey's Honest Significant Difference Test at a significance level of 0.05.

## Results and Discussion

*Plant response of verbena*. Verbena growth was not significantly influenced by P source, P rate, or DL rate at 14 or 28 DAP (Table 1). At 42 DAP verbena growth, measured using a growth index, increased 9.5% from 40.0 to 44.2 across both P sources as DL rate increased from 1.5 to 3.0 kg·m$^{-3}$. However, in the case of shoot dry weight, DL affected verbena growth differently depending on P source and rate of application (Table 2). Increasing DL rate from 1.5 to 3.0 kg·m$^{-3}$ did not increase verbena shoot dry weights at 21.2 g and 23.2 g, respectively, in combination with the lower SP application rate. However, increasing DL application rate at the higher SP application rate of 280 g P·m$^{-3}$ resulted in higher dry weight of 30.4 g compared to 19.8 g. For PLA, increasing the DL application rate increased verbena shoot dry weight 5.9 g at the lower PLA application rate. In fact,

Table 1. **Effects of phosphorus rate and dolomitic limestone rate on growth index of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' over experimental periods of 42 and 70 days, respectively.**

| | | | **Verbena** | | | **Lantana** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Growth index[x]** | | | | | | | |
| **P source[z]** | **P rate $(g\cdot m^{-3})$** | **DL rate[y] $(kg\cdot m^{-3})$** | **14 DAP[w]** | **28 DAP** | **42 DAP** | **14 DAP** | **28 DAP** | **42 DAP** | **56 DAP** | **70 DAP** |
| — | 140 | — | 25.5a[v] | 35.9a | 42.1a | 15.3a | 22.9a | 36.4a | 45.8a | 51.3a |
| — | 280 | — | 26.7a | 33.3a | 42.1a | 16.3a | 25.6a | 33.1a | 42.5b | 47.3a |
| — | | | *NS*[u] | *NS* | *NS* | *NS* | *NS* | *NS* | *0.029* | *NS* |
| — | — | 1.5 | 25.1a | 33.6a | 40.0b | 15.3a | 24.1a | 31.8b | 41.1b | 46.8b |
| — | — | 3.0 | 27.1a | 35.7a | 44.2a | 16.3a | 24.5a | 37.7a | 47.2a | 51.8a |
| | | | *NS* | *NS* | *0.048* | *NS* | *NS* | *0.013* | *0.001* | *0.047* |

[z] SP = superphosphate; PLA = poultry litter ash.

[y] DL = pulverized dolomitic limestone.

[x] Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[w] Days after potting.

[v] Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

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

the combination of DL at 3.0 $kg\cdot m^{-3}$ and PLA at 140 $g\cdot m^{-3}$ resulted in shoot dry weight of 26.6 g comparable to 27.3 and 28.1 g as the DL rate increased at 280 g $P\cdot m^{-3}$of PLA. An increasing effect of DL on plant dry weight was not evident at the higher PLA application rate.

Phosphorus application rate, regardless of P source, had the greatest effect on verbena flower counts throughout the experiment (Table 3). Flower counts increased from 7.4 to 12, 12.8 to 19.2, and 11.1 to 13.3, at 14, 28, and 42 DAP, respectively, as the rate of P increased from 140 to 280 $g\cdot m^{-3}$. Over the 42-day experiment, total flower counts increased 42% from 31.3 to 44.5 as P rate increased from 140 to 280 $g\cdot m^{-3}$. In general, verbenas fertilized with 280 g $P\cdot m^{-3}$ across all DL rates resulted in greater flowering than verbena fertilized at 140 g $P\cdot m^{-3}$.

Table 2. **Effects of phosphorus source, phosphorus rate, and dolomitic lime rate on shoot dry weights of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' harvested at 42 and 70 days after potting, respectively.**

