Pelletized Soy-based Bioplastic Fertilizers for Container-crop Production

Kenneth G. McCabe¹, Christopher J. Currey, and James A. Schrader

Department of Horticulture, Iowa State University, 106 Horticulture Hall, Ames, IA 50011

David Grewell and Jake Behrens

Department of Materials Science and Engineering, Iowa State University, Ames, IA 50011

William R. Graves

Department of Horticulture, Iowa State University, 106 Horticulture Hall, Ames, IA 50011

Additional index words. biopolymer, nutrients, protein, sustainability, biochar, poly(lactic) acid, polyhydroxyalkanoates

Abstract. Research examining biocontainers for container-crop production has demonstrated that bioplastics made from soybean [*Glycine max* (L.) Merr.] can supply mineral nutrients to plants. Using soybean-based bioplastics and biochar (BC), we created pelletized fertilizer designed to be incorporated into soilless substrate. We evaluated the growth of ‘Honeycomb’ marigold (*Tagetes patula* L.), ‘Montego White’ snapdragon (*Antirrhinum majus* L.), and ‘Laser Synchron Scarlet’ cyclamen (*Cyclamen persicum* Mill.) grown with pelletized soy-based bioplastic fertilizers [soy-bioplastic polymer (SP.A) compounded with poly(lactic) acid (PLA) or polyhydroxyalkanoates (PHA), containing 15% or 25% BC] or a synthetic controlled-release fertilizer (CRF). Our objectives were to evaluate the effectiveness of prototype SP.A-based fertilizers and compare their performance to that of a traditional CRF for growing common greenhouse crops. In our first experiment, treatments of 0, 346, or 691 g nitrogen (N)/m³ of substrate from different fertilizer types were applied to marigold in containers with 15.2-cm top diameter, and in our second experiment, 0, 211, 423, 819, or 1638 g N/m³ were applied to marigold, snapdragon, and cyclamen in containers with 11.4-cm top diameter. Marigolds grown in larger containers accumulated more shoot dry mass (SDM) when supplied with 346 or 691 g N/m³ from each type of the SP.A-based fertilizers than did plants in the nonfertilized control group. Plants supplied with synthetic CRF accumulated similar or greater SDM than plants supplied with the same rate of N from SP.A-based fertilizers. In smaller containers, marigold and cyclamen provided with 211 or 423 g N/m³ from SP.A-based fertilizers accumulated more SDM than nonfertilized plants. Snapdragon provided with SP.A-based fertilizer grew poorly, and plants of this species died before the end of 5 weeks when provided the high and heavy rates of SP.A-based fertilizers. Plants fertilized with CRF had the largest SDM across the three species at most fertilizer concentrations. Tissue N concentration and N uptake were greater for plants provided with SP.A-based fertilizers at most N rates (211, 423, 819 g N/m³) or synthetic CRF (all four rates) than for nonfertilized plants. The effectiveness of prototype SP.A-based fertilizers was better at common application rates (211 and 423 g N/m³), but showed a diminishing return at high and heavy rates of application (819 and 1638 g N/m³). The SP.A-based fertilizers made with PLA copolymer were more effective than those made with PHA. Our results serve as proof-of-concept that pelletized soy-based bioplastic fertilizers can be effective for meeting the nutrient needs of plants during containerized-crop production, but formulations require further development to improve their properties for use with a broad range of species and application rates.

Received for publication 2 Mar. 2016. Accepted for publication 25 Aug. 2016.

This research was supported in part by the National Institute of Food and Agriculture, USDA, Specialty Crops Research Initiative (award no. 2011-51181-30735), and by Iowa State University.

We thank Peter Lawlor and Nicholas Flax for their helpful critiques of the manuscript.

¹Corresponding author. E-mail: kgmccabe@iastate.edu.

The floriculture industry is a large sector within commercial horticulture that had a value of \$4.25 billion in 2013 (U.S. Department of Agriculture, 2014). Floricultural crops grown in containers include annual bedding and garden plants, potted flowering plants, foliage plants, and potted herbaceous perennials. Most plants grown in containers are provided water-soluble fertilizers or granular CRF. These fertilizers are typically synthetically derived, and sustainability of

their use has been questioned because of energy involved in their manufacturing and nutrient contamination to the environment during their use (Carpenter et al., 1998; Pelletier et al., 2008).

To address environmental concerns and sustainability issues related to synthetic fertilizers for container-crop production, alternative fertilizers made from biorenewable, nonsynthetic sources have been explored. Some sources include fish emulsions, liquid soybean-based fertilizer, corn gluten meal, millorganite, and, more recently, soy-based bioplastics (Calabria et al., 2012; Nelson et al., 2010; Schrader et al., 2013, 2015; Yang et al., 2015). Schrader et al. (2013, 2015) have explored soy-based bioplastics as potential alternatives to petroleum plastics for container manufacturing and discovered that bioplastics that contain soy proteins can supply nutrients to plants growing in the containers.

Soy bioplastics show strong potential for use in fertilizers that can be more sustainable than common synthetic fertilizers. Soy-based materials are biologically based (bio-based) and readily available, and unlike synthetic N fertilizers that require large amounts of fossil-based energy to fix N₂ using the Haber–Bosch process, the plant-available N from soy bioplastic is fixed by symbiotic N₂ fixation in root nodules of soybean using energy from the sun through photosynthesis (Calabria et al., 2012; Sawyer et al., 2010; Schrader et al., 2013). Components typically used in soy bioplastic formulations include soy flour, soy protein concentrate, and/or soy protein isolate, and all of these soy-based products contain plant-essential macronutrients and micronutrients (U.S. Department of Agriculture, 2015).

In terms of function, soy bioplastic has some disadvantages when it is used without combining it with other bioplastic copolymers. High-percentage soy bioplastic has low stability in water and undergoes rapid decomposition and excessive nutrient release when used for horticultural applications (Schrader et al., 2013). Blending soy bioplastics with more stable bioplastics, such as PLA or PHA, eliminates these drawbacks (Currey et al., 2014; Grewell et al., 2014; Schrader et al., 2013). Bioplastic composite materials of PLA and soy bioplastics used for container manufacturing provide beneficial fertilizer nutrients to plants and can reduce or eliminate the need for supplemental synthetic fertilizers (McCabe et al., 2016; Schrader et al., 2013; Yang et al., 2015).

BC retains fertilizer chemicals (Laird et al., 2010; Yao et al., 2012), enhances plant growth, buffers detrimental effects of elevated pH conditions (Grabber et al., 2010; Northup, 2013), and acts as a means for carbon sequestration when used as a soil additive or amendment (Matovic, 2011; Spokas and Reicosky, 2009). Because some forms of BC are a fine black powder, it is difficult to apply without the addition of a binder or carrier. It is not feasible to apply unmodified BC powder because wind can carry the powder uncontrollably, and the dust is an inhalation

hazard. Thus, we developed novel, patent-pending fertilizers made from SP.A, PLA or PHA, and BC that are formed into dry pellets, and can be easily applied by common methods used for granular fertilizers. Pelletized SP.A-based fertilizers can be incorporated into growing media, could help reduce or eliminate the usage of synthetic fertilizers during plant production, and could improve sustainability of container-crop production. We hypothesized that SP.A-based bioplastics could serve as an effective fertilizer supplying biorenewable nutrients, as well as stabilize BC for ease of application.

