Horticultural evaluation of soy-based bioplastics for container-crop production

by

Kenneth Gene McCabe

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Horticulture

Program of Study Committee:
William R. Graves, Co-major Professor
Christopher J. Currey, Co-major Professor
David Grewell

Iowa State University

Ames, Iowa

2015

Copyright © Kenneth Gene McCabe, 2015. All rights reserved.
# TABLE OF CONTENTS

**CHAPTER 1. GENERAL INTRODUCTION, THESIS ORGANIZATION, AND LITERATURE REVIEW**

- Introduction 1
- Thesis Organization 3
- Literature Review 3
- Literature Cited 9

**CHAPTER 2. SOY-COMPOSITE BIOCONTAINERS ALLOW FOR REDUCED FERTILIZER INPUTS DURING CONTAINER-CROP PRODUCTION**

- Abstract 11
- Introduction 12
- Materials and Methods 16
- Results 19
- Discussion 21
- Literature Cited 25
- Tables and Figures 28

**CHAPTER 3. PELLETIZED SOY-BASED BIOPLASTIC FERTILIZERS FOR CONTAINER-CROP PRODUCTION**

- Abstract 43
- Introduction 44
- Materials and Methods 47
- Results 51
- Discussion 56
- Literature Cited 60
- Tables and Figures 62

**CHAPTER 4. GENERAL CONCLUSIONS**

- General Discussion 75
- Recommendation for Future Research 76

**ACKNOWLEDGMENTS** 79
CHAPTER 1. GENERAL INTRODUCTION, THESIS ORGANIZATION, AND LITERATURE REVIEW

Introduction

Petroleum-based plastics and fertilizers have become ubiquitous in the horticulture industry, and their use has raised concerns about the sustainability of producing plants in containers. Bioplastic materials have been developed as replacements that are more sustainable, but their use has been limited. More evaluations are needed to expand on current knowledge surrounding the use of bioplastics made from composites of soy-based [Glycine max (L.) Merr.] ingredients. Various soy-based bioplastic composites were used to fabricate containers and pelletized fertilizers to understand nutrient-release characteristics of bioplastic composites while producing plants. My first objective was to evaluate the growth and mineral nutritional status of a common greenhouse species [marigold (Tagetes patula L.)] grown in biocontainers that were manufactured with composite bioplastics containing various amounts of a soy-based biopolymer (soy bioplastic) and poly(lactic) acid (PLA) or polyhydroxyalkanoates (PHA), while fertilizing plants with five differing treatments. Five biocontainers types and petroleum-plastic containers were injection-molded on a prototype container mold and were used for a six-week growing period. The fertilizer treatments ranged from a low amount of fertilizer up to a standard amount used when producing marigold in petroleum-plastic containers. After six weeks of growth, shoots were harvested, dried, weighed for shoot dry mass (SDM), and analyzed for nutrient concentrations. Plants produced in soy-bioplastic composite containers had similar or higher SDM, as well as nutrient concentration and content, depending on the amount of fertilizer applied. Plants were healthiest in containers that were made from composite materials that contained soy bioplastic (50% by weight), and plants grown in containers made of soy bioplastic
and PHA were similar to plants grown in petroleum-plastic containers. When comparing plants in 50% soy bioplastic-50% PLA containers with plants produced in petroleum-plastic containers, nearly five times as much fertilizer was needed to ensure comparable plant growth in petroleum-plastic containers. This represents around an 80% reduction in fertilizer needed to produce quality plants in soy-based composite biocontainers.

My second objective was to evaluate the usage of soy-bioplastic composites that have been pelletized for use as a biologically-based (bio-based) fertilizer while growing three greenhouse-grown ornamental species [marigold, snapdragon (Antirrhinum majus L.), and cyclamen (Cyclamen persicum Mill.)]. Pelletized fertilizers were made from composites of soy bioplastic mixed with PLA or PHA and biochar (15% or 25% by weight), and were incorporated into soilless substrate. Two experiments were conducted. The first study consisted of growing marigold in round 15.2-cm (top diameter) containers with four bio-based fertilizers and a controlled-release fertilizer supplying nitrogen (N) at two concentrations (0.72 and 1.44 g N), as well as an untreated control (0 g N). After eight weeks of growth, root-zone leachate samples collected following the PourThru extraction procedure were analyzed for nutrient concentrations. Shoots were also harvested, dried, weighed for SDM, and then analyzed for nutrient concentrations. The second experiment consisted of growing marigold, snapdragon, and cyclamen in round 11.4-cm (top diameter) containers with two bio-based fertilizers and a controlled-release fertilizer supplying N at five concentrations [0 (control), 0.16, 0.32, 0.62, or 1.24 g N]. After five (marigold and snapdragon) and 10 (cyclamen) weeks of growth, root-zone leachate samples were collected. Shoots were also harvested, dried, weighed for SDM, and then analyzed for nutrient concentrations. In general, plants grown with a standard amounts of fertilizer, regardless of fertilizer source, showed similar growth or slightly less (not significant)
growth when fertilized with soy-bioplastic composites, throughout both experiments. A point of excess was reached when using any soy-bioplastic composites at amounts higher than would normally be applied (≥0.62 g N per plant). Plant uptake of nutrients did occur when fertilized with soy-bioplastic composite fertilizers, but diminished growth or death was observed at higher-than-normal concentrations of N. Pelletized soy-bioplastic composites are a promising fertilizer source for plants grown in containers, but more work should focus on reducing fertilizer toxicity and improving performance.

**Thesis Organization**

This thesis contains two manuscripts. The first manuscript, chapter 2, is formatted for submission to *HortScience*. It provides information about the fertilizing effects that can be achieved when using soy-bioplastic composite biocontainers for container-crop production. The second manuscript, chapter 3, is also formatted for submission to *HortScience*. It provides information about the usage and effectiveness of pelletized soy-based bioplastics as a fertilizer source while producing three greenhouse species. Chapter 4 provides general conclusions and recommendations for future research.

**Literature Review**

Container-crop production is a large sector of the horticulture industry, valued at $10.5 billion in 2009 (U.S. Department of Agriculture, 2010). Typical plant material produced in the container-crop industry includes herbaceous perennials, annual bedding and garden plants, foliage and florist plants, flowering plants, nursery stock, and young plants (plug seedlings, liners, tissue culture plantlets, and prefinished plants). The diversity of plant material grown in
the industry manifests problems related to production considerations, and that is where conventional-plastics and fertilizers have helped the industry excel. Plastic containers of all shapes and sizes and numerous fertilizers are used to grow plants throughout various young plant stages to finished plant material for retailing.

Petroleum plastics have become an essential tool in the horticulture industry and are utilized in numerous products including plant containers, sheeting and films for general covering, greenhouse coverings, pesticide containers, labels, trays, packs, irrigation supplies, etc. One area of horticulture that uses a great deal of plastic is container-crop production. Plastic containers have remained popular in the container-crops industry because of their consistent performance and adaptability to mechanization in various production systems. It is estimated that the industry uses nearly two billion pounds of petroleum plastic for production of four billion containers annually (Koeser et. al, 2013a; Schrader, 2013). Plastic containers facilitate better growing conditions for individual plants and allow for convenient handling. They are also light-weight, compatible with mechanized production, and suitable for shipping (Helgeson et al., 2009; McCabe et al., 2014). Plastic containers are adaptable to numerous types of plant-production systems regardless of species being grown and production time, but exhibit one functional problem. The nonporous characteristics of smooth-walled plastic containers facilitate root circling which can result in poor transplant establishment (Appleton, 1993; Evans and Karcher, 2004; Struve, 1993). Many of the environmental drawbacks of petroleum plastics are associated with disposal (Botts, 2007; Evans and Karcher, 2004; Helgeson et al., 2009). Plastic containers are typically used for a single production cycle and discarded in landfills. National recycling rates are low and only 9% of plastics that went into the municipal solid waste stream was recycled in 2013 (U.S. Environmental Protection Agency, 2015).
Fertilizers are also used extensively in horticulture and the container-crops industry. Because plants are grown in containers, it is important that the growing substrate used to culture plants is lightweight, has good drainage, and has adequate water-holding capacity. These requirements have pushed the expanded use of soilless growing mixes that primarily consist of sphagnum peat moss, perlite, vermiculite, bark, and other components or amendments that lack adequate amounts of mineral nutrients for plant production. Synthetic or inorganic fertilizers have filled the niche, and producers of plants in containers use large amounts of water-soluble fertilizers (WSF) and controlled-release fertilizers (CRF). The greenhouse industry uses around 54,500 metric tons of fertilizers annually which are typically synthetically produced and water-soluble (Nelson et al., 2010). Bio-based fertilizers are considered more sustainable and can reduce energy usage, global-warming impact, ozone depletion, and acidic emissions by 7.9 times, 6.4 times, 935 times, and 1.8 times, respectively when compared to synthetic N fertilizers in field production (Pelletier et al., 2008). Fertilizers derived from bio-based sources are gaining popularity among producers and consumers, and show potential to be an adequate source of nutrients for plants, but aren’t abundantly available for producers to employ.