| | | | **Shoot dry weight (g)** | |
|---|---|---|---|---|
| **P source[z]** | **P rate $(g\cdot m^{-3})$** | **DL rate[y] $(kg\cdot m^{-3})$** | **Verbena** | **Lantana** |
| SP | — | 1.5 | 20.5c[x] | 24.9b |
| SP | — | 3.0 | 26.8a | 28.9a |
| PLA | — | 1.5 | 23.9b | 29.2a |
| PLA | — | 3.0 | 27.3a | 26.6ab |
| | | | *0.0217*[w] | *0.0029* |
| SP | 140 | 1.5 | 21.2c | 25.9ab |
| SP | 280 | 1.5 | 19.8c | 24.0b |
| SP | 140 | 3.0 | 23.2bc | 27.9ab |
| SP | 280 | 3.0 | 30.4a | 29.8ab |
| PLA | 140 | 1.5 | 20.6c | 26.9ab |
| PLA | 280 | 1.5 | 27.3a | 31.6a |
| PLA | 140 | 3.0 | 26.5ab | 25.4ab |
| PLA | 280 | 3.0 | 28.1a | 27.9ab |
| | | | *<0.0001* | *NS* |

[z] SP = superphosphate; PLA = poultry litter ash.

[y] DL = pulverized dolomitic limestone.

[x] Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

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

*Plant response of lantana.* As noted with verbena, P source did not affect lantana growth. However, lantana growth index was affected by DL rate and P rate (Table 1). Lantana growth increased from 31.8 to 37.7, 41.1 to 47.2, and 46.8 to 51.8, at 42, 56, and 70 DAP, respectively, as DL rate increased from 1.5 to 3.0 $kg\cdot m^{-3}$. In general, P application rate did not affect growth index of lantana with the exception of a 7% decrease at 56 DAP when P rate was increased. Shoot dry weight of lantana was not singularly affected by P source, P rate, or DL rate (Table 2). However, increasing DL rate from 1.5 to 3.0 $kg\cdot m^{-3}$ increased shoot biomass from 24.9 to 28.9 g of lantanas fertilized with SP, but did not affect those fertilized with PLA.

Similar to verbena, flower counts of lantana were affected by P application rate throughout the experiment (Table 3). Flower counts increased from 48.8 to 66.8, 110.8 to 150.3, 106.8 to 116.3, and 93.8 to 123.7, at 28, 42, 56, and 70 DAP, respectively, when P application rate of either P source was increased from 140 to 280 g $P\cdot m^{-3}$. For the experiment, there was an overall increase of 26%, from 382.8 to 483.5 flowers, when P application rate was increased. Similar to shoot dry weight, increasing DL rate from 1.5 to 3.0 $kg\cdot m^{-3}$, increased total flower counts of lantana fertilized with SP from 387.7 to 469.8, but did not affect flower counts of lantanas fertilized with PLA.

*Substrate leachate-pH and EC from lantana camara.* Substrate leachate-pH was affected at every measurement date by P source and DL rate (Table 4). Average leachate-pH increased 25%, from pH 5.18 to 6.48, when the P source was changed from SP to PLA, and 9.3%, from pH 5.57 to 6.09, when DL rate was increased 1.5 to 3.0 kg $DL\cdot m^{-3}$. As DL rate increased from 1.5 to 3.0 kg $DL\cdot m^{-3}$, substrate leachate-pH increased an average of 11%, from 4.87 to 5.48, for plants fertilized with SP, but only 6%, from 6.27 to 6.69, for those fertilized with PLA.

Substrate leachate-EC was also affected by P source at 0, 7, 14, 21, 49, and 63 DAP (Table 5). Leachate-EC was highest when plants were fertilized with PLA at 0, 7, 49, and 63 DAP, but was higher for SP-fertilized plants 14 and 21 DAP. Increasing the P application rate from 140 g $P\cdot m^{-3}$

**Table 3. Effects of phosphorus source, phosphorus rate, and dolomitic limestone rate on bi-weekly and cumulative flower counts of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' over experimental periods of 42 and 70 days, respectively.**