Our objectives were to 1) perform initial trials of pelletized soy-bioplastic fertilizer to evaluate feasibility and proof of concept, 2) determine the effectiveness of soy-bioplastic fertilizer for meeting the nutrient requirements of three common greenhouse-grown species, 3) quantify SDM, plant health, and nutrient (N, P, and K) concentration, content, and uptake in plant shoots, and N, P, and K concentrations in leachate from containerized plants fertilized with soy-bioplastic fertilizers, and 4) compare the effectiveness of soy-bioplastic fertilizers to that of a commercial synthetic CRF.

Materials and Methods

Fertilizer production. The soy-based fertilizers were made from blends of soy bioplastic (SP.A) formulated with soy protein isolate (26%), soy flour (26%), water (31%), glycerin (8%), phthalic anhydride (4%), adipic acid (4%), sodium sulfite (1%), and potassium sorbate (<1%) by weight and compounded with Ingeo™ PLA 3001D (NatureWorks LLC, Minnetonka, MN) or PHA M2200 (Metabolix Inc., Cambridge, MA) and 70 mesh BC (Biochar Now LLC, Loveland, CO). The BC was produced from insect-killed and fire-damaged trees that were heated using a slow-pyrolysis combustion process and has a water-holding capacity 5.6 times its weight and a surface area of 400 m²/g of material. Before mixing with SP.A, the PLA was blended with polyethylene glycol (80:20 by weight) to lower its melt temperature to avoid thermal degradation of SP.A during extrusion. All ingredients (SP.A, PLA or PHA, and BC) were inserted into a 42-mm, corotating, extruder (Leistritz Advanced Technologies Corp., Nuremberg, Germany) via a screw-driven feeding hopper and compounded in one extrusion pass. After extrusion, the bioplastics were pulled across stainless steel tables to cool and into a pelletizer that chopped the strands into pellets that were 2 to 3 mm³ in size.

Fertilizer application. Four SP.A-based fertilizers were developed and used alongside a synthetic CRF [Nutricote 18.00N–2.60P–6.60K with a 140-d release period (Florikan ESA LLC, Sarasota, FL)]. Information for each fertilizer type is presented in Table 1. Fertilizers were applied by weighing the appropriate amount of fertilizer for the volume of substrate and incorporating it individually for each container. Fertilizer concentrations

Table 1. Nutrient concentrations [nitrogen (N), phosphorus (P), and potassium (K)] of soy bioplastic (SP.A)-based fertilizers and synthetic controlled-release fertilizer (CRF) used during experiments to grow ‘Honeycomb’ marigold, ‘Montego White’ snapdragon, and ‘Laser Synchro Scarlet’ cyclamen.

Fertilizer type	Nutrient concn (%)		
	N	P	K
SP.A–PLA–BC (42.5/42.5/15) ^a	3.33	0.23	0.57
SP.A–PLA–BC (37.5/37.5/25)	2.85	0.20	0.44
SP.A–PHA–BC (62.5/22.5/15) ^a	5.01	0.34	0.80
SP.A–PHA–BC (37.5/37.5/25)	3.08	0.21	0.48
CRF (140-d release)	18.00	2.60	6.60

SP.A = soy-based polymer; PLA = poly(lactic acid); PHA = polyhydroxyalkanoates; BC = biochar, CRF = synthetic controlled-release fertilizer [Nutricote (18.00N–2.60P–6.60K) (Florikan ESA LLC, Sarasota, FL)].

^aPercentage by weight of material (SP.A, PLA or PHA, and BC) in each fertilizer.

^bUsed during production of marigold, snapdragon, and cyclamen in 11.4-cm diameter containers.

were based on manufacturer’s N recommendations for the CRF. In Expt. 1, treatments of 346 and 691 g N/m³ of substrate corresponded to low and medium rates of application based on the CRF label, respectively. In Expt. 2, treatments of 211, 423, 819, and 1638 g N/m³ of substrate correspond to low, medium, high, and heavy application rates based on the CRF label, respectively. Seedlings were transplanted after each fertilizer treatment was mixed into the container substrate on an individual basis.

Expt. 1. Production of marigold with four SP.A-based fertilizers and CRF. The first experiment was conducted to evaluate the efficacy of four SP.A-based fertilizers with a common annual species under suitable fertility levels. ‘Honeycomb’ marigolds were grown from seed in 288-celled plug trays (T.O. Plastics, Inc., Clearwater, MN) to ≈5 cm in height and transplanted into standard greenhouse containers with 15.2-cm top diameter (volume = 2.08 L) (Myers Industries, Akron, OH) filled with a soilless substrate (Sunshine® LB–2; Sun Gro Horticulture, Agawam, MA) that was amended with fertilizer-specific (type and concentration) treatments. The fertilizer treatments consisted of incorporating a defined amount of N (0-untreated, 346, or 691 g N/m³) on an individual-container basis, supplied from each fertilizer type (Table 1). The plant-container units were then placed in a glass-glazed greenhouse and were spaced 30-cm apart on expanded metal benches in a completely randomized design (n = 5 for each fertilizer type × concentration treatment) with no supplemental irradiance provided. Plants were irrigated individually with tap water only supplying enough water to moisten the media without causing leaching from the container substrate, and no additional fertilizer was provided beyond the original fertilizer treatments. Average daily temperature was 23.8 ± 2.0 °C, relative humidity (RH) ranged from 37.8% to 92.0% (mean = 74.7%), and the daily mean photosynthetically active radiation (PAR) between 1000 and 1400 hr was 340.8 μmol·m⁻²·s⁻¹.

After 4 and 8 weeks of growth, leachate samples were collected from each plant/container unit by using the PourThru extraction procedure (Cavins et al., 2008; LeBude and Bilderback, 2009) and were analyzed for pH and electrical conductivity (EC) using a handheld pH-EC meter (HI 9813-6; Hanna

Instruments, Smithfield, RI). At termination of the experiment (8 weeks), plants in each experimental unit were rated for health (blind rating by two experienced horticulturists on a scale of 0 = worst/dead to 5 = best). Indicators of good health that resulted in high ratings included vigorous growth, dark green foliage, and an abundance of open flowers. Indicators of poor health that resulted in lower ratings included chlorosis, necrosis, stunted growth, and a lack of open flowers. After ascribing health ratings, plants were severed at the substrate surface, dried, and weighed to determine SDM. After SDM was recorded, three dried shoot samples from each treatment group were randomly selected and were analyzed for nutrients concentrations [N was determined using a flow injection analysis analyzer (8500 FIA; LACHAT Instruments, Loveland, CO) and P and K were determined using an inductively coupled argon plasma atomic emission spectrophotometer (Optima 7300 V ICP-OES; PerkinElmer Inc., Waltham, MA)] at AgSource Harris Laboratories (Lincoln, NE). Shoot nutrient content was calculated (nutrient content = nutrient concentration × SDM) for each plant-container unit analyzed. Results reported for SDM, health rating, and leachate pH and EC represent the mean of all replicates (n = 5), while results reported for shoot nutrient concentration and content represent the mean of three (n = 3) randomly selected replicates from the original five samples.