To address concerns associated with the sustainability of the container-crops industry, alternative materials for containers and fertilizers are being explored. Biocontainers are being evaluated and promoted as new products that are sustainable and biorenewable (Helgeson et al., 2009; Helgeson et al., 2010; Kuehny et al., 2011; Koeser et al., 2013a; Koeser et al., 2013b; Beeks and Evans, 2013a and 2013b; Evans et al., 2010; Schrader et al., 2013 and 2015; Evans and Karcher, 2004). Biocontainers are loosely defined as containers not derived from petroleum plastic that degrade when composted or buried in soil (Evans et al., 2010). Many biocontainers exist and are already commercially available. The base material of most is plant fiber, but such
containers lead to poor water-use efficiency and have other production inadequacies such as lack of durability (Koeser et al., 2013b; McCabe et al., 2014). Newly developed bioplastics made from soy-based materials show improved potential for use in horticultural products such as containers and fertilizers.

Soy-based bioplastics are bio-based and offer several advantages compared to petroleum plastics. The raw materials for soy-based bioplastics are readily available, they contain and release plant-available nutrients, and the degradability of other bioplastic polymers may be enhanced when blended with soy-based bioplastics (Grewell et al., 2013; Schrader et al., 2013). The main components of soy-based bioplastics are soy flour, soy protein isolate (SPI), or soy protein concentrate, all of which contain protein that comprises plant-essential macronutrients and micronutrients in varying amounts (U.S. Department of Agriculture, 2015). The two primary drawbacks associated with using soy bioplastics for horticultural applications are low stability of the bioplastic in water and rapid breakdown coupled with excessive nutrient release (Schrader et al., 2013). These issues may be mitigated or eliminated by compounding soy bioplastics with other bioplastics that are more stable.

Another bioplastic that shows promise for use in the horticulture industry is PLA. Poly(lactic) acid is the most widely produced biopolymer, and the largest producer of biopolymers in the world reports an annual production of 140 million kilograms (NatureWorks LLC, 2015). This production capacity shows the potential to replace a portion of the 750 million kilograms of plastic required by the horticulture industry for containers (Schrader, 2013; Schrader et al., 2013; U.S. Department of Agriculture, 2010). Poly(lactic) acid is durable and functionally very similar to conventional plastics, including its capacity to be molded. It is not biodegradable in soil, but can be composted, and doesn’t have to be clean to be recycled to lactic
acid (NatureWorks LLC, 2015). Poly(lactic) acid is a stable bioplastic material that can enhance stability in moisture-rich environments, durability, and regulation of nutrient release from soy bioplastics.

Another bioplastic, PHA, also compares favorably to conventional plastics for use in the horticulture industry. It is biodegradable in soil and can be produced synthetically, in bacteria, or in transgenic plants (Mooney, 2009). Metabolix, Inc., Ball Horticultural Company, and Floral Plant Growers, LLC produced a PHA-based (Mirel®) biocontainer called the SoilWrap® that is biodegradable. Mirel® is biodegradable in soil, as well as marine environments, and is said to perform similar to petroleum plastics (Metabolix Inc., 2015). SoilWrap® biocontainers function as a sleeve because there is no bottom. This means that the containers must be placed in a shuttle/transport tray to keep media from falling out the bottom until plants have become established. Koeser et al. (2013a) evaluated the SoilWrap® alongside other biocontainers and determined that the SoilWrap® is a viable option because of a balance between water use and plant growth. Unfortunately, the supply of PHA has been limited, and cost of PHA bioplastics has remained relatively expensive compared to petroleum plastics.

Many bioplastics can be molded similar to petroleum-based plastics, are biorenewable, and are biodegradable or compostable (NatureWorks LLC, 2015; Metabolix Inc., 2015). This allows for multiple methods of molding and expands the availability of various options of disposal. Depending on the type of bioplastics used for manufacturing, consumers can dispose of bioplastics by burying in soil or composting. If the bioplastics aren’t biodegradable or cannot be composted, they can be recycled through industrial composting at applicable facilities.

Bioplastics developed and evaluated at Iowa State University that contain soy-based biopolymer, show promise for container and pelletized fertilizer manufacturing. Preliminary and published
research has shown that containers made with a high-percentage soy bioplastic (100%) disintegrated quickly (< 4 weeks) and released N at an excessive amount, whereas composite bioplastics of soy-based bioplastic and PLA were more favorable. Blending soy-based bioplastic with PLA reduced N release to acceptable levels for plant growth, and increased structural durability compared to containers with a high-percentage soy-bioplastic (Schrader et al., 2013). Soy–PLA biocontainers released N at a more favorable rate (275 mg·L⁻¹) compared to both high-percentage soy-bioplastic containers (623 mg·L⁻¹) and petroleum-plastic containers (68 mg·L⁻¹) after three weeks of plant growth. Schrader et al. (2013) also observed that soy–PLA containers reduced root circling of plants. This can be of particular interest for producers of perennial plant material and nursery stock, because root circling can be detrimental when plants are removed from the original container and transplanted into the landscape without proper root-ball preparation.

In summary, soy-based bioplastic composites show potential to be an alternative to petroleum plastics for containers, as well as a source of mineral nutrients for plants during crop production. To further understand how soy-based bioplastics and composites can be implemented in the horticulture industry, it will be important to assess how these new materials fit into current greenhouse operations. More evaluations are key to ensuring successful implementation and will help expand the use of renewable materials in the horticulture industry.
Literature Cited


CHAPTER 2. SOY-COMPOSITE BIOCONTAINERS ALLOW FOR REDUCED FERTILIZER INPUTS DURING CONTAINER-CROP PRODUCTION

A paper to be submitted to HortScience

Kenneth G. McCabe, James A. Schrader, Christopher J. Currey, David Grewell, Samy Madbouly, and William R. Graves

Abstract

Various biocontainers are emerging into the horticultural containerized-plant market as potential alternatives to petroleum-plastic containers. Most commercially-available biocontainers are manufactured using natural fiber-based materials, but growers’ acceptance and use has been limited because of their relatively high cost, low structural strength and durability, and poor water-use efficiency (McCabe et al., 2014). Another group of emerging materials that exhibit more favorable characteristics for container fabrication are bioplastics and bioplastic composites. Because biocontainers made from composite materials of soy [Glycine max (L.) Merr.] bioplastic and poly(lactic) acid (PLA) released nitrogen (N) at an amount suitable for quality plant growth, we hypothesized that fertilizer applications can be reduced, while maintaining adequate nutrition levels for quality plant growth when growing in soy-composite biocontainers. To test this hypothesis and quantify potential reduction of fertilizer, we grew marigold ‘Honeycomb’ (Tagetes patula L.) in five soy-composite biocontainers and petroleum-plastic containers with five fertilizer treatments. The five biocontainers consisted of composites of soy bioplastic compounded with PLA or polyhydroxyalkanoates (PHA), as well as a proprietary bioplastic material (Protein + PLA). Petroleum-plastic containers were made from green polypropylene and
all containers were injection-molded on the same mold. The five fertilizer treatments administered consisted of supplying [in mg of N–phosphorus (P)–potassium (K)]; 1) 60–4–49; 2) 75–5–61; 3) 105–7–85; 4) 150–10–122; 5) 300–20–244. Marigolds growing in all Soy–PLA composite biocontainers and Protein + PLA biocontainers had higher concentrations and contents of N and P compared to plants growing in petroleum-plastic containers across all fertilizer treatments. Shoot K concentrations were highest for plants growing in all Soy–PLA and Soy–PHA biocontainers compared to plants growing in petroleum-plastic containers across all fertilizer treatments, while shoot K concentrations in plants growing in Protein + PLA biocontainers were equal to or lower than plants in petroleum-plastic containers. Total plant dry mass (shoot and root) was highest for plants growing in 50% Soy–50% PLA and Protein + PLA biocontainers across all fertilizer treatments but were similar when supplied with 300–20–244 mg of N–P–K. Our results support the hypothesis that reductions in fertilizer are possible when using soy-composite biocontainers, and the amount of soy bioplastic and copolymer (PLA vs. PHA) used in the biocontainer formulation impacts availability of nutrients for plants. PLA was a superior copolymer with soy bioplastic compared to PHA. Making composite biocontainers from equal parts soy bioplastic and PLA showed promise for plant growth, and demonstrated that fertilizer can be reduced by up to 80% when growing marigold.

**Introduction**

The bedding and garden plant industry, valued at $1.96 billion in 2013, is a large facet of the containerized-plant market. Within the potted-plant market, annual bedding and garden plants were valued at $1.36 billion and potted herbaceous perennials were valued at $602 million in 2012 (U.S. Department of Agriculture, 2014). A total of 609 million plants in containers were
sold in 2012 from both of the two plant categories, while approximately four billion plants in containers were sold throughout the entire container-crops industry. This is approximately 750 million kilograms of plastic waste generated by the container-crops industry for single-use plastic containers (Schrader, 2013; Schrader et al., 2013; U.S. Department of Agriculture, 2014). This large amount of nonrenewable plastic usage raises concerns about the sustainability of container-crop production. Disposal of used plastic materials accounts for many environmental drawbacks of petroleum-plastic containers, and only 8.8% of plastic waste generated in the municipal solid waste stream is recycled (Botts, 2007; U.S. Environmental Protection Agency, 2013; Evans and Karcher, 2004; Helgeson et al., 2009). Because large amounts of plastic waste generated and increasing concern about sustainable plant-production systems, producers and consumers are exploring alternatives that can perform similar to or better than petroleum plastic.