|  |  |  | Flower count[z] |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Verbena |  |  |  | Lantana |  |  |  |  |  |
| P source[y] | P rate (g·m$^{-3}$) | DL rate[x] (kg·m$^{-3}$) | 14 DAP[w] | 28 DAP | 42 DAP | Total | 14 DAP | 28 DAP | 42 DAP | 56 DAP | 70 DAP | Total |
| — | 140 | — | 7.4b[v] | 12.8b | 11.1b | 31.3b | 22.8a | 48.8b | 110.8b | 106.8b | 93.8b | 382.8b |
| — | 280 | — | 12.0a | 19.2a | 13.3a | 44.5a | 26.5a | 66.8a | 150.3a | 116.3a | 123.7a | 483.5a |
|  |  |  | *<0.0001*[u] | *<0.0001* | *0.0492* | *<0.001* | *NS* | *<0.0001* | *<0.0001* | *0.0391* | *0.0012* | *<0.0001* |
| SP | — | 1.5 | 9.0a | 13.5a | 10.7a | 33.2b | 18.8b | 52.2b | 113.8b | 102.0a | 100.8a | 387.7b |
| SP | — | 3.0 | 11.0a | 15.7a | 12.8a | 39.5ab | 32.0a | 65.5a | 147.0a | 114.0a | 111.3a | 469.8a |
| PLA | — | 1.5 | 10.2a | 17.3a | 12.7a | 40.2a | 23.8b | 57.2ab | 118.8b | 114.8a | 114.3a | 429.0ab |
| PLA | — | 3.0 | 8.7a | 17.3a | 12.7a | 38.7ab | 23.8b | 56.2ab | 142.3a | 115.3a | 108.3a | 446.0a |
|  |  |  | *0.0311* | *NS* | *NS* | *0.0276* | *0.0276* | *0.0259* | *NS* | *NS* | *NS* | *0.0105* |
| SP | 140 | 1.5 | 7.0c | 11.0d | 10.3a | 28.3b | 17.7b | 47.3cd | 96.3d | 98.3a | 94.7a | 354.3c |
| SP | 280 | 1.5 | 11.0abc | 16.0abcd | 11.0a | 38.0ab | 20.0b | 57.0bcd | 131.3c | 105.7a | 107.0a | 421.0bc |
| SP | 140 | 3.0 | 7.7bc | 12.3cd | 13.0a | 33.0b | 29.7ab | 53.7bcd | 128.0c | 114.0a | 97.3a | 422.7bc |
| SP | 280 | 3.0 | 14.3a | 19.0abc | 12.7a | 46.0a | 34.3a | 77.3a | 166.0a | 114.0a | 125.3a | 517.0a |
| PLA | 140 | 1.5 | 8.0bc | 13.3bcd | 11.7a | 33.0b | 23.7ab | 49.3bcd | 94.0d | 106.7a | 98.0a | 371.7c |
| PLA | 280 | 1.5 | 12.3ab | 21.3a | 13.7a | 47.3a | 24.0ab | 65.0abc | 143.7bc | 123.0a | 130.7a | 486.3ab |
| PLA | 140 | 3.0 | 7.0c | 14.3abcd | 9.3a | 30.7b | 20.0b | 44.7d | 124.7c | 108a | 85.0a | 382.3c |
| PLA | 280 | 3.0 | 10.3abc | 20.3ab | 16.0a | 46.7a | 27.7ab | 67.7ab | 160.0ab | 122.7a | 131.7a | 509.7a |
|  |  |  | *NS* | *NS* | *NS* | *NS* | *NS* | *NS* | *NS* | *NS* | *NS* | *NS* |

[z] Flower buds showing color at the time of data collection.

[y] SP = superphosphate; PLA = poultry litter ash.

[x] DL = pulverized dolomitic limestone.

[w] Days after potting.

[v] Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

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

**Table 4. Effects of phosphorus source and dolomitic lime rate on substrate leachate-pH measured weekly from *Lantana camara* 'New Gold' over an experimental period of 63 days.**