Expt. 2. Production of marigold, snapdragon, and cyclamen with two SP.A-based fertilizers and CRF. Two SP.A-based fertilizers containing 15% BC were chosen for evaluation in the second experiment, because reducing the BC content allowed for an increased concentration of SP.A in the fertilizer blend, thus reducing the amount of SP.A-based fertilizer required to supply equivalent N rates. ‘Montego White’ snapdragon produced in 288-celled plug trays and ‘Laser Synchro Scarlet’ cyclamen produced in 72-celled plug trays were received from a commercial greenhouse (Wagner’s greenhouse, Minneapolis, MN), and ‘Honeycomb’ marigolds were grown as in Expt. 1. Seedlings were transplanted into 11.4-cm top diameter containers (volume = 613 mL) (Myers Industries, Akron, OH) filled with soilless substrate (Sunshine® LB–2) that were amended with fertilizer-specific (type and concentration) treatments. Treatments consisted of

incorporating each fertilizer type (SP.A-based fertilizers or CRF) based on a defined amount of N (0-untreated, 211, 423, 819, or 1638 g N/m³) on an individual-container basis. The plant-container units were then placed in a glass-glazed greenhouse and spaced 25 cm apart on expanded metal benches in a completely randomized design with each species grown separately (n = 9 for each fertilizer type × concentration factorial treatment). Supplemental irradiance (16-h photoperiod) was provided via 1000-W high-pressure sodium lamps when ambient PAR decreased below 280 μmol·m⁻²·s⁻¹ and was discontinued when ambient PAR exceeded 380 μmol·m⁻²·s⁻¹. Plants were irrigated individually with tap water only supplying enough water to moisten the media without causing any leaching from the container substrate, and no additional fertilizer was provided beyond the original fertilizer treatments. When growing snapdragon and cyclamen, air temperature was maintained at 20.9 ± 0.3 °C and RH ranged from 14.3% to 70.8% (mean = 28.2%) for the first 5 weeks of production, after which snapdragons were harvested. Air temperature was maintained at 21.0 ± 0.5 °C and RH ranged from 10.7% to 70.8% (mean = 27.9%) for 10 weeks of production, after which cyclamen plants were harvested. Marigolds were grown in a separate greenhouse in which air temperature was maintained at 22.5 ± 1.9 °C and RH ranged from 5.9% to 93.0% (mean = 29.2%) for 5 weeks of production.

After 5 (all species) and 10 weeks (cyclamen only), leachate samples were collected from each plant/container unit by using the PourThru extraction procedure. Leachate samples were analyzed for nutrients [N was determined using a flow injection analysis analyzer (8500 FIA) and P and K were determined using an inductively coupled argon plasma atomic emission spectrophotometer (Optima 7300 V ICP-OES)] at AgSource Harris Laboratories. Shoots of marigold, snapdragon (after 5 weeks of growth) and cyclamen (after 10 weeks of growth) were severed at the substrate surface, dried, and weighed to determine SDM. Three

randomly compiled replicates comprising three plant samples of shoot tissue and leachate from each treatment factorial were analyzed for nutrients [N was determined using a flow injection analysis analyzer (8500 FIA) and P and K were determined using an inductively coupled argon plasma atomic emission spectrophotometer (Optima 7300 V ICP-OES)] at AgSource Harris Laboratories. Plants of snapdragon grown with either source of SP.A-based fertilizer incorporated at the two highest rates (819 or 1638 g N/m³) died, as well as marigolds grown with the highest rate (1638 g N/m³) of SP.A–PHA–BC, so no shoot analyses were conducted for these treatments. Shoot nutrient content was calculated similarly to Expt. 1 and was used in conjunction with initial seedling nutrient content to determine shoot nutrient uptake (shoot nutrient content—seedling shoot nutrient content = shoot nutrient uptake). The results reported for SDM represent the mean of all replicates (n = 9), while results reported for shoot nutrients and leachate represent the mean of three (n = 3) randomly compiled replicates of three samples within each treatment factorial.

Statistical analysis. Raw data were analyzed for analysis of variance (ANOVA), interactions, and mean-separation statistics by using JMP® Statistical Software (version Pro 10; SAS Institute, Cary, NC). Mean separations were determined using Tukey's honestly significant difference at *P* ≤ 0.05. No transformations were performed on data reported as percentages, because variances were homogeneous. Interaction and ANOVA statistics were only conducted on plants of snapdragon grown with 0, 211, or 423 g N/m³, and marigold grown with 0, 211, or 423, and 819 g N/m³, because of missing data from dead plants that received the higher rates of fertilizers.

Results

Expt. 1. Production of marigold with four SP.A-based fertilizers and CRF

Marigolds provided with SP.A-based fertilizers (all four types, at both rates) and the

synthetic CRF accumulated much more SDM, received much higher health ratings, and had much higher macronutrient content in their shoots after 5 weeks than nonfertilized control plants, but no differences were observed for nutrient concentrations (N, P, or K) in plant shoots receiving any treatment (Table 2). Within the low fertilizer rate treatment (346 g N/m³), SDM accumulation was similar for plants that received SP.A-based fertilizers compared with those that received synthetic CRF, except that SDM was lower for plants that received SP.A–PHA–BC (37.5–37.5–25). At the low application rate, visual health ratings were higher for plants that received CRF than for those that received SP.A-based fertilizers, but the health ratings were acceptable (>3.0) for plants that received the four SP.A-based fertilizer types (Table 2). At the medium fertilizer rate (691 g N/m³), SDM accumulation was similar for plants provided with SP.A–PLA–BC (37.5–37.5–25) and SP.A–PHA–BC (37.5–37.5–25) compared with those provided the synthetic CRF, but SDM was slightly lower for plants in two of the SP.A-based fertilizer treatments [SP.A–PLA–BC (42.5–42.5–15) and SP.A–PHA–BC (62.5–22.5–15)] than for those that received synthetic CRF (Table 2). Health ratings for plants receiving each SP.A-based fertilizer at the medium rate (691 g N/m³) were higher compared with the same fertilizers at the low rate (346 g N/m³). Alternatively, health ratings for plants in two of the SP.A fertilizer treatments [SP.A–PLA–BC (42.5–42.5–15) and SP.A–PLA–BC (37.5–37.5–25)] did not differ from those that received synthetic CRF at the medium rate (691 g N/m³). There were no differences in SDM across SP.A-based fertilizer types when the rate of N was the same (Table 2).