To address concerns surrounding petroleum-plastic containers, biocontainers are being developed as alternatives that are sustainable and biorenewable (Helgeson et al., 2009; Helgeson et al., 2010; Kuehny et al., 2011; Koeser et al., 2013a; Koeser et al., 2013b, Beeks and Evans, 2013a; Beeks and Evans, 2013b; Schrader et al., 2013; Evans and Karcher, 2004; McCabe et al., 2014). Many biocontainers are already commercially available, but the primary material of most is plant fiber, and such containers lead to poor water-use efficiency during plant production, inadequate structural strength when wet, and insufficient degradation in soil for end-of-life decomposition (Beeks and Evans, 2013b; Koeser et al., 2013b; McCabe et al., 2014). Newly developed biocontainers made from plant-protein and carbohydrate-based bioplastics show more potential than traditional fiber-based biocontainers for use in container-crop production.

Soy-based bioplastics offer several advantages for container fabrication because soy materials are abundantly available, soy-based bioplastics release plant-available nutrients, and
can enhance degradation of other bioplastic polymers (Grewell et al., 2014; Schrader et al., 2013). The components of soy-based bioplastics are soy flour (≈50% protein), soy protein concentrate (≈70% protein), and/or soy protein isolate (SPI) (≥90% protein), all of which contain plant-essential primary macronutrients and micronutrients (U.S. Department of Agriculture, 2015). Although soy bioplastics offer many advantages compared to petroleum plastics, they do have some drawbacks. Potential issues are low stability in water and excessive nutrient release coupled with rapid breakdown during plant production. These issues can be easily mitigated by compounding soy bioplastics with more stable bioplastics such as PLA and PHA (Grewell et al., 2014; Schrader et al., 2013; Currey et al., 2014). Previous bioplastic-container research has indicated that biocontainers made of composites of PLA and soy bioplastics exhibited adequate performance and additional functions over petroleum-plastic containers. These include intrinsic fertilizer and root improvement of plants produced in composite biocontainers, as well as enhanced degradation of compounded PLA compared to pure PLA in soil (Schrader et al., 2013; Yang et al., 2015).

Poly(lactic) acid is another bioplastic that shows promise for container manufacturing and is the most widely produced biopolymer. NatureWorks LLC (Minnetonka, MN), the largest producer of biopolymers in the world, can produce nearly 140 million kilograms annually (NatureWorks LLC, 2013a). This production capacity shows potential to replace a portion of the 750 million kilograms of plastic required by the horticulture industry for containers (Schrader, 2013; Schrader et al., 2013; U.S. Department of Agriculture, 2014). PLA is durable and functionally very similar to petroleum plastics and comes in various formulations for specific applications. Life-cycle assessment of PLA have reported that PLA production consumes less nonrenewable energy and material resources and generates fewer greenhouse gas and acidic
emissions compared to petroleum plastics (Groot and Borén, 2010; Hermansson, 2013). PLA exhibits slow (1–2 years or more) or no biodegradation in soil similar to petroleum plastic, but degradation can be improved by incorporation of biodegradable compounds (plant proteins, natural biomass fillers, and soy bioplastics) to facilitate end-of-life options for disposal in soil (Grewell et al., 2014). Postconsumer PLA can also be converted to lactic acid and repolymerized without any loss of polymer integrity (NatureWorks LLC, 2013b).

Biocontainers made of >50% soy bioplastic can degrade too quickly for greenhouse production and release excessive N. Schrader et al. (2013) found that N concentrations in leachate collected after three weeks of greenhouse culture were 623 mg·L⁻¹ for high-percentage soy-bioplastic biocontainers (> 50% soy bioplastic content) and N was predominately (>99%) in the form of NH₄⁺, leachate from plants growing in petroleum-plastic containers contained 68 mg·L⁻¹ of N, which was mainly from NO₃⁻. Excessive N concentrations from high percentage soy-bioplastic biocontainers resulted in plants with smaller shoot size and had lower plant dry weights than plants grown in Soy–PLA (50% Soy/50% PLA) composite biocontainers and petroleum-plastic containers. Blending soy bioplastic with PLA reduced N release to 275 and 457 mg·L⁻¹ after three and seven weeks, respectively, which were acceptable for greenhouse crop production. Composites with equal parts soy bioplastic and PLA also showed increased structural durability compared to high-percentage soy-bioplastic biocontainers.

To expand on previous research demonstrating nutrient-release characteristics from soy-composite biocontainers, we hypothesized that the release of nutrients from the bioplastics containing soy can allow for reduced fertilizer inputs during production of high-quality plants. To test this hypothesis, our objectives were to grow a common greenhouse species in various soy-composite biocontainers under differing fertilizer treatments. We specifically aimed to
evaluate plant growth and nutrient parameters of marigold grown in five soy-composite biocontainers and petroleum-plastic containers under five fertilizer treatments. To understand the nutrient-release dynamics of the bioplastic material, we also evaluated nutrient disassociation of N, P, and K from bioplastic pieces in water over time to elucidate the mechanism of nutrient release.

**Materials and Methods**

*Expt. 1. Container nutrition experiment*

Seeds of marigold ‘Honeycomb’ were sown in 288-celled plug trays (T.O. Plastics, Inc. Clearwater, MN) filled with a soilless germination substrate (Fafard Germination Mix, Sun Gro Horticulture, Agawam, MA). Once seedlings were ≈5 cm height, they were individually transplanted into five types of soy-composite biocontainers and petroleum-plastic containers filled with a soilless substrate (Sunshine® LB–2, Sun Gro Horticulture).

The container design was a smooth-walled round container with a flat bottom and four drainage holes, 11.4-cm top diameter, 9.7-cm height, a volume of 680 mL, and the wall thickness was 1.5 mm. The soy-composite biocontainers evaluated consisted of soy bioplastic [made of a soy-based polymer formulated with SPI (26%), soy flour (26%), water (31%), glycerin (8%), phthalic anhydride (4%), adipic acid (4%), sodium sulfite (1%), and potassium sorbate (<1%)] compounded with Ingeo™ PLA 3001D (NatureWorks LLC, Minnetonka, MN) at a 50/50% (by weight), soy bioplastic compounded with PLA at 33/67%, soy bioplastic compounded with PLA at 30/60% with an additional 10% of dried distillers grains and solubles (DDGS) as a low cost filler, and soy bioplastic compounded with PHA M2200 (Metabolix Inc., Cambridge, MA) at 33/67%. Polyhydroxyalkanoates bioplastic was used because it is a unique bioplastic that is
biodegradable, but we only developed one container material because of high cost and limited availability of the bioplastic. A proprietary bioplastic material [(Protein + PLA) Aspen Research, Maple Grove, MN] was also used. Petroleum-plastic containers were made of green polypropylene, and all container types were injection-molded on the same prototype container mold.

All container-plant units were arranged 10 cm apart in a glass-glazed greenhouse with fog cooling and radiant hot water heating on expanded metal benches. Each container-plant unit was fertilized once weekly with treatments outlined in Table 1. Supplemental lighting was supplied from 400-watt high-pressure sodium lamps suspended 1m above the plant canopy. Air temperature was maintained at 24.5 ± 6.4°C, relative humidity ranged from 30.2% to 87.9% (mean = 61.2%), and the mean photosynthetically active radiation (PAR) at 1200 HR was 656 μmol·m⁻²·s⁻¹ during the experiment.

After three and six weeks of plant growth, leachate samples were collected following the PourThru extraction procedure (Cavins et al., 2008; LeBude and Bilderback, 2009) and analyzed at the Soil and Plant Analysis Laboratory (Iowa State University, Ames, IA) for pH, electrical conductivity (EC), and concentrations of N, P, and K (data not reported). Upon termination of the experiment (six weeks of plant growth), all shoots and roots were dried and then measured for shoot dry mass, root dry mass, and total plant dry mass (shoot dry mass + root dry mass). After dry mass was recorded, dried shoots were analyzed for N, P, and K concentrations. Shoot nutrient content (mg) was calculated by multiplying concentration of nutrient (mg/g) in dried shoot tissue by shoot dry mass (g).
Expt. 2. Immersion of soy-bioplastic composite material in water

To understand the mechanism of N, P, and K mineral nutrient release from soy-composite materials, biocontainers samples were immersed in distilled-deionized water for a total of 12 immersion durations (0, 1, 2, 4, 8, 16, 24, 32, 48, 72, 96, and 120 hr). Biocontainer samples (2 g sample for each replicate) consisted of two square pieces (1 cm × 1 cm × 0.15 cm thick) that were cut from the sidewall of biocontainers made out of a mixture of soy bioplastic, PLA, and lignin (33% soy bioplastic/67% PLA/10% Lignin). Biocontainer samples were immersed in water by filling 60-mL sealable vials with 50 mL of distilled-deionized water and inserting the samples into solution for one of 12 immersion durations. Biocontainers samples were immersed randomly starting with the longest immersion time (120 hr) and finishing with the shortest immersion time (0 hr) to ensure that all water samples were ready for analysis at the same time and the bioplastic samples were removed immediately at the end of the experiment. For each immersion time, there were also samples of distilled-deionized water that didn’t contain biocontainer material to serve as an untreated control. The experiment was conducted in the dark at 20°C and consisted of a total of four replicates (vials) for each immersion duration and treatment combination. The pH and EC of samples were measured by using a handheld pH-EC meter (HI 9813-6; Hanna Instruments, Smithfield, RI), and analyzed for concentrations of N, P, and K [Harris Laboratories (Lincoln, NE)].

Experimental design and statistical analysis

All container-plant units were arranged in a completely randomized design (n = 5 for each container type × fertilizer treatment). Analyses of variance and mean-separation statistics were performed for all data using JMP® Statistical Software (version Pro 10; SAS Institute, Cary, NC). Mean-separation was performed using Tukey’s honestly significant difference (HSD) test
at $P \leq 0.05$. Regression analyses were performed using SigmaPlot (version 13: Systat Software, Inc., San Jose, CA).