|  |  |  | Substrate leachate-pH |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P source[z] | P rate (g·m$^{-3}$) | DL rate[y] (kg·m$^{-3}$) | 0 DAP[x] | 7 DAP | 14 DAP | 21 DAP | 28 DAP | 35 DAP | 42 DAP | 49 DAP | 56 DAP | 63 DAP | Average |
| SP | — | — | 4.33b[w] | 4.65b | 4.79b | 4.89b | 5.03b | 5.17b | 5.49b | 5.69b | 5.82b | 5.89b | 5.18b |
| PLA | — | — | 5.93a | 6.27a | 6.31a | 6.52a | 6.59a | 6.68a | 6.68a | 6.57a | 6.57a | 6.65a | 6.48a |
|  |  |  | *<0.0001*[v] | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* |
| — | — | 1.5 | 4.93b | 5.19b | 5.30b | 5.44b | 5.53b | 5.63b | 5.81b | 5.86b | 5.90b | 6.06b | 5.57b |
| — | — | 3.0 | 5.32a | 5.72a | 5.80a | 5.97a | 6.10a | 6.22a | 6.36a | 6.39a | 6.49a | 6.48a | 6.09a |
|  |  |  | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* |
| SP | — | 1.5 | 4.05d | 4.30d | 4.44d | 4.62d | 4.74d | 4.87d | 5.16d | 5.36d | 5.48d | 5.65d | 4.87d |
| SP | — | 3.0 | 4.61c | 4.99c | 5.14c | 5.17c | 5.33c | 5.46c | 5.82c | 6.03c | 6.16c | 6.13c | 5.48c |
| PLA | — | 1.5 | 5.81b | 6.08b | 6.16b | 6.27b | 6.33b | 6.39b | 6.46b | 6.37b | 6.32b | 6.47b | 6.27b |
| PLA | — | 3.0 | 6.05a | 6.45a | 6.45a | 6.77a | 6.87a | 6.97a | 6.90a | 6.77a | 6.82a | 6.84a | 6.69a |
|  |  |  | *0.0004* | *<0.0001* | *<0.0001* | *NS* | *NS* | *NS* | *0.028* | *0.0001* | *0.0035* | *NS* | NS |
| SP | 140 | 1.5 | 4.17e | 4.41f | 4.49f | 4.70d | 4.74c | 4.94f | 5.22f | 5.58d | 5.62d | 5.84f | 4.97ef |
| SP | 280 | 1.5 | 3.94e | 4.19f | 4.38f | 4.52d | 4.74e | 4.80f | 5.10f | 5.13e | 5.33e | 5.46g | 4.76f |
| SP | 140 | 3.0 | 4.78c | 5.16d | 5.44d | 5.57c | 5.54c | 5.69d | 6.00d | 6.22b | 6.25bc | 6.07ef | 5.67d |
| SP | 280 | 3.0 | 4.43d | 4.83e | 4.85e | 4.78d | 5.11d | 5.23e | 5.65e | 5.84c | 6.07c | 6.18de | 5.30e |
| PLA | 140 | 1.5 | 5.78b | 6.02c | 6.11c | 6.16b | 6.27b | 6.21c | 6.33c | 6.38b | 6.23bc | 6.39cd | 6.19c |
| PLA | 280 | 1.5 | 5.83ab | 6.13bc | 6.22bc | 6.37ab | 6.38b | 6.56b | 6.60bc | 6.36b | 6.41b | 6.55bc | 6.34bc |
| PLA | 140 | 3.0 | 6.06a | 6.33ab | 6.34b | 6.77a | 6.84a | 6.89a | 6.85ab | 6.71a | 6.88a | 6.78ab | 6.64ab |
| PLA | 280 | 3.0 | 6.04a | 6.58a | 6.57a | 6.76a | 6.91a | 7.05a | 6.94a | 6.83a | 6.76a | 6.89a | 6.73a |
|  |  |  | *NS* | *NS* | *0.0002* | *NS* | *0.0152* | *NS* | *NS* | *NS* | *0.0012* | *0.0011* | *NS* |

[z] SP = superphosphate; PLA = poultry litter ash.

[y] DL = pulverized dolomitic limestone.

[x] Days after potting.

[w] Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

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

**Table 5. Effects of phosphorus source and phosphorus rate on substrate leachate-EC measured from *Lantana camara* 'New Gold'.**