All substrates containing the different fertilizers and rates had a pH value that was within the recommended range of 5.0 to 6.5 for containerized crops in substrates after 4 and 8 weeks of growth. The EC values from

Table 2. Effects of fertilizer type and applied fertilizer (fert.) on shoot dry mass, plant health rating, PourThru leachate pH and electrical conductivity[EC (dS·cm⁻¹)], shoot nutrient concentration [nitrogen (N), phosphorus (P), and potassium (K)], and shoot nutrient content (N, P, and K) of marigold 'Honeycomb' grown for 8 weeks in containers with 15.2-cm top diameter.²

Fertilizer type	Applied Fertilizer (g N/m ³)	Shoot dry mass (g)	Health rating (0–5) ³	PourThru leachate				Shoot nutrient concn (%)			Shoot nutrient content (mg)		
				4 wk		8 wk		N	P	K	N	P	K
				pH	EC	pH	EC						
Untreated-pure water only	0	1.8 d ^c	0.5 f	5.8	2.5	5.9	0.9	1.64 a	0.37 a	2.09 a	32 b	7 c	38 c
CRF	346	21.1 ab	5.0 a	5.8	1.9	6.0	0.6	2.55 a	0.35 a	2.16 a	543 a	75 ab	461 ab
SP.A–PLA–BC (42.5–42.5–15) ^w	346	18.1 bc	4.0 c	5.8	2.8	5.9	0.5	1.61 a	0.42 a	2.24 a	300 ab	79 ab	417 ab
SP.A–PHA–BC (62.5–22.5–15)	346	19.1 bc	3.4 e	5.9	2.0	6.0	0.5	2.55 a	0.34 a	1.99 a	447 a	60 b	353 b
SP.A–PLA–BC (37.5–37.5–25)	346	18.3 bc	3.9 cd	5.9	2.3	6.0	0.6	2.12 a	0.37 a	2.21 a	390 ab	69 ab	405 b
SP.A–PHA–BC (37.5–37.5–25)	346	17.0 c	3.5 de	5.9	1.5	6.0	0.4	2.48 a	0.34 a	1.98 a	421 a	57 b	337 b
CRF	691	24.1 a	5.0 a	6.0	2.1	6.0	0.6	1.92 a	0.41 a	2.17 a	497 a	107 a	562 a
SP.A–PLA–BC (42.5–42.5–15)	691	17.9 bc	5.0 a	5.9	4.3	5.9	1.1	2.35 a	0.31 a	1.91 a	407 a	54 b	330 b
SP.A–PHA–BC (62.5–22.5–15)	691	18.5 bc	4.0 c	6.0	1.8	5.9	0.7	1.44 a	0.33 a	1.89 a	265 ab	61 b	353 b
SP.A–PLA–BC (37.5–37.5–25)	691	21.8 ab	4.8 ab	6.2	3.0	6.0	0.9	2.14 a	0.32 a	1.92 a	461 a	67 b	410 ab
SP.A–PHA–BC (37.5–37.5–25)	691	20.6 abc	4.5 b	6.1	1.6	6.0	0.5	2.07 a	0.37 a	2.07 a	424 a	77 ab	429 ab

CRF = controlled-release fertilizer [Nutricote (18.00N–2.60P–6.60K) with a 140-d release period (Florikan ESA LLC, Sarasota, FL)]; SP.A = soy-based polymer; PLA = poly(lactic) acid; PHA = poly(hydroxyalkanoates); BC = biochar.

²Container volume = 2.08 L.

³Plant health ratings were on a scale of 0 to 5 with 5 being best and 0 being worst. Each datum was the mean of blind ratings by two horticulturists.

⁴Letters indicate mean separation across all treatments by Tukey's honestly significant difference test at *P* ≤ 0.05 (n = 5 for shoot dry mass and health rating, n = 3 for shoot nutrient concentration and content).

⁵Numbers in parentheses indicate the relative percentage by weight of each bio-based component in the formulation.

leachate ranged from 1.6 to 4.3 after 4 weeks of growth and 0.4 to 1.1 after 8 weeks of growth indicating higher soluble salt release early in production followed by release amounts that were within recommended ranges for container substrates (Robbins and Evans, 2010) (Table 2). Although there were no differences in shoot nutrient concentrations (N, P, or K) for any of the fertilizer types at either of the application rates or the untreated plants, shoot nutrient content (total amount of each nutrient) was greater for plants that received each type of fertilizer than for plants in the nonfertilized control treatment (Table 2). Shoot N content was not different between plants that received SP.A-based fertilizers and those that received the synthetic CRF, regardless of rate. Shoot P and K contents were greater for plants fertilized with synthetic CRF than for plants in some of the SP.A-based fertilizer treatments, but none of plants that received SP.A-based fertilizer showed nutrient levels that would be considered deficient. Nonfertilized plants had the lowest P and K content compared with plants grown with all other fertilizer treatments (Table 2). The P content in plants receiving any fertilizer ranged from ≈ 7 to 15 times greater than the amount of P in the nonfertilized plants, and K content ranged from ≈ 9 to 15 times greater for plants receiving any fertilizer treatment than for plants in the nonfertilized control treatment (Table 2).

Expt. 2. Production of marigold, snapdragon, and cyclamen with two SP.A-based fertilizers and CRF

Marigold. The SDM of marigold was greater for plants fertilized with low and medium rates (211 and 423 g N/m³) of all three fertilizers than for plants in the nonfertilized control treatment (Table 3). The SDM of plants was also greater than the nonfertilized controls when plants received the high rate (819 g N/m³) of SP.A-PLA-BC fertilizer or synthetic CRF, as well as plants that received the heavy rate (1638 g N/m³) of CRF. Plants fertilized with 423 g N/m³ from SP.A-PLA-BC had greater SDM than plants fertilized with the same rate from SP.A-PHA-BC. Plants died when supplied with the heavy rate (1638 g N/m³) from SP.A-PHA-BC fertilizer, and SDM was reduced for plants receiving the heavy rate of SP.A-PLA-BC fertilizer compared with those that received lower rates (Table 3). Shoot N, P, and K concentrations were higher for plants fertilized with either type of SP.A-based fertilizer compared with plants that received synthetic CRF and those in the nonfertilized control, with the exception of plants fertilized with CRF supplying 1638 g N/m³ (Fig. 1). Shoot N uptake was greater for plants provided with the low rate (211 g N/m³) of SP.A-based fertilizers than for those that received CRF, and N uptake was similar across fertilizer types for plants fertilized at the medium rate (423 g N/m³), but N uptake diminished at higher rates when plants were fertilized with either of the SP.A-based fertilizers (Fig. 2). Few differences were observed in shoot P and K uptake of plants, except that plants

Table 3. Effect of fertilizer type and rate on shoot dry mass (g) for 'Honeycomb' marigold, 'Montego White' snapdragon, and 'Laser Synchron Scarlet' cyclamen grown in 11.4-cm top diameter containers² for 5, 5, and 10 weeks, respectively.

Fertilizer type	Applied fertilizer (g N/m ³)				
	0	211	423	819	1,638
Shoot dry mass (g)					
Marigold					
CRF	0.6 C ^a x	1.5 Ba	1.9 Ba	2.5 Aa	3.0 Aa
SP.A-PLA-BC	0.6 Ca	1.2 ABb	1.3 Ab	1.1 Bb	0.4 Cd
SP.A-PHA-BC	0.6 Ca	1.3 Aab	1.0 Bc	0.7 Cb	—
Fertilizer (F)	*** ^w				
Concentration (C)	***				
F × C	***				
Snapdragon					
CRF	0.26 Da	0.89 CDa	1.49 BCa	2.06 B	3.34 A
SP.A-PLA-BC	0.28 Ba	0.47 ABb	0.51 Ab	—	—
SP.A-PHA-BC	0.26 Aa	0.47 Ab	0.46 Ab	—	—
Fertilizer (F)	***				
Concentration (C)	***				
F × C	***				
Cyclamen					
CRF	0.5 Da	2.5 Ca	3.7 Ba	4.7 Ba	7.5 Aa
SP.A-PLA-BC	0.5 Da	2.1 BCab	2.8 ABab	3.3 Ab	1.4 Cb
SP.A-PHA-BC	0.5 Ca	1.8 Ab	2.0 Ab	1.4 Bc	0.6 Cb
Fertilizer (F)	***				
Concentration (C)	***				
F × C	***				

CRF = synthetic controlled-release fertilizer (18.00N–2.60P–6.60K with a 140-d release period); SP.A = soy-based polymer; PLA = poly(lactic) acid; PHA = polyhydroxyalkanoates; BC = biochar.