**Results**

*Plant dry mass*

Total dry mass was greater for plants grown in 50%–50% Soy–PLA biocontainers (9.2 g) compared to plants in petroleum-plastic containers (5.6 g) when supplied with 60–4–49 mg N–P–K. No differences in dry mass were observed when supplying 300–20–244 mg N–P–K between all plants produced in soy-composite biocontainers and petroleum-plastic containers. Plants produced in 33%–67% Soy–PLA biocontainers had similar dry mass to plants produced in petroleum-plastic containers across all fertilizer treatments. Plants grown in Soy–PHA biocontainers had less dry mass compared to plants in petroleum-plastic containers when fertilized with 105–7–85 or 300–20–244 mg N–P–K (Table 2). The SDM was ≈1.8 times (60 mg N) greater for plants grown in 50%–50% Soy–PLA biocontainers (7.0 g) and Protein + PLA biocontainers (6.8 g) compared to plants grown in petroleum-plastic containers (3.8 g). No differences in SDM were noted when supplying 300–20–244 mg N–P–K for plants produced in any container type (Table 2, Fig. 1).

*Shoot nutrient concentration*

Shoot N concentrations were 1.5 (300–20–244 mg N–P–K) to 4.1 (60–4–49 mg N–P–K) times greater for plants grown in 50%–50% Soy–PLA biocontainers compared to shoots of plants grown in petroleum-plastic containers. Plants grown in biocontainers with reduced amounts of soy bioplastic (Soy–PLA at 33%–67%, Soy–PLA + DDGS, and Soy–PHA) had lower shoot N concentrations than plants in 50%–50% Soy–PLA biocontainers across all
fertilizer treatments except for Soy–PLA + DDGS, when plants were supplied with 300–20–244 mg N–P–K (Table 3). Shoot P concentrations were greater for plants produced in 50%–50% Soy–PLA biocontainers compared to petroleum-plastic containers across all fertilizer treatments. Plants grown in biocontainers made from Protein + PLA had greater shoot P concentration across all fertilizer treatments when compared to plants grown in all other containers (Table 3). Shoot K concentrations were 1.5 to 2.2 times greater for plants grown in 50%–50% Soy–PLA biocontainers compared to plants grown in petroleum-plastic containers. The lowest concentration of K was in plants produced in Protein + PLA biocontainers and provided with 75–5–61 or 105–7–85 mg N–P–K, and plants grown in Soy–PLA + DDGS biocontainers also had lower concentrations of K when provided with 105–7–85 mg N–P–K treatment (Table 3).

Shoot nutrient content

Since SDM varied across container and fertilizer treatments, we calculated shoot N content and it was 1.6 to 7.7 times greater for plants grown in 50%–50% Soy–PLA biocontainers compared to plants in petroleum-plastic containers. The N content in plants grown in Soy–PHA biocontainers was similar to plants grown in petroleum-plastic containers. Marigolds in both 50%–50% Soy–PLA biocontainers and in Protein + PLA biocontainers had the highest N content across all fertilizer treatments, except for 300–20–244 mg N–P–K, and plants in Soy–PLA + DDGS biocontainers had similar N content (Table 4). Plants grown in 50%–50% Soy–PLA biocontainers also had 1.6 to 5.0 times greater P content compared to plants in petroleum-plastic containers, while plants grown in Protein + PLA containers had the highest shoot P content across all fertilizer treatments when compared to all other container types. Plants produced in Soy–PHA biocontainers had similar P content compared to plants in petroleum-plastic containers when fertilized with 105–7–85, 150–10–122, or 300–20–244 mg N–P–K (Table 4). Shoot K
content was also greater (1.6 to 4.0 times) for plants produced in 50%–50% Soy–PLA biocontainers compared to plants in petroleum-plastic containers. Plants produced in 50%–50% Soy–PLA biocontainers had the highest shoot K content compared to plants in all other container types across all fertilizer treatments, except for plants fertilized with 300–20–244 mg N–P–K and grown in Soy–PLA + DDGS biocontainers (Table 4).

*Immersion of soy-bioplastic composite material in water*

Over time, pH decreased initially then leveled off in water samples containing biocontainer material and the pH of water only samples decrease slightly but remained near the same level (pH ~ 5.8) regardless of immersion time (Fig. 2). The EC for water samples containing biocontainer material increased with an increase in immersion duration, while no ions were detected for samples that contained water only (EC = 0) (Fig. 3). The EC in samples that contained biocontainer material increased the most during the first 48 hr of immersion and then slowed, but still continued to increase through 120 hr (Fig. 3). Similar to EC, concentrations of both P and K increased over time, while concentration of N was unaffected by time. Both P and K concentrations increased similarly and were at similar concentrations (Fig. 4). Concentrations of P and K increased rapidly within the first 48 hr and followed a similar trend when compared to EC readings over time (Figs. 3 and 4).

**Discussion**

Reluctance to change from growers and producers has been an issue driving development and implementation of alternatives to petroleum plastics for container manufacturing (Koeser et al., 2013a). This may be diminished with the introduction of new bioplastics and biocomposites that perform similar to or better than petroleum-plastics for plant containers. Soy-composite
biocontainers have additional functions compared to petroleum-plastic containers beyond material renewability, and this may be a driving force that facilitates expanded use of biocontainers for plant production. Soy-composite biocontainers open up new end-of-life options for container disposal, can reduce fertilizer inputs during crop production, and can enhance transplant establishment because of improvements in root structure and growth (Schrader et al., 2013). These are all added benefits that may allow growers and producers to market plant material grown in soy-composite biocontainers in various niche markets and produce plants more sustainably, while becoming less dependent on finite and fossil-based resources.

The fertilizer function of soy-composite biocontainers has the potential to reduce fertilizer inputs during plant production and the inherent source of nutrients that are supplied by the bioplastics is also an attribute. Most synthetic N fertilizers are manufactured by the Haber-Bosch process, which consumes large amounts of energy (Pelletier et al., 2011; Razon, 2014) compared to N supplied from soy-bioplastics, which is from natural and biological N fixation. It’s estimated that using plant-derived N fertilizers can reduce energy usage, global-warming impact, ozone depletion, and acidic emissions by 7.9 times, 6.4 times, 935 times, and 1.8 times, respectively, when compared to synthetic N fertilizers (Pelletier et al., 2008). Beyond benefits of the fertilizer source, intrinsic fertilizer supplied by soy-composite biocontainers could also facilitate reductions in cost and labor that are directly associated with fertilizer applications during plant production.

Plant growth varies with the type of soy-composite biocontainer used. Of the five biocontainer types we evaluated, two materials (50% Soy–50% PLA and Protein + PLA) provided adequate amounts of fertilizer for quality growth of marigolds when supplied with 100 mg·L⁻¹ N once per week for two weeks only (60–4–49 mg N–P–K). Fertilizer provided from
these two biocontainer types was enough to sustain similar plant growth under the lowest fertility level (60 mg N) when compared to plants that were grown in petroleum-plastic containers fertilized with a more typical amount of fertilizer (200 mg·L⁻¹ N once per week for six weeks–300 mg N). Shoot N content was also greater in many of the plants grown in soy-composite biocontainers compared to the amount of N applied for each fertilizer treatment. This indicates the possibility to reduce fertilizer inputs by up to 80% when growing common species such as marigold.

Results show that fertilizer applications (50–100 mg·L⁻¹ N) are crucial in early stages of growth, but can be discontinued approximately two weeks after transplant. This lag time may be because both physical and microbial breakdown of the soy-bioplastic fraction. Results from immersing biocontainer material in water suggest both forms of breakdown (microbial and physical) work in conjunction to release nutrients and make them available to plants. When examining concentration of N compared to P or K, there was no increase of N, while both P and K increased over time (Fig. 4). This is in agreement with Calabria et al. (2012) who found that a bioplastic blend of SPI and PLA released ions (did not differentiate between N, P, and K) into an aqueous solution over time, contributing to an elevated EC. This suggests both P and K may be readily released through nutrient disassociation in an aqueous environment. Alternatively, N release may be influenced by microbial breakdown of the soy bioplastic. Schrader et al. (2013) found NH₄⁺ and NO₃⁻ were present in leachate collected from soy-composite biocontainers after three and seven weeks of culture in a greenhouse, with higher proportions of NH₄⁺ early (three weeks) in production and higher proportions of NO₃⁻ later (seven weeks), suggesting microbial conversion of N may be taking place by nitrifying microorganisms. Growers might overcome the
short lag time (2 weeks) by using growing substrates containing a starter fertilizer charge and irrigate with water only during the crop cycle.

Our results also indicate that more stable bioplastic materials are better suited for compounding with soy bioplastic than other, less stable materials. Soy bioplastic compounded with PLA at 33% soy bioplastic and 67% PLA was a superior material than containers made from 33% soy bioplastic and 67% PHA. This could be the result of PLA being less degradable than PHA, and thus, impacting the bioavailable C to N ratio in biocontainers. When comparing blends of PLA and PHA with 33% soy bioplastic, PLA was a better co-polymer for container production, indicated by higher nutritional content in plants and bioplastic stability of Soy–PLA biocontainers during production. All Soy–PLA biocontainers maintained integrity compared to Soy–PHA biocontainers, which degraded too quickly and began to lose structural integrity before termination of the experiment.