| P source$^{z}$ | P rate (g·m$^{-3}$) | Substrate leachate-EC | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 DAP$^{y}$ | 7 DAP | 14 DAP | 21 DAP | 28 DAP | 35 DAP | 42 DAP | 49 DAP | 56 DAP | 63 DAP | Average |
| SP | — | 2.24b$^{x}$ | 2.51b | 2.48a | 1.98a | 1.38a | 1.10a | 0.85a | 0.66b | 0.66a | 0.57b | 1.44a |
| PLA | — | 2.92a | 2.99a | 2.36b | 1.86b | 1.39a | 1.09a | 0.82a | 0.73a | 0.70a | 0.66a | 1.55a |
| | | *<0.0001*$^{w}$ | *<0.0001* | *0.0017* | *0.04* | *NS* | *NS* | *NS* | *0.0043* | *NS* | *0.0112* | *NS* |
| — | 140 | 2.36b | 2.34b | 2.10b | 1.60b | 1.13b | 0.91b | 0.74b | 0.59b | 0.58b | 0.56b | 1.29b |
| — | 280 | 2.80a | 3.16a | 2.75a | 2.25a | 1.64a | 1.28a | 0.93a | 0.80a | 0.78a | 0.67a | 1.71a |
| | | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *0.0031* | 0.0015 |
| SP | 140 | 2.04d | 2.12d | 2.14c | 1.77b | 1.29c | 0.99c | 0.79bc | 0.59c | 0.59c | 0.52b | 1.28b |
| SP | 280 | 2.44c | 2.91b | 2.84a | 2.20a | 1.49b | 1.20b | 0.90ab | 0.74b | 0.73b | 0.62ab | 1.60ab |
| PLA | 140 | 2.68b | 2.56c | 2.06c | 1.43c | 0.97d | 0.82d | 0.68c | 0.59c | 0.57c | 0.60ab | 1.30b |
| PLA | 280 | 3.16a | 3.42a | 2.66b | 2.30a | 1.80a | 1.36a | 0.96a | 0.86a | 0.82a | 0.71a | 1.81a |
| | | *NS* | *NS* | *NS* | *0.001* | *<0.0001* | *0.0001* | *0.0312* | *0.0036* | *0.0027* | *NS* | NS |

$^{z}$SP = superphosphate; PLA = poultry litter ash.

$^{y}$Days after potting.

$^{x}$Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

$^{w}$P-value derived from analysis of variance; NS = not significant.

to 280 g P·m$^{-3}$ than for at every measurement date and was increased by an average of 33% for the 70 day experiment. While leachate-EC was affected by both P source and P application rate, increasing P rate from 140 to 280 g P·m$^{-3}$ increased leachate-EC for plants fertilized with PLA by a higher margin than for those fertilized with SP at 21, 28, 35, 42, 49, and 56 DAP.

*Foliar nutrient concentrations in verbena.* Foliar concentrations of Ca, Mn, and P were affected by P source for verbenas (Table 6). Foliar Ca and P concentrations increased from 0.61 to 0.78% and 0.26 to 0.33%, respectively, when verbenas were fertilized with PLA compared to SP, while Mn concentrations decreased from 122.97 to 65.01 mg·kg$^{-1}$. A similar trend was also exhibited, across both P sources, as foliar P increased from 0.27 to 0.31%, and foliar Mn decreased from 106.01 to 81.96 mg·kg$^{-1}$ with P application rate increase from 140 to 280 g P·m$^{-3}$. Across both P sources and P rates, increasing DL rate from 1.5 to 3.0 kg·m$^{-3}$ decreased foliar Mn concentrations from 100.21 to 87.77 mg·kg$^{-1}$. At

**Table 6. Effects of phosphorus source, phosphorus rate, and dolomitic lime rate on foliar nutrient concentrations of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold'.**