SP.A-PLA-BC (3.33N–0.23P–0.57K) and SP.A-PHA-BC (5.01N–0.34P–0.80K).

²Container volume = 613 mL.

^aUppercase letters indicate mean separation within a fertilizer type across applied N by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$ ($n = 3$).

^xLowercase letters indicate mean separation within an applied N treatment across fertilizer type by Tukey's HSD test at $P \leq 0.05$ ($n = 3$).

^wInteraction analyses were only performed on concentrations 0, 211, and 423 for snapdragon and 0, 211, 423, and 819 for marigold across the fertilizer types.

***Significant at $P \leq 0.001$.

—No means available because plants died.

supplied with the heavy rate (1638 g N/m³) from both SP.A-based fertilizers showed lower P and K uptake compared with plants fertilized with synthetic CRF at the same rate (Fig. 2). Nutrient concentrations in leachate were higher for container-plant units receiving SP.A-based fertilizers when compared with CRF as the rate of fertilizer increased, and were much higher than synthetic CRF at the high (819 g N/m³) and heavy (1638 g N/m³) application rates (Fig. 3). Leachate N concentrations were also higher for plant-container units receiving SP.A-PLA-BC compared with units receiving SP.A-PHA-BC across all fertilizer concentrations, except when supplied the medium rate (423 g N/m³).

Snapdragon. The SP.A-based fertilizers were not as effective during the production of snapdragon. At the lowest application rate (211 g N/m³), SDM was not different for plants that received any of the fertilizer treatments (including CRF) compared with the nonfertilized control (Table 3). At the medium application rate (423 g N/m³), plants that received SP.A-PLA-BC fertilizer and those that received the synthetic CRF accumulated greater SDM than the control, but SDM of plants that received SP.A-PHA-BC fertilizer was not different from nonfertilized control plants. At the high (819 g N/m³) and heavy (1638 g N/m³) application rates, plants that received synthetic CRF had even greater SDM, but plants that received high and heavy

rates of SP.A-based fertilizers died before the end of 5 weeks (Fig. 4). The N concentration in plants was greatest when plants were fertilized with 211 and 423 g N/m³ from either SP.A-PLA-BC or SP.A-PHA-BC, and was lower when fertilized with synthetic CRF (Fig. 1). Shoot P and K concentrations were similar for plants fertilized at the low rate (211 g N/m³) with each of the fertilizer types, but at the medium rate (423 g N/m³), P and K concentrations were greater for plants supplied with SP.A-PLA-BC fertilizer than for those supplied with CRF or SP.A-PHA-BC. Unlike the results for marigold, which showed similar nutrient uptake for SP.A fertilizers compared with CRF at most of the application rates, uptake of N, P, and K by snapdragon was greater for plants grown with synthetic CRF compared with plants grown with either SP.A-based fertilizer at all application rates except for the lowest (211 g N/m³) (Fig. 2). The N, P, and K concentrations in leachate were similar among the two types of SP.A-based fertilizers and the synthetic CRF at the low and medium rates of application, but nutrient content in leachate increased disproportionately for the two SP.A-based fertilizers at the high and extreme application rates compared with the synthetic CRF (Fig. 3).

Cyclamen. The SDM of cyclamen was greater for plants fertilized with low, medium, and high rates (211, 423, and 819 g N/m³) of

Fig. 1. Concentration (%) of nitrogen (N), phosphorus (P), and potassium (K) in shoots of marigold, snapdragon, and cyclamen. Marigolds and snapdragons were grown for 5 weeks and cyclamen were grown for 10 weeks in 11.4-cm top diameter containers (container volume = 613 mL) in a glass-glazed greenhouse and supplied with 0, 211, 423, 819, or 1638 g N/m³ from one of three fertilizers sources [SP.A-PLA-BC (3.33N–0.23P–0.57K), SP.A-PHA-BC (5.01N–0.34P–0.80K), or synthetic controlled-release fertilizer (CRF) (18.00N–2.60P–6.60K)] incorporated into soilless substrate. SP.A-PLA-BC consisted of a pelletized bioplastic that contained 42.5% (by weight) soy bioplastic (SP.A), 42.5% poly(lactic acid) (PLA), and 15% biochar (BC). SP.A-PHA-BC consisted of a pelletized bioplastic that contained 62.5% (by weight) of SP.A, 22.5% polyhydroxyalkanoates (PHA), and 15% BC. Uppercase letters indicate mean separation within an applied fertilizer treatment across fertilizer type by Tukey's honestly significant difference test at $P \leq 0.05$ ($n = 3$).

all three fertilizers than for plants in the nonfertilized control treatment (Table 3; Fig. 4). The SDM was greatest when plants were supplied with CRF at the heavy rate (1638 g N/m³), but no differences were observed when comparing plants grown with 211 or 423 g N/m³ from either CRF or SP.A-PLA-BC. At the high and heavy rates of application (819 or 1638 g N/m³), SDM was lowest for plants supplied with SP.A-PHA-BC; however, there was no difference in SDM between plants grown with SP.A-PHA-BC and SP.A-PLA-BC fertilizer supplied at 211 or 423 g N/m³ (Table 3). Within the SP.A-PHA-BC fertilizer type, plants grown with SP.A-PHA-BC applied at low and medium rates (211 or 423 g N/m³) had the greatest SDM, and SDM was lower for

plants receiving this fertilizer at higher rates (819 or 1638 g N/m³). Unlike the results for the other two species, shoot N concentrations were greatest in plants fertilized with CRF across all application rates, and plants fertilized with SP.A-PLA-BC and SP.A-PHA-BC fertilizer types had similar N concentrations across all fertilizer rates (Fig. 1). Shoot P concentrations were greater for plants fertilized with either SP.A-PLA-BC or SP.A-PHA-BC when compared with plants fertilized with CRF at medium, high, or heavy rates (423, 819, or 1638 g N/m³). Shoot K concentrations did not differ among plants fertilized at rates of 211 or 423 g N/m³ supplied from any of the three fertilizers, but K concentration was greater in shoots of plants that received the two SP.A-based

fertilizers at the heavy rate (1638 g N/m³), than in those that received CRF (Fig. 1). Shoot N uptake of plants grown with CRF was greater than plants fertilized with either of the SP.A-based fertilizers across all application rates (Fig. 2). The N uptake for plants that received CRF was 2.4 to 9.6 times greater than plants fertilized with SP.A-PLA-BC at high (819 g N/m³) and heavy rates (1638 g N/m³) of application, respectively, and 6 to 30 times greater than plants fertilized with SP.A-PHA-BC at high (819 g N/m³) and heavy rates (1638 g N/m³) of application, respectively (Fig. 2). Uptake of P and K by cyclamen increased similarly with increasing application rate for plants that received CRF and the SP.A-based fertilizers at the low, medium, and high rates, but