In conclusion, soy-composite bioplastics show potential to be a sustainable option for replacement of petroleum plastics commonly used in manufacturing of plant containers. The fertilizer effect was particularly promising when growing marigold in biocontainers made from equal parts soy bioplastic and PLA. Plants produced in these biocontainers were of better quality across all fertility treatments, and when fertilized with 60 mg N, were of equal dry mass or greater than, plants grown in petroleum-plastic containers fertilized with five times the amount of fertilizer (300 mg N). This attribute of soy-bioplastic biocontainers may propel expanded development and use of biorenewable and sustainable plant containers in the horticulture industry and beyond.
Literature Cited


Table 1. Five fertilizer treatments (TRT) administered by applying 300 mL of a 16.6% nitrogen (N)–5% phosphorus (P)–16.3% potassium (K) water-soluble fertilizer mixed to supply N (mg·L⁻¹) at the corresponding fertilizer (Fert.) concentrations (conc.) once per week. The duration of time that the fertilizer was administered and the total mineral nutrients (mg N, P, and K) applied from that particular treatment are also included.

<table>
<thead>
<tr>
<th>TRT</th>
<th>Fert. conc. (mg·L⁻¹ N)</th>
<th>Duration</th>
<th>Applied nutrient (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>2 weeks only</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>5 weeks</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>100, 50</td>
<td>2 weeks, 3 weeks</td>
<td>105</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>5 weeks</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>5 weeks</td>
<td>300</td>
</tr>
</tbody>
</table>
Table 2. Effect of fertilizer treatment [five fertilizer treatments consisted of fertilizing once per week with 300 mL of a water-soluble fertilizer [16.6% nitrogen (N)–5% phosphorus (P)–16.3% potassium (K)] mixed to supply N at the corresponding concentrations; 1) 100 mg·L⁻¹ N for 2 weeks followed by no fertilizer for 3 weeks (60–4–49: mg N–P–K); 2) 50 mg·L⁻¹ N for 5 weeks (75–5–61: mg N–P–K); 3) 100 mg·L⁻¹ N for 2 weeks followed by 50 mg·L⁻¹ N for 3 weeks (105–7–85: mg N–P–K); 4) 100 mg·L⁻¹ N for 5 weeks (150–10–122: mg N–P–K); 5) 200 mg·L⁻¹ N for 5 weeks (300–20–244: mg N–P–K)] on total dry mass, shoot dry mass, and root dry mass of ‘Honeycomb’ marigold grown in five soy-composite biocontainers and a petroleum-plastic container.

<table>
<thead>
<tr>
<th>Container type (% by wt.)</th>
<th>60–4–49</th>
<th>75–5–61</th>
<th>105–7–85</th>
<th>150–10–122</th>
<th>300–20–244</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soy/PLA – 50/50</td>
<td>9.2 A⁺ᵇyz</td>
<td>9.0 Ab</td>
<td>10.4 ABb</td>
<td>10.9 ABab</td>
<td>12.5 ABa</td>
</tr>
<tr>
<td>Soy/PLA – 33/67</td>
<td>6.9 Bcd</td>
<td>6.6 BCd</td>
<td>8.2 Cbc</td>
<td>8.5 CDb</td>
<td>12.2 ABa</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>7.1 Bc</td>
<td>7.8 ABc</td>
<td>9.8 Bb</td>
<td>9.5 BCb</td>
<td>12.6 Aa</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>5.0 Cbc</td>
<td>4.0 Dc</td>
<td>5.7 Db</td>
<td>6.4 Db</td>
<td>10.6 Ba</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>9.4 Ac</td>
<td>9.7 Abc</td>
<td>11.4 Aabc</td>
<td>11.9 Aab</td>
<td>12.7 Aa</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>5.6 BCc</td>
<td>5.1 CDc</td>
<td>7.6 Cb</td>
<td>8.4 CDb</td>
<td>12.4 ABa</td>
</tr>
</tbody>
</table>

Container (C) ***
Fertilizer (F) ***
Table 2 continued

<table>
<thead>
<tr>
<th></th>
<th>Shoot dry mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shoot dry mass (g)</td>
</tr>
<tr>
<td>C × F</td>
<td>***</td>
</tr>
<tr>
<td>Soy/PLA – 50/50</td>
<td>7.0 Ac 6.7 Ac 7.7 ABbc 8.5 Aab 9.1 ABa</td>
</tr>
<tr>
<td>Soy/PLA – 33/67</td>
<td>5.0 Bcd 4.4 Bd 5.3 Cbc 6.0 CDb 8.3 BCa</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>5.2 Bc 5.5 Bc 6.8 Bb 7.1 BCb 9.5 ABa</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>3.2 Cbc 2.4 Cc 3.7 Db 3.9 Eb 7.4 Ca</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>6.8 Ac 6.9 Abc 8.3 Aab 8.2 ABabc 9.7 Aa</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>3.8 Cc 3.1 Cc 4.9 Cb 5.4 Db 8.5 ABCa</td>
</tr>
<tr>
<td>C</td>
<td>***</td>
</tr>
<tr>
<td>F</td>
<td>***</td>
</tr>
<tr>
<td>C × F</td>
<td>***</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Root dry mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Root dry mass (g)</td>
</tr>
<tr>
<td>C × F</td>
<td>***</td>
</tr>
<tr>
<td>Soy/PLA – 50/50</td>
<td>2.2 ABB 2.3 ABB 2.7 ABab 2.4 Aab 3.4 Aa</td>
</tr>
<tr>
<td>Soy/PLA – 33/67</td>
<td>1.9 ABB 2.2 ABB 2.9 ABab 2.5 Ab 3.9 Aa</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>1.9 ABB 2.3 ABab 3.0 ABA 2.4 Aab 3.1 Aa</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>1.8 ABB 1.6 Bb 2.0 Bb 2.5 Aab 3.2 Aa</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>2.6 Aa 2.8 Aa 3.1 Aa 3.7 Aa 3.0 Aa</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>1.8 ABD 2.0 ABcd 2.7 ABbc 3.0 Ab 3.9 Aa</td>
</tr>
<tr>
<td>C</td>
<td>***</td>
</tr>
<tr>
<td>F</td>
<td>**</td>
</tr>
<tr>
<td>C × F</td>
<td>*</td>
</tr>
</tbody>
</table>
Table 2 continued

\(^a\) Uppercase letters indicate mean separation within a fertilizer treatment across container type by Tukey’s honestly significant difference (HSD) test at \( P < 0.05 \).

\(^b\) Lowercase letters indicate mean separation within a container type across fertilizer treatment by Tukey’s HSD test at \( P < 0.05 \).

\(^*, **, ***\) Significant at \( P < 0.05, 0.01, \) or 0.001, respectively.

Soy = soy-based polymer, PLA = poly(lactic) acid, DDGS = dried distiller’s grains and solubles, PHA = polyhydroxyalkanoates, and AR = Aspen Research (Maple Grove, MN).
Table 3. Effect of fertilizer treatment [five fertilizer treatments consisted of fertilizing once per week with 300 mL of a water-soluble fertilizer [16.6% nitrogen (N)–5% phosphorus (P)–16.3% potassium (K)] mixed to supply N at the corresponding concentrations; 1) 100 mg·L⁻¹ N for 2 weeks followed by no fertilizer for 3 weeks (60–4–49: mg N–P–K); 2) 50 mg·L⁻¹ N for 5 weeks (75–5–61: mg N–P–K); 3) 100 mg·L⁻¹ N for 2 weeks followed by 50 mg·L⁻¹ N for 3 weeks (105–7–85: mg N–P–K); 4) 100 mg·L⁻¹ N for 5 weeks (150–10—122: mg N–P–K); 5) 200 mg·L⁻¹ N for 5 weeks (300–20–244: mg N–P–K)] on N, P, and K shoot concentration of ‘Honeycomb’ marigold grown in five soy-composite biocontainers and a petroleum-plastic container.

<table>
<thead>
<tr>
<th>Container type (% by wt.)</th>
<th>60–4–49</th>
<th>75–5–61</th>
<th>105–7–85</th>
<th>150–10–122</th>
<th>300–20–244</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoot N conc. (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soy/PLA – 50/50</td>
<td>3.3 A’ab y</td>
<td>3.9 Aa</td>
<td>3.3 Aab</td>
<td>3.9 Aa</td>
<td>3.2 Ab</td>
</tr>
<tr>
<td>Soy/PLA – 33/67</td>
<td>1.9 Bb</td>
<td>2.2 Cab</td>
<td>1.8 Cb</td>
<td>2.4 BCa</td>
<td>2.6 Ca</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>1.8 Bb</td>
<td>2.9 Ba</td>
<td>2.6 Ba</td>
<td>3.0 Ba</td>
<td>3.0 ABa</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>1.5 BCc</td>
<td>1.8 CDbc</td>
<td>1.6 CDc</td>
<td>2.2 Cab</td>
<td>2.2 Ca</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>3.0 Aa</td>
<td>3.1 Ba</td>
<td>3.2 ABa</td>
<td>3.0 Ba</td>
<td>3.4 Aa</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>0.8 Cd</td>
<td>1.4 Dc</td>
<td>1.1 Dc</td>
<td>1.8 Cb</td>
<td>2.2 Ca</td>
</tr>
<tr>
<td>Container (C)</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer (F)</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C × F</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Shoot P conc. (%)
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Shoot K conc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soy/PLA – 50/50</td>
<td>2.9 Ab 3.0 Aab 2.8 ABb 3.0 Aab 3.4 Aa</td>
</tr>
<tr>
<td>Soy/PLA – 33/67</td>
<td>2.7 Ac 3.0 Aabc 2.8 ABbc 3.2 Aab 3.3 Aa</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>2.5 Ab 2.8 Aab 2.6 Bab 2.8 Aab 3.0 Aa</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>2.6 Ab 3.0 Aab 3.0 Aab 3.4 Aa 3.2 Aa</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>1.0 Bc 1.1 Cc 1.2 Dbc 1.6 Bb 2.2 Ba</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>1.3 Bc 1.8 Bb 1.7 Cbc 2.0 Bab 2.3 Ba</td>
</tr>
</tbody>
</table>

C  ***
F  ***
C × F  **

$^*$ Uppercase letters indicate mean separation within a fertilizer treatment across container type by Tukey’s honestly significant difference (HSD) test at $P \leq 0.05$. 
Table 3 continued

Lowercase letters indicate mean separation within a container type across fertilizer treatment by Tukey’s HSD test at $P \leq 0.05$.