| P source$^{z}$ | P rate (g·m$^{-3}$) | DL rate$^{y}$ (kg·m$^{-3}$) | Verbena | | | | | Lantana | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ca$^{x}$ | Mg | Mn | P | K | Ca | Mg | Mn | P | K |
| SP | — | — | 0.61b$^{w}$ | 0.52a | 122.97a | 0.26b | 1.89a | 0.56b | 0.32b | 257.50a | 0.21b | 1.24a |
| PLA | — | — | 0.78a | 0.49a | 65.01b | 0.33a | 1.90a | 0.80a | 0.38a | 130.02b | 0.34a | 1.46a |
| | | | *0.0072*$^{v}$ | *NS* | *<0.0001* | *<0.0001* | *NS* | *<0.0001* | *<0.0001* | *<0.0001* | *<0.0001* | *NS* |
| — | 140 | — | 0.68a | 0.52a | 106.01a | 0.27b | 1.88a | 0.65b | 0.31b | 204.67a | 0.24b | 1.43a |
| — | 280 | — | 0.71a | 0.48a | 81.96b | 0.31a | 1.92a | 0.71a | 0.40a | 182.84b | 0.31a | 1.27a |
| | | | *NS* | *NS* | *<0.0001* | *0.0014* | *NS* | *0.0021* | *<0.0001* | *0.0024* | *0.0003* | *NS* |
| — | — | 1.5 | 0.69a | 0.49a | 100.21a | 0.29a | 1.88a | 0.64b | 0.33b | 184.54b | 0.28a | 1.38a |
| — | — | 3.0 | 0.70a | 0.51a | 87.77b | 0.29a | 1.92a | 0.73a | 0.37a | 202.98a | 0.27a | 1.32a |
| | | | *NS* | *NS* | *0.0063* | *NS* | *NS* | *0.0001* | *<0.0001* | *0.0077* | *NS* | *NS* |
| SP | 140 | 1.5 | 0.51a | 0.50a | 131.66a | 0.26bc | 1.98ab | 0.45e | 0.22e | 241.36b | 0.18c | 1.56a |
| SP | 280 | 1.5 | 0.60a | 0.48a | 126.53a | 0.27bc | 2.02ab | 0.53de | 0.36bcd | 255.88ab | 0.25bc | 1.22a |
| SP | 140 | 3.0 | 0.71a | 0.61a | 145.53a | 0.22c | 1.71ab | 0.66bc | 0.32d | 291.06a | 0.16c | 1.09a |
| SP | 280 | 3.0 | 0.64a | 0.47a | 88.16b | 0.31ab | 1.86ab | 0.60cd | 0.38bc | 241.70b | 0.26bc | 1.07a |
| PLA | 140 | 1.5 | 0.82a | 0.52a | 87.61b | 0.32ab | 1.84ab | 0.71bc | 0.33d | 138.70cd | 0.29b | 1.32a |
| PLA | 280 | 1.5 | 0.84a | 0.46a | 55.04c | 0.33ab | 1.67b | 0.85a | 0.40b | 102.20d | 0.39a | 1.41a |
| PLA | 140 | 3.0 | 0.69a | 0.45a | 59.26c | 0.30ab | 1.99ab | 0.77ab | 0.35cd | 147.58c | 0.33ab | 1.75a |
| PLA | 280 | 3.0 | 0.77a | 0.51a | 58.13c | 0.35a | 2.11a | 0.88a | 0.45a | 131.58cd | 0.33ab | 1.37a |
| | | | *NS* | *NS* | *<0.0001* | *NS* | *NS* | *NS* | *0.0006* | *0.0031* | *0.0416* | *NS* |

$^{z}$SP = superphosphate; PLA = poultry litter ash.

$^{y}$DL = pulverized dolomitic limestone.

$^{x}$Macronutrients reported as percentage of dry matter. Mn reported in mg·kg$^{-1}$ dry matter.

$^{w}$Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

$^{v}$P-value derived from analysis of variance; NS = not significant.

the high DL rate, increasing P rate from 140 to 280 g·m$^{-3}$ decreased foliar Mn concentration from 145.53 to 88.16 mg·kg$^{-1}$ for verbenas fertilized with SP, but did not affect foliar Mn concentrations of verbenas fertilized with PLA.

*Foliar nutrient concentrations in* lantana. For lantanas, foliar Ca, Mg, Mn, and P concentrations were affected by P source and P application rate (Table 6). When PLA was used as the P source, foliar Ca, Mg, and P increased from 0.56 to 0.80%, 0.32 to 0.38%, and 0.21 to 0.34%, respectively. However, similar to verbena, foliar Mn concentrations were decreased from 257.5 to 130.02 mg·kg$^{-1}$ when PLA was the P source. The same general trend existed for P application rate. As P rate increased from 140 to 280 g·m$^{-3}$ foliar Ca, Mg, and P concentrations increased from 0.65 to 0.71%, 0.31 to 0.40%, and 0.24 to 0.31%, respectively, while foliar Mn concentrations decreased from 204.67 to 182.84 mg·kg$^{-1}$. When P source was SP and the DL rate was highest, foliar Mn concentrations decreased from 291.06 to 241.70 mg·kg$^{-1}$ as P rate increased from 140 to 280 g·m$^{-3}$, but Mn concentrations were not affected when PLA was applied.