Fig. 2. Uptake (mg) of nitrogen (N), phosphorus (P), and potassium (K) in shoots of marigold, snapdragon, and cyclamen. Marigolds and snapdragons were grown for 5 weeks and cyclamen were grown for 10 weeks in 11.4-cm top diameter containers (container volume = 613 mL) in a glass-glazed greenhouse and supplied with 0, 211, 423, 819, or 1638 g N/m³ from one of three fertilizers sources [SP.A-PLA-BC (3.33N–0.23P–0.57K), SP.A-PHA-BC (5.01N–0.34P–0.80K), or synthetic controlled-release fertilizer (CRF) (18.00N–2.60P–6.60K)] incorporated into soilless substrate. SP.A-PLA-BC consisted of a pelletized bioplastic that contained 42.5% (by weight) soy bioplastic (SP.A), 42.5% poly(lactic) acid (PLA), and 15% biochar (BC). SP.A-PHA-BC consisted of a pelletized bioplastic that contained 62.5% (by weight) of SP.A, 22.5% polyhydroxyalkanoates (PHA), and 15% BC. Uppercase letters indicate mean separation within an applied fertilizer treatment across fertilizer type by Tukey's honestly significant difference test at $P \leq 0.05$ ($n = 3$).

uptake of P and K was much greater for plants provided the heavy rate of CRF compared with those that received SP.A-based fertilizers at the same rate (Fig. 2).

After 5 weeks of growth, N concentrations in leachate were similar for plant-container units of cyclamen that received SP.A-PLA-BC fertilizer and synthetic CRF at the low, medium, and high rates (211, 423, and 819 g N/m³), but N concentration was higher in leachate from units provided the heavy rate (1638 g N/m³) of SP.A-PLA-BC fertilizer than for those provided with CRF at the same rate (Fig. 3). The N concentration was lowest in leachate from units provided with SP.A-PHA-BC fertilizer, regardless of the rate. Leachate P concentrations from plant-container units fertilized with

SP.A-PLA-BC were greater across all fertilizer concentrations, except for those provided the heavy application rate (1638 g N/m³), where P concentrations were similar in leachate samples from units fertilized with the two types of SP.A-based fertilizer (Fig. 3). The concentration of P in leachate was similar for units that received CRF and those that received SP.A-PHA-BC at the low, medium, and high rates (Fig. 3). Concentrations of K were also greater for samples from units fertilized with SP.A-PLA-BC compared with either of the other fertilizer types at all application rates except 819 g N/m³, in which K concentrations were not different for units in the SP.A-PLA-BC and SP.A-PHA-BC fertilizer treatments supplied at the high rate (819 g N/m³) (Fig. 3).

After 10 weeks of growth, N concentration in leachate was highest for samples from plant-container units fertilized with CRF at the medium (423 g N/m³), high (819 g N/m³), and heavy (1638 g N/m³) rates of application (Fig. 3). Leachate samples obtained from plant-container units fertilized with either SP.A-based fertilizer had similar N concentrations regardless of application rate (Fig. 3). The P and K concentrations in leachate were similar or slightly higher for plant-container units fertilized with either SP.A-based fertilizer when compared with units fertilized with synthetic CRF at the low, medium, or high application rates. Plant-container units fertilized with either of the SP.A-based fertilizers at the heavy rate (1638 g N/m³) had much higher concentrations of P and K in leachate

Fig. 3. Concentration ($\text{mg}\cdot\text{L}^{-1}$) of nitrogen (N), phosphorus (P), and potassium (K) in leachate samples collected following the PourThru extraction procedure from marigold, snapdragon, and cyclamen grown in 11.4-cm top diameter containers (container volume = 613 mL). Samples were collected from marigolds and snapdragons after 5 weeks of growth and collected from cyclamen after 5 and 10 weeks of growth. All plants were grown in a glass-glazed greenhouse and supplied with 0, 211, 423, 819, or 1638 $\text{g N}\cdot\text{m}^{-3}$ from one of three fertilizer sources [SP.A-PLA-BC (3.33N-0.23P-0.57K), SP.A-PHA-BC (5.01N-0.34P-0.80K), or synthetic controlled-release fertilizer (CRF) (18.00N-2.60P-6.60K)] incorporated into soilless substrate. SP.A-PLA-BC consisted of a pelletized bioplastic that contained 42.5% (by weight) soy bioplastic (SP.A), 42.5% poly(lactic acid) (PLA), and 15% biochar (BC). SP.A-PHA-BC consisted of a pelletized bioplastic that contained 62.5% (by weight) of SP.A, 22.5% poly(hydroxyalkanoates) (PHA), and 15% BC. Uppercase letters indicate mean separation within an applied N treatment across fertilizer type by Tukey's honestly significant difference test at $P \leq 0.05$ ($n = 3$).

samples than units that were fertilized with CRF at the same fertilizer concentration (Fig. 3).

Discussion

Our research represents the first formal horticultural evaluations of pelletized, soy-based bioplastic (SP.A-based) fertilizers.

Results of our evaluations with prototype SP.A-based fertilizers show that all four fertilizer prototypes were easy to apply, provided plant-available macronutrients (N, P, and K) that were taken up by plants, were beneficial to plants at common rates of N application, improved the growth and health of plants compared with the nonfertilized controls, and were similarly effective

compared with synthetic CRF at common application rates, but with some variation by fertilizer type and plant species. Based on these results, this report serves as proof of concept that pelletized bioplastic fertilizers containing soy proteins are effective as alternative fertilizers that can replace synthetic fertilizers for containerized horticultural crops. Results of our evaluations also provide

Fig. 4. Plants of marigold, snapdragon, and cyclamen fertilized with 0, 211, 423, 819, or 1638 g N/m³ from one of three fertilizers sources [SP.A-PLA-BC (3.33N–0.23P–0.57K), SP.A-PHA-BC (5.01N–0.34P–0.80K), or synthetic controlled-release fertilizer (CRF) (18.00N–2.60P–6.60K)] incorporated into soilless substrate in 11.4-cm top diameter containers (container volume = 613 mL). SP.A-PLA-BC consisted of a pelletized bioplastic that contained 42.5% (by weight) soy bioplastic (SP.A), 42.5% poly(lactic) acid (PLA), and 15% biochar (BC). SP.A-PHA-BC consisted of a pelletized bioplastic that contained 62.5% (by weight) of SP.A, 22.5% polyhydroxyalkanoates (PHA), and 15% BC.

data that can be used to make specific conclusions about the performance, effectiveness, and limitations of the fertilizer prototypes, and provide information that may be helpful for improving future SP.A-based fertilizer formulations.