**, *** Significant at $P \leq 0.01$, or 0.001, respectively.

Soy = soy-based polymer, PLA = poly(lactic) acid, DDGS = dried distiller’s grains and solubles, PHA = polyhydroxyalkanoates, and AR = Aspen Research (Maple Grove, MN).
Table 4. Effect of fertilizer treatment [five fertilizer treatments consisted of fertilizing once per week with 300 mL of a water-soluble fertilizer [16.6% nitrogen (N)–5% phosphorus (P)–16.3% potassium (K)] mixed to supply N at the corresponding concentrations; 1) 100 mg·L⁻¹ N for 2 weeks followed by no fertilizer for 3 weeks (60–4–49: mg N–P–K); 2) 50 mg·L⁻¹ N for 5 weeks (75–5–61: mg N–P–K); 3) 100 mg·L⁻¹ N for 2 weeks followed by 50 mg·L⁻¹ N for 3 weeks (105–7–85: mg N–P–K); 4) 100 mg·L⁻¹ N for 5 weeks (150–10–122: mg N–P–K); 5) 200 mg·L⁻¹ N for 5 weeks (300–20–244: mg N–P–K)] on N, P, and K shoot content of ‘Honeycomb’ marigold grown in five soy-composite biocontainers and a petroleum-plastic container.

<table>
<thead>
<tr>
<th>Container type (% by wt.)</th>
<th>N–P–K (mg)</th>
<th>Shoot N content (mg)</th>
<th>Shoot P content (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soy/PLA – 50/50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soy/PLA – 33/67</td>
<td>227 A²c²</td>
<td>253 Abc</td>
<td>254 Abc</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>93 Bc</td>
<td>97 Dc</td>
<td>96 Cc</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>192 Cc</td>
<td>160 Cc</td>
<td>179 Bbc</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>203 Ab</td>
<td>213 Bb</td>
<td>261 Ab</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>30 Cd</td>
<td>44 Ec</td>
<td>56 Cc</td>
</tr>
<tr>
<td>Container (C)</td>
<td>***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer (F)</td>
<td>***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C × F</td>
<td>***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Shoot N content (mg) values followed by different letters indicate significant differences at p < 0.05.

* Shoot P content (mg) values followed by different letters indicate significant differences at p < 0.05.
Table 4 continued

<table>
<thead>
<tr>
<th></th>
<th>Shoot K content (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soy/PLA – 33/67</td>
<td>16 Cd 17 Ccd 20 Cc 26 Db 38 Ca</td>
</tr>
<tr>
<td>Soy/PLA + DDGS – 30/60 + 10</td>
<td>18 Cd 29 Bc 26 Bc 30 Cb 45 Ba</td>
</tr>
<tr>
<td>Soy/PHA – 33/67</td>
<td>9 Dc 10 Dc 11 Dc 15 Eb 28 Da</td>
</tr>
<tr>
<td>Protein + PLA (AR)</td>
<td>40 Ac 42 Abc 46 Abc 48 Ab 57 Aa</td>
</tr>
<tr>
<td>Petroleum plastic</td>
<td>5 Ed 6 Ed 9 Dc 14 Eb 28 Da</td>
</tr>
<tr>
<td>C</td>
<td>***</td>
</tr>
<tr>
<td>F</td>
<td>***</td>
</tr>
<tr>
<td>C × F</td>
<td>**</td>
</tr>
</tbody>
</table>

*Uppercase letters indicate mean separation within a fertilizer treatment across container type by Tukey’s honestly significant difference (HSD) test at $P \leq 0.05$.**
Table 4 continued

Lowercase letters indicate mean separation within a container type across fertilizer treatment by Tukey’s HSD test at $P \leq 0.05$.

**, *** Significant at $P \leq 0.01$, or 0.001, respectively.

Soy = soy-based polymer, PLA = poly(lactic) acid, DDGS = dried distiller’s grains and solubles, PHA = polyhydroxyalkanoates, and AR = Aspen Research (Maple Grove, MN).
Fig 1. ‘Honeycomb’ marigold (*Tagetes patula*) plants grown in five soy-composite biocontainers and petroleum-plastic containers at two fertilizer treatments supplying a total of 60–4–49 mg nitrogen (N)–phosphorus (P)–potassium (K), as well as 300–20–244 mg of N–P–K from a water-soluble fertilizer (16.6N–5P–16.3K). The various soy-composite biocontainers consisted of soy bioplastic compounded with poly(lactic) acid (PLA) at a 50% soy bioplastic/50% PLA (by weight), soy bioplastic compounded with PLA at 33 soy bioplastic/67% PLA, soy bioplastic compounded with PLA at 30 soy bioplastic/60% PLA with an additional 10% of dried distillers grains and solubles (DDGS), soy bioplastic compounded with polyhydroxyalkanoates (PHA) at 33% soy bioplastic/67% PHA, and a proprietary bioplastic material (Protein + PLA (AR)). The
petroleum-plastic containers were made of green polypropylene (PP). AR = Aspen Research, Maple Grove, MN.
Fig 2. The pH of 50mL water samples (n = 4) that contained either 2 g of soy-composite biocontainer material or water only across 12 immersion times (0, 1, 2, 4, 8, 16, 24, 32, 48, 72, 96, and 120 hr). *** Significant at $P \leq 0.001$. 

- $y = 4.4594 + 0.2616(e^{-0.3741x})$
  $R^2 = 0.87^{***}$
- $y = 5.8287 - 0.0008x$
  $R^2 = 0.39^*$
Fig 3. Electrical conductivity (EC) of 50mL water samples (n = 4) that contained either 2 g of soy-composite bioccontainer material or water only across 12 immersion times (0, 1, 2, 4, 8, 16, 24, 32, 48, 72, 96, and 120 hr). ***, NS Significant at $P \leq 0.001$ or not significant, respectively.
Fig. 4. Nutrient-release of nitrogen, phosphorus, and potassium in 50mL water samples (n = 4) that contained 2 g of soy-composite biocontainer material across 12 immersion times (0, 1, 2, 4, 8, 16, 24, 32, 48, 72, 96, and 120 hr). ***, NS Significant at $P \leq 0.001$ or not significant, respectively.
CHAPTER 3. PELLETIZED SOY-BASED BIOPLASTIC FERTILIZERS FOR CONTAINER-CROP PRODUCTION

A paper to be submitted to *HortScience*

Kenneth G. McCabe, Christopher J. Currey, James A. Schrader, David Grewell, Jake Behrens, and William R. Graves

**Abstract**

Research examining bioplastic biocontainers for container-crop production has demonstrated that soybean-based [*Glycine max* (L.) Merr.] bioplastics can supply mineral nutrients to plants. Using materials of bioplastics, as well as biochar, we created pelletized fertilizer to be incorporated into soilless substrate. We evaluated the growth of ‘Honeycomb’ marigold (*Tagetes patula*), ‘Montego White’ snapdragon (*Antirrhinum majus* L.), and ‘Laser Synchro Scarlet’ cyclamen (*Cyclamen persicum* Mill.) grown with pelletized soy-based bioplastic fertilizers [soy-based bioplastic polymer (SP.A) compounded with poly(lactic) acid (PLA) or polyhydroxyalkanoates (PHA), containing 15% or 25% biochar] or a commercially-available controlled-release fertilizer (CRF). Our objectives were to evaluate the usage of SP.A-based fertilizers compared to a traditional CRF for growing common greenhouse crops. Plants were grown in containers filled with a soilless substrate comprising of sphagnum peat moss and perlite. Containers received 0, 0.72, or 1.44 g nitrogen (N) from different fertilizer sources for marigold in 15.2-cm top diameter containers and 0, 0.16, 0.32, 0.62, or 1.24 g N when producing marigold, snapdragon, and cyclamen in 11.4-cm top diameter containers. Plants were grown for
five (marigold and snapdragon), eight (marigold in larger containers), or ten (cyclamen) weeks. Marigolds in larger containers supplied with 0.72 or 1.44 g N from any SP.A-based fertilizers had similar or smaller SDM compared to plants supplied with CRF providing equivalent N. When growing plants in smaller containers, snapdragons supplied with 0.62 or 1.24 g N from either type of SP.A-based fertilizer and marigolds supplied with 1.24 g N from SP.A–PHA–BC died before the end of five weeks, whereas marigold, snapdragon, and cyclamen fertilized with CRF had the largest SDM across all fertilizer concentrations. The N concentration of snapdragon and marigold was greater in plants fertilized with either SP.A-based fertilizer compared to plants fertilized with CRF within applied N, but N uptake was less because of diminished growth. Cyclamen fertilized with SP.A-based fertilizers had similar or smaller SDM, depending on the amount of N applied and source; similar trends occurred for the nutrient content in the foliage. The effectiveness of SP.A-based fertilizers was better at lower application amounts (0.16 and 0.32 g N), but showed a diminishing return at higher concentrations (0.62 and 1.24 g N). Our results show that SP.A could be an optional fertilizer, however, formulations require further development to improve their properties for use with a broad range of species across a wide range of application concentrations.