Poultry litter ash is an acceptable P source for verbena and lantana greenhouse container production compared to water-soluble, phosphate rock ore-based fertilizers such as SP. Verbena and lantana growth, measured using a growth index, and in terms of biomass, exhibited similar patterns to plants fertilized using SP. Codling (10) reported similar results for wheat (*Triticum aestivum* L.) grown on two differing soil types when comparing PLA to potassium phosphate as P fertilizer sources. Similarly, in an experiment conducted to determine the effects of PLA on soil-P pools and P uptake, Bachmann and Eichler-Lobermann (5) reported no differences in biomass per species of buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), or ryegrass (*Lolium multiflorum westerwoldicum* Gordo) when comparing PLA and potassium phosphate. In addition, flower count, a common measurement used for ornamental plant quality, increased as P rate increased for PLA and SP. James and Van Iersel (20) reported flower numbers, of other ornamental species, to be positively affected by increasing P fertility. Bi et al. (8) reported increased flower numbers for marigold with increasing poultry litter application rates. Therefore, under the conditions tested for ornamental plant production, PLA, a low water soluble P source, was able to provide adequate P concentrations throughout the 42 and 70 day production cycles to result in marketable quality plants without any observable deleterious effects.

Although PLA was primarily examined for its suitability as a P source, PLA also affected substrate pH known to influence nutrient availability and uptake. Research has shown substrate amendments such as fertilizers and pH-adjusting materials can greatly affect plant growth and quality as a direct result of changes in substrate chemical properties (3, 4, 37). Unlike SP, which is known to reduce substrate pH (18) and require higher lime additions to maintain a range of optimal pH, PLA did not lower substrate pH. In fact, verbena and lantana growth, within species, was similar for PLA across both the lower and higher DL rates.

Poultry litter ash contains a high concentration of Ca as a result of litter composition prior to ashing that can result in a high alkaline compound (11). Although substrate leachate-pH often exceeded the recommended range of 5.4 to 6.8 for proper plant growth (15) during the experiment, P plant uptake was not negatively affected at the higher DL in combination with PLA. Solution pH-dependent dissociation constants for $H_3PO_4$ of 2.1 and 7.2 suggest the monovalent P species ($H_2PO_4^-$) available for plant uptake would not be affected within the pH ranges measured for PLA-fertilized plants during the course of the experiment (33). Therefore, PLA has the added benefit of adjusting media pH while supplying P that should reduce liming requirements of soilless substrates.

Because PLA is not a pure P source and contains constituents that can affect substrate chemical properties and crop nutrition (11, 5), effects of PLA incorporation on salt leaching and ancillary nutrient uptake should be characterized. Substrate EC was not affected by DL rate, but was affected by P source and P rate, with P rate having the most consistent effect. Exceedingly high substrate EC was not observed with PLA incorporation. Leachate-EC measurements generally remained within an optimal range of 0.5 to 3.0 mS·cm$^{-1}$ (28, 29) throughout the experiment, with the only exceptions occurring at the highest rate of PLA at 0 and 7 DAP. In general, PLA did not affect the availability or uptake of required nutrients other than P. However, Ca uptake was increased and Mn uptake was decreased for plant fertilized with PLA. Increased Ca uptake was most likely due to increased Ca concentrations as a result of PLA application. More interesting were the changes in foliar Mn across P sources, P rates, and DL rates. In the case of SP-fertilized plants, Mn uptake increased due to higher Mn availability at lower substrate pH compared to plants fertilized with the more alkaline PLA. Although plant Mn toxicities occur in organic soils and soilless substrates, toxicity levels have been shown to be ameliorated with applications of Fe (17), K (1), Ca (2), or Mg (23). Manganese toxicity symptoms were not observed in this experiment likely due to Fe, Ca, K, and Mg being supplied in adequate concentrations.

Substrate pH was affected throughout the experiment and substrate EC was increased for the first week due to PLA incorporation, but adequate concentrations of P were supplied to plants verbena and lantana. However, based on data recorded for this experiment, it is unknown what salts contributed to leachate-EC. High concentrations of P have been shown to be rapidly released from SP in soilless substrates (42), but P dissolution rates from PLA in a soilless substrate have not previously been reported. Continued research should determine the rate and concentration of P dissolution from PLA when used as a P source in a soilless substrate.

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