Hall et al. (2009) has reported that adoption of sustainable practices by horticultural producers is mostly influenced by ease of implementation and perceived associated risk. Our evaluations of SP.A-based fertilizers at the prototype stage demonstrate that the technology and practices related to pelletized bioplastic fertilizer could be easily implemented into a production setting. In our trials, the ease of application of SP.A-based fertilizers was identical to that of the commercial CRF. Issues related to perceived risk will need to be resolved before SP.A-based fertilizers can be commercialized. The prototype fertilizers performed well at common rates of N application (low and medium N) in both experiments (Tables 2 and 3), but a point of diminishing returns was reached at a lower application rates compared with the synthetic CRF, and there was a species-specific sensitivity to the SP.A-based fertilizers shown by snapdragon plants (Table 3; Fig. 4). Nelson et al. (2010) and Eaton et al. (2013) observed similar positive results producing containerized species with common fertilizer rates (49, 98, 196 mg N/L and 175 followed by 225 mg N/L) from soybean-based liquid fertilizers and organic fertilizers, respectively. Toxicity from excessive nutrient release early in production was most likely the cause of diminishing returns with SP.A-based fertilizers applied at high and heavy rates (Table 2; Fig. 3). This is in agreement with Bi et al. (2010) who found that substrate EC levels were higher during the beginning of experimentation (4 d after planting) compared with later (28 and 40 d after planting) when supplying fertilizer from noncomposted broiler litter-based organic fertilizers to containerized marigolds. Indications of excessive nutrient release from SP.A-based fertilizers can also be observed in results from leachate samples collected from cyclamen after 5 and 10 weeks. Concentrations of N and K in leachate were much higher in samples collected after 5 weeks when compared with samples collected after 10 weeks (Fig. 3). Although it is unlikely that growers would choose to fertilize any crop at an application rate considered to be heavy, our results indicate that it could be done successfully with synthetic CRF, but would be harmful to plants if attempted with the SP.A-based fertilizer prototypes. To ensure that growers are not reluctant to switch to novel SP.A-based fertilizers, more research will be required to improve formulations, minimize risks related to excessive application, and ensure reliability over a wider range of species and application rates.

Plants fertilized with SP.A-PHA-BC formulations in our experiments exhibited poorer growth at high application rates when compared with plants fertilized with SP.A-PLA-BC formulations (Table 3) and showed

lower health ratings at low and medium application rates compared with those receiving SP.A–PLA–BC (Table 2). These findings are in agreement with Schrader et al. (2015) who found that PLA was a better copolymer with SP.A than was PHA for promoting beneficial nutrient functions of SP.A bioplastics. The slightly poorer performance of SP.A-based fertilizers that included PHA as the stabilizing copolymer instead of PLA may be related to the higher degradability of PHA compared with PLA. As a result of their faster degradation, formulations that include PHA likely provide an increased carbon (C) availability for microbes (a microbe-friendly C/N ratio), and therefore a greater overall nutrient demand by microbes in the growing medium. If this is the case, the use of PHA as the stabilizing copolymer may increase nutrient uptake by microbes, which sequester a portion of the fertilizer N, making it unavailable for plant uptake. This explanation is consistent with our results for leachate nutrient concentration, which showed lower N concentration in leachate of SP.A–PHA–BC compared with SP.A–PLA–BC applied at the same rates of N (Fig. 3).

To improve formulations of SP.A-based fertilizers for more controlled nutrient release and reduced species sensitivity, future research should include blends that contain varying proportions of SP.A and PLA, blends with and without BC, and blends with additional nutrient-rich biorenewable materials, such as algae, chitin, or whey. Because we only examined a limited range of prototype formulations, all of which included BC, it could be beneficial for future studies with container crops to focus on blends that do not contain BC. BC was included in our prototype formulations because research has shown that it sequesters nutrients (Laird et al., 2010), enhances plant growth, buffers pH (Grabber et al., 2010; Northup, 2013), and acts as a means of carbon sequestration in field-crop production (Matovic, 2011; Spokas and Reicosky, 2009). Powdered BC is also difficult to apply due to uncontrolled dispersal by wind, and it poses an inhalation hazard. The objective of blending BC with SP.A-based bioplastics was to capitalize on benefits of BC in the fertilizer mixture and to determine if BC can be stabilized with bioplastics similar to previous research showing success incorporating other bio-based additives or fillers into bioplastics (Lu et al., 2014a, 2014b; Madbouly et al., 2014; Yang et al., 2015). Although our plant-growth results were variable compared with a commercial fertilizer, our results show that compounding BC with SP.A-based bioplastics can eliminate hazards associated with BC application. We theorized that BC in our formulations would help sequester nutrients and slowly release them back to plants over time, and this theory may be even more applicable in other production systems where BC can be used as a soil amendment. Although our experiments were not designed to determine the specific effects of BC in our prototype fertilizers, we can conclude that our fertilizers were effective with the BC

included. Research conducted by Schrader et al. (2013) demonstrated that blending SP.A and PLA at equal proportions results in a bioplastic that is more durable and more functional than bioplastics made entirely of SP.A, and that blending PLA with SP.A helped moderate nutrient release to beneficial levels for plant growth. Our results indicate that the effectiveness of SP.A–PLA blends for providing plant-available nutrients may be reduced when BC is included in the formulation. More research is needed to provide a definitive conclusion on the value of including BC in SP.A-based fertilizer formulations.

Because of the lower nutrient concentrations, specifically N (2.85–5.01% N), in the SP.A-based fertilizer prototypes compared with CRF, a larger quantity had to be applied to achieve equivalent N across fertilizer types (Table 1). Incorporating other protein sources or biorenewable fertilizing products into bioplastic formulations could increase nutrient concentrations and help reduce the amount of fertilizer needed. Reducing the amount of fertilizer applied may be important because we visually observed prolific microbial growth in the substrate of containers that received higher rates of SP.A-based fertilizers (high and heavy rates), which may have contributed to the high EC values observed in leachate after 4 weeks of growth (Table 2). Microbial growth was concentrated around individual pellets of SP.A-based bioplastics. This observation is in agreement with Schrader et al. (2013) and Helgeson et al. (2009) who observed microbial growth on SP.A-based and zein bioplastic containers, respectively, and that microbial growth plays a beneficial role in nutrient conversion and disassociation from the bioplastics. In our trials, the root medium was maintained under consistently moist conditions, and it is likely that the moist conditions led to heavier microbial growth and more rapid nutrient disassociation than if plants were grown at more moderate moisture levels. Increasing the nutrient concentrations (N, P, or K) of the bioplastics would decrease the amount of fertilizer needed and may reduce available surface area for microbial growth to occur, thus facilitating a better rate of nutrient release when used for container crops. Another possibility to achieve more favorable nutrient release would be applying smaller portions of fertilizer over time by topdressing on a weekly, biweekly, or monthly basis. Applying smaller portions would reduce the total amount of bioplastic fertilizer entering the system at any specific time, and would potentially reduce microbial growth and expand the period of nutrient release for the duration of crops grown.