**Introduction**

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 CRF. These fertilizers are typically inorganic or synthetically derived, and
sustainability of their use has been questioned because of energy involved in manufacturing and nutrient contamination to the environment (Carpenter et al., 1998; Pelletier et al., 2008).

To address environmental concerns and sustainability issues related to inorganic fertilizers for container-crop production, alternative fertilizers made from non-synthetic or biorenewable 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; Schrader et al., 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 supply nutrients to plants growing in the containers.

Soy bioplastics have several advantages for use as fertilizer when compared to synthetic fertilizers. Soy-based materials are biologically based (bio-based) and readily available, and soy bioplastics release plant-available nutrients (Calabria et al., 2012; Schrader et al., 2013). Components typically used in soy bioplastic formulations include soy flour, soy protein concentrate, and/or soy protein isolate. All of these soy-based products contain various amounts of plant-essential macronutrients and micronutrients (U.S. Department of Agriculture, 2015).

Although soy bioplastics have many attributes, disadvantages include low stability in water and rapid decomposition coupled with excessive nutrient release (Schrader et al., 2013). Compounding soy bioplastics with more stable bioplastics such as PLA and PHA can reduce some of these problems (Currey et al., 2014; Grewell et al., 2014; Schrader et al., 2013). Bioplastic composite materials of PLA and soy bioplastics used for container manufacturing exhibited beneficial fertilizer release, as well as enhanced degradation of compounded PLA compared to pure PLA (Schrader et al., 2013; Yang et al., 2015).
Biochar retains fertilizing 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 biochar are a fine, black powder, it is difficult to disperse without the addition of a binder or carrier. It is not feasible to apply biochar powder because wind can carry the powder uncontrollably, and the dust is an inhalation hazard. Thus, we developed pellets from SP.A, PLA or PHA, and biochar that can be easily dispersed and serve as a fertilizer. Soy-bioplastic fertilizers could help reduce the usage of synthetic fertilizers during plant production, and improve sustainability of container-crop production. We have developed pelleted SP.A-based fertilizers that can be incorporated into growing media and investigated the use of SP.A compounded with either PLA or PHA, and biochar, in a composite material that functions as a biorenewable fertilizer that can sequester and release nutrients. Our theory was that SP.A-based bioplastics with biochar could serve as an effective “slow-release” fertilizer supplying biorenewable nutrients, as well as stabilizing biochar for ease of application.

Our objectives were to evaluate plant growth and nutritional status of three common greenhouse-grown species when fertilized with pelleted SP.A-based fertilizers incorporated into soilless substrate. We specifically aimed to evaluate SDM, nutrient (N, P, and K) concentration, content, and uptake in plant shoots and nutrient concentrations (N, P, and K) in leachate obtained from plants fertilized with SP.A-based fertilizers, as well as a commercial CRF.
Materials and Methods

Fertilizer manufacturing

The SP.A-based fertilizers were made from mixtures of SP.A [formulated with (by weight) soy protein isolate (26%), soy flour (26%), water (31%), glycerin (8%), phthalic anhydride (4%), adipic acid (4%), sodium sulfite (1%), and potassium sorbate (<1%)] compounded with Ingeo™ PLA 3001D (NatureWorks LLC, Minnetonka, MN) or PHA M2200 (Metabolix Inc., Cambridge, MA) and 70 mesh biochar (BC) (Biochar Now LLC, Loveland, CO). The PLA was blended with polyethylene glycol (80:20 by weight) to lower the melt temperature of the resin to avoid thermal degradation of SP.A during extrusion. All ingredients (SP.A, PLA or PHA, and biochar) were inserted into a 42-mm, co-rotating, extruder (Leistritz Advanced Technologies Corp., Nuremberg, Germany) via a screw-driven feeding hopper and compounded in one extrusion. After extrusion, the bioplastics were pulled across stainless steel tables to cool and into a pelletizer that chopped the strands into pellets that were around 2 to 3 mm³ in size.

Fertilizer application

Four SP.A-based fertilizers were developed and used alongside a CRF [Nutricote 18.0N–2.6P–6.6K with a 140-d release period (Florikan ESA LLC, Sarasota, FL)] (Table 1). Fertilizers were applied by weighing the appropriate amount of fertilizer for the volume of substrate and incorporated individually for each container. Fertilizer concentrations were based on manufacturer’s recommendations for the CRF. The treatments of 0.16, 0.32, 0.62, and 1.24 g N corresponds to low, medium, heavy, and extreme application concentrations based on the CRF label, respectively. Fertilizers were partitioned individually for each container and mixed into the
container substrate on an individual basis after each container was filled and then plants were transplanted.

**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 under sufficient 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 15.2-cm top diameter containers (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, 0.72, or 1.44 g N) on an individual-container basis, supplied from all fertilizers (Table 1). The plant-container units (n = 5) 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 with tap water only, and no supplemental fertilizer was provided. 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) was 99.6 µmol·m⁻²·s⁻¹.

After eight 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). Electrical conductivity (EC) and pH of leachate samples were measured with a handheld pH–EC meter (HI 9813–6; Hanna Instruments, Smithfield, RI) to measure nutrient (salt) concentration and pH of the substrate (data not reported). Plants were then severed at the substrate surface, dried, and weighed to determine SDM. After SDM was recorded, three
samples from each treatment group (dried shoots and leachate) were randomly selected and were analyzed for nutrients (N, P, and K). Shoot nutrient content was calculated (nutrient content = nutrient concentration × SDM) for each plant-container unit analyzed. Results reported for SDM represent the mean of all replicates (n = 5), while results reported for shoot nutrient 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**

Based on results from Expt. 1, two SP.A-based fertilizers containing 15% biochar were used because reducing the biochar content allowed for an increased concentration of SP.A in the fertilizer blend. ‘Montego White’ snapdragon grown in 288-celled plug trays and ‘Laser Synchro Scarlet’ cyclamen grown 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, were transplanted into 11.4-cm top diameter containers (Myers Industries, Akron, OH) filled with soilless substrate (Sunshine® LB–2) that was amended with fertilizer-specific (type and concentration) treatments. The fertilizer treatments consisted of incorporating a defined amount of N (0-untreated, 0.16, 0.32, 0.62, or 1.24 g N) on an individual-container basis supplied from the SP.A-based fertilizers or CRF. The plant-container units (n = 9) 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 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 with tap water and no supplemental fertilizer was provided. When growing snapdragon and cyclamen, air
temperature was maintained at 20.9 ± 0.3°C, RH ranged from 70.8% to 14.3% (mean = 28.2%), and the daily mean PAR was 110.6 µmol·m⁻²·s⁻¹ for the first five weeks of production after which snapdragon plants were harvested. Air temperature was maintained at 21.0 ± 0.5°C, RH ranged from 70.8% to 10.7% (mean = 27.9%), and the daily mean PAR was 125.1 µmol·m⁻²·s⁻¹ for 10 weeks of production after which cyclamen plants were harvested. Marigolds were grown in a separate greenhouse with an air temperature was maintained at 22.5 ± 1.9°C, RH ranged from 93.0% to 5.9% (mean = 29.2%), and the daily mean PAR was 171.1 µmol·m⁻²·s⁻¹ for five weeks of production.

After five (all species) and 10 weeks (cyclamen only), leachate samples were collected from each plant/container unit by using the PourThru extraction procedure. The pH and EC of leachate samples were measured using a handheld pH–EC meter to assess nutrient (salt) concentration and pH of the substrate environment (data not reported). Leachate samples were analyzed for nutrients (N, P, and K) at a commercial lab (AgSource Harris Laboratories, Lincoln, NE). Shoots of snapdragon (after five 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 from each treatment factorial (shoots and leachate) were analyzed for nutrients (N, P, and K). Plants of snapdragon grown with either source of SP.A-based fertilizer incorporated at 0.62 or 1.24 g N died, as well as marigolds grown with 1.24 g N from SP.A–PHA–BC, so no shoot analyses were conducted. 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 nutrient uptake 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 separation was performed using Tukey’s honestly significant difference at $P < 0.05$. No transformations were performed on data reported as percentages because of homogenous variances. Interaction and ANOVA statistics were only conducted on plants of snapdragon grown with 0, 0.16, or 0.32 g N, and marigold grown with 0, 0.16, or 0.32, and 0.62 g N because of missing data from dead plants grown with higher concentrations of fertilizers.

Results

Expt. 1. Efficacy of four SP.A-based bioplastic fertilizers while growing marigold

Marigolds grown with 1.44 g of N from CRF had the greatest SDM compared to plants grown with any SP.A-based fertilizer at the same N concentration, except for plants grown with either SP.A-based fertilizer containing 25% BC at the same N concentration (Table 2). The SDM was 17.0 to 24.1 g greater for plants that received any fertilizer concentration compared to untreated plants (1.8 g), but there were no differences in SDM across all SP.A-based fertilizers when N was the same (Table 2).

No differences were noted between concentration of nutrients (N, P, and K) in the shoots of plants (data not presented). Shoot P content was greatest when plants were fertilized with 1.44 g of N supplied from CRF, except when compared to plants grown with fertilizer supplied from CRF, SP.A–PLA–BC (15% biochar) and SP.A–PLA–BC (25% biochar) at 0.72 g of N, as well
as SP.A–PHA–BC (25% biochar) applied at 1.44 g of N (Table 2). Shoot K content of plants fertilized with 0.72 or 1.44 g of N supplied from CRF was greater compared to plants grown in all other fertilizer treatments, except when plants received 0.72 g N provided from SP.A–PLA–BC (15% biochar) and SP.A–PLA–BC (25% biochar) or 1.44 g N from SP.A–PHA–BC (25% biochar) (Table 2). Untreated plants had the lowest P and K content compared to plants grown with all other fertilizer treatments (Table 2). The P content in plants receiving any fertilizer ranged from ≈ 7 to 15 (54 to 107 mg) times greater the amount of P in the untreated plants (7 mg) (Table 2).

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

Marigold. The SDM of marigold was greatest when fertilized with 0.32, 0.62, or 1.24 g N from CRF, while there were no differences among plants fertilized with either CRF or SP.A–PHA–BC or between SP.A–PLA–BC and SP.A–PHA–BC when supplying 0.16 g N. Plants fertilized with 0.32 g N from SP.A–PLA–BC had a larger SDM compared to plants fertilized with SP.A–PHA–BC. Plants died when supplied with 1.24 g N from SP.A–PHA–BC (Table 3). Shoot N, P, and K concentrations were typically higher in plants fertilized with either SP.A-based fertilizer source with the exception of untreated plants and plants fertilized with CRF supplying 0.16 or 1.24 g N (Fig. 1). Shoot N uptake was similar for plants fertilized 0.32 g N across fertilizer types and sources, but N uptake diminished at higher concentrations when plants were fertilized with either SP.A-based fertilizer (Fig. 2). No differences were observed in shoot P and K uptake of plants, except when plants were supplied with 1.24 g N from CRF had higher P and K uptake compared to plants fertilized with SP.A–PLA–BC (Fig. 2).
Leachate N and P concentrations were higher for container-plant units receiving SP.A-based fertilizers when compared with CRF as the amount of fertilizer increased (Fig. 3). Leachate N concentrations were also higher for plant-container-units receiving SP.A–PLA–BC compared to units receiving SP.A–PHA–BC across all fertilizer concentrations, except when supplied with 0.32 g N, or were untreated (Fig. 3). Leachate K concentrations were also higher in plant-container units receiving SP.A-based fertilizers as compared to CRF, but only when supplied with 0.62 and 1.24 g N (Fig. 3).

Snapdragon. The SDM of snapdragon was greatest when grown with CRF compared to plants grown with either SP.A-based fertilizers. Plants died when grown with 0.62 or 1.24 g of N from either SP.A-based fertilizer, whereas SDM was similar for plants grown with both types of SP.A-based fertilizers which supplied 0.16 or 0.32 g of N (Table 3 and Fig. 4). The N concentration in plants was greatest when plants were fertilized with either SP.A–PLA–BC or SP.A–PHA–BC (3.7 or 4.1 %, respectively), and was lowest when fertilized with CRF (2.2 %) (Fig. 1). Shoot P and K concentrations were similar for plants fertilized with 0.32 g of N supplied by either CRF or SP.A–PHA–BC, and greater in plants when supplied fertilizer from SP.A–PLA–BC. Nitrogen uptake was greatest for plants grown with CRF compared to plants grown with either SP.A-based fertilizer, except when plants were provided with 0.16 g of N from CRF or SP.A–PLA–BC, which were similar (Fig. 2). Phosphorus and K uptake of plants was also greatest for plants fertilized with CRF compared to either SP.A-based fertilizer supplying 0.32 g of N, while no differences were observed for P uptake between plants grown with 0.16 g of N supplied from any one of the three fertilizer types (Fig. 2).

The N concentration in leachate was greatest when SP.A–PLA–BC was the fertilizer source across all concentrations (> 0 g), and this was greater than CRF supplying 0.16 g of N and
greater than SP.A–PHA–BC supplying 0.16, 0.32, and 1.24 g of N (Fig. 3). Phosphorus and K concentrations in leachate samples were greater for both SP.A-based fertilizers across all concentrations (except untreated) when compared to CRF, and samples that had either SP.A-based fertilizer as the nutrient source had similar concentrations of P across all application concentrations (Fig. 3).

Cyclamen. The SDM of cyclamen was largest when grown with CRF supplying 1.24 g of N (7.5 g), but no differences were observed when comparing plants grown with 0.16 or 0.32 g N from either CRF or SP.A–PLA–BC (Table 3 and Fig. 4). The SDM was smallest for plants supplied with 0.62 or 1.24 g N from SP.A–PHA–BC, however, this wasn’t different when compared to plants grown with SP.A–PLA–BC fertilizer supplying 0.16 or 0.32 g of N (Table 3). Plants grown with SP.A–PHA–BC had the greatest SDM when fertilized with 0.16 or 0.32 g of N. Shoot N concentrations were greatest in plants fertilized with CRF across all amounts of N and plants fertilized with SP.A-based fertilizer had similar N concentrations across fertilizer types (Fig. 1). Shoot P concentrations were greater for plants fertilized with either SP.A–PLA–BC or SP.A–PHA–BC when compared to plants fertilized with CRF supplying 0.32, 0.62, or 1.24 g of N, while plants fertilizer with 0.16 g of N had greater concentration of P when fertilized with SP.A–PLA–BC (Fig. 1). Shoot K concentrations didn’t differ among plants fertilized with 0.16 or 0.32 g of N supplied from any of the three fertilizers (Fig. 1). Shoot N uptake of plants grown with CRF was greatest (228.3 mg) compared to plants fertilized with either of the SP.A-based fertilizers across all N treatments and was 2.4 to 9.6 times greater than plants fertilized with SP.A–PLA–BC at 0.62 (47.2 mg) and 1.24 g of N (23.8 mg), respectively (Fig. 2). Plants fertilized with CRF also had six to 30 times greater N uptake than plants
fertilized with SP.A–PHA–BC supplying 0.62 (19.2 mg) and 1.24 g of N (7.5 mg), respectively (Fig. 2).

*Nutrient concentrations in leachate from cyclamen at 5 weeks*

Leachate samples obtained from plant-container units fertilized with SP.A–PLA–BC supplying 1.24 g of N had greater concentrations of N, while leachate samples from plant-container units fertilized with SP.A–PHA–BC had the lowest N concentration. Leachate samples from plant-container units grown with CRF or SP.A–PLA–BC had similar concentrations of N when fertilized with 0.32 or 0.62 g of N (Fig. 3). Leachate P concentrations from plant-container units fertilized with SP.A–PLA–BC were greater across all fertilizer concentrations, except the 1.24 g of N concentration where it was similar to concentrations from leachate samples obtained from plant-container units fertilized with SP.A–PHA–BC (Fig. 3). Plants fertilized with CRF had the lowest concentrations of P, which was lower compared to plants fertilized with SP.A–PLA–BC (Fig. 3). Concentrations of K were also greater for samples from plant-container units fertilized with SP.A–PLA–BC compared to either of the other fertilizer types, with the exception of leachate samples obtained from plant-container units fertilized with SP.A–PHA–BC supplying 0.62 g of N (Fig. 3).

*Nutrient concentrations in leachate from cyclamen at 10 weeks*

Nitrogen concentration was greatest in leachate samples from plant-container units fertilized with CRF supplying 0.32, 0.62, or 1.24 g of N (12.5, 46.7, 96.9 mg·L\(^{-1}\), respectively) when compared to both SP.A-based fertilizers at the same concentrations (ranged from 1.8 to 9.2 mg·L\(^{-1}\)) (Fig. 3). Leachate samples obtained from plant-container units fertilized with either SP.A-based fertilizer had similar N concentrations regardless of application concentration (Fig. 3). Phosphorus concentrations in leachate were similar or greater for plant-container units
fertilized with either SP.A-based fertilizer when compared to plant-container units fertilized with CRF. Plant-container units fertilized with either SP.A-based fertilizer supplying 1.24 g of N (58.0 and 53.3 mg·L⁻¹) had greater concentrations of K in leachate samples compared to plant-container units that were fertilized with CRF at the same fertilizer concentration (4.5 mg·L⁻¹) (Fig. 3).

Discussion

The objectives of this study were to evaluate the use of SP.A-based bioplastics as a pelletized fertilizer that can be used in container-crop production similar to CRF. We measured nutrient release from SP.A-based bioplastics, and plant uptake of nutrients, but a point of diminishing returns was reached at a lower concentration of fertilizer compared to the commercial fertilizer (Table 3). Excessive nutrient release early in production was most likely the cause of diminishing returns (Fig. 3), and Schrader et al. (2013) observed similar results from containers manufactured with high percentages of SP.A bioplastics. Hall et al. (2009) reported that producers’ adoption of sustainable practices was mostly influenced by implementation ease and perceived associated risk, so to ensure that growers aren’t reluctant to switch to novel SP.A-based fertilizer sources, more work needs to focus on minimizing risk and ensuring reliability over a wide range of application concentrations.

Plants fertilized with SP.A–PHA–BC formulations in our experiment exhibited poorer growth at higher application amounts when compared to plants fertilized with SP.A–PLA–BC formulations (Table 3). These findings are in agreement