This report demonstrates proof of concept that pelletized SP.A-based bioplastics can be effective as fertilizer for plants growing in containers, as well as act as an effective means for application of BC. Although our results indicate that the prototype SP.A-based fertilizers in our trial do not match the effectiveness of a commercial synthetic fertilizer at all application rates and for all species, our results demonstrate the strong

potential for development of pelletized bioplastic fertilizer that can consistently meet the nutritional requirements of plants when incorporated into soilless substrate. Continued development of pelletized bioplastic fertilizer should improve its effectiveness across application rates, reduce potential species sensitivity risks, and ensure growers can easily implement the fertilizers into their current production systems. With increased demand by consumers for sustainably produced products, horticulturists must address the industry's heavy dependence on synthetic fertilizers that consume extensive amounts of fossil fuels during manufacturing and are considered among the greatest sources of environmental pollution (Carpenter et al., 1998; Pelletier et al., 2008; Sawyer et al., 2010). With additional research and development, pelletized bioplastic fertilizers may provide growers with a simple, effective, and sustainable way to meet the nutrient requirements of crops, while avoiding the environmental drawbacks of synthetic fertilizers.

Literature Cited

- Bi, G., W.B. Evans, J.M. Spiers, and A.L. Witcher. 2010. Effects of organic and inorganic fertilizers on marigold growth and flowering. *HortScience* 45:1373–1377.
- Calabria, L., N. Vieceli, O. Bianchi, R.V.B. de Oliveria, I. do Nascimento Filho, and V. Schmidt. 2012. Soy protein isolate/poly(lactic) acid injection-molded biodegradable blends for slow release of fertilizers. *Ind. Crops Prod.* 36:41–46.
- Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* 8:559–568.
- Cavins, T.J., B.E. Whipker, and W.C. Fonteno. 2008. PourThru: A method for monitoring nutrition in the greenhouse. *Acta Hort.* 779:289–297.
- Currey, C., J. Schrader, K. McCabe, W. Graves, D. Grewell, G. Srinivasan, and S. Madbouly. 2014. Soy containers: Growing promise, growing plants. *GrowerTalks* 79:60–65.
- Eaton, T.E., D.A. Cox, and A.V. Barker. 2013. Sustainable production of marigold and calibrachoa with organic fertilizers. *HortScience* 48:637–644.
- Grabber, E.R., Y.M. Harel, M. Kolton, E. Cytryn, A. Silber, D.R. David, L. Tsechansky, M. Borenshtein, and Y. Elad. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant Soil* 337:481–496.
- Grewell, D., G. Srinivasan, J. Schrader, W. Graves, and M. Kessler. 2014. Sustainable materials for horticultural application. *Plast. Eng.* 70:44–52.
- Hall, T.J., J.H. Dennis, R.G. Lopez, and M.I. Marshall. 2009. Factors affecting growers' willingness to adopt sustainable floriculture practices. *HortScience* 44:1346–1351.
- Helgeson, M.S., W.R. Graves, D. Grewell, and G. Srinivasan. 2009. Degradation and nitrogen release of zein-based bioplastic containers. *J. Environ. Hort.* 27:123–127.
- Laird, D., P. Fleming, B. Wang, R. Horton, and D. Karlen. 2010. Biochar impact on nutrient leaching from a midwestern agricultural soil. *Geoderma* 158:436–442.
- LeBude, A.V. and T.E. Bilderback. 2009. The pour-through extraction method: A nutrient

- management tool for nursery crops. N.C. State Univ. Coop. Ext. Bul. AG-717-W.
- Lu, H., S.A. Madbouly, J.A. Schrader, G. Srinivasan, K. Liu, K.G. McCabe, D. Grewell, M.R. Kessler, and W.R. Graves. 2014a. Biodegradation behavior of poly(lactic acid) (PLA)/distiller's dried grains with solubles (DDGS) composites. *ACS Sustain. Chem. Eng.* 2:2699–2706.
- Lu, H., S.A. Madbouly, J.A. Schrader, M.R. Kessler, D. Grewell, and W.R. Graves. 2014b. Novel bio-based composites of polyhydroxyalkanoates (PHA)/distillers dried grains with solubles (DDGS). *RSC Advances* 4:39802–39808.
- Madbouly, S.A., J.A. Schrader, G. Srinivasan, K. Liu, K.G. McCabe, D. Grewell, W.R. Graves, and M.R. Kessler. 2014. Biodegradation behavior of bacterial-based polyhydroxyalkanoates (PHA) and DDGS composites. *Green Chem.* 16:1911–1920.
- Matovic, D. 2011. Biochar as a viable carbon sequestration option: Global and Canadian perspective. *Energy* 36:2011–2016.
- McCabe, K.G., J.A. Schrader, C.J. Currey, D. Grewell, and W.R. Graves. 2016. Soy-composite biocontainers allow for reduced fertilizer inputs during container-crop production. *HortScience* 51:927–934.
- Nelson, P.V., D.S. Pitchay, C.E. Niedziela, Jr., and N.C. Mingis. 2010. Efficacy of soybean-based liquid fertilizer for greenhouse crops. *J. Plant Nutr.* 33:351–361.
- Northup, J.I. 2013. Biochar as a replacement for perlite in greenhouse soilless substrates. MS Thesis, Iowa State Univ., Ames, IA. Abstr. 13399.
- Pelletier, N., N. Arsenault, and P. Tyedmers. 2008. Scenario modeling potential eco-efficiency gains from a transition to organic agriculture: Life cycle perspectives on Canadian canola, corn, soy, and wheat production. *Environ. Mgt.* 42:989–1001.
- Robbins, J.A. and M.R. Evans. 2010. Growing media for container production in a greenhouse or nursery, part II (physical and chemical properties). 16 May 2016. <<http://www.uaex.edu/publications/PDF/FSA-6098.pdf>>.
- Sawyer, J.E., H.M. Hanna, and D. Petersen. 2010. Farm energy: Energy conservation in corn nitrogen fertilization. Agriculture and Environment Extension Publications. Book 196. 5 May 2016. <http://lib.dr.iastate.edu/extension_ag_pubs/196>.
- Schrader, J.A., G. Srinivasan, D. Grewell, K.G. McCabe, and W.R. Graves. 2013. Fertilizer effects of soy-plastic containers during crop production and transplant establishment. *HortScience* 48:724–731.
- Schrader, J.A., K.G. McCabe, G. Srinivasan, K. Haubrich, D. Grewell, S. Madbouly, and W.R. Graves. 2015. Development and evaluation of bioplastic container for sustainable greenhouse and nursery production. *Acta Hort.* 1104:79–88.
- Spokas, K.A. and D.C. Reicosky. 2009. Impacts of sixteen different biochars on soil greenhouse gas production. *Ann. Environ. Sci.* 3:179–193.
- U.S. Department of Agriculture. 2014. Floriculture crops 2013 summary. 5 May 2015. <https://www.nass.usda.gov/Statistics_by_State/New_Jersey/Publications/Floriculture_Statistics/FlorCrop-06-19-2014.pdf>.
- U.S. Department of Agriculture. 2015. National nutrient database for standard reference release 27. 5 May 2016. <<http://ndb.nal.usda.gov/ndb/foods>>.
- Yang, S., S.A. Madbouly, J.A. Schrader, G. Srinivasan, D. Grewell, K.G. McCabe, M.R. Kessler, and W.R. Graves. 2015. Characterization and biodegradation behavior of bio-based poly(lactic acid) and soy protein blends for sustainable horticultural applications. *Green Chem.* 17:380–393.
- Yao, Y., B. Gao, M. Zhang, M. Inyang, and A.R. Zimmerman. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* 89:1467–1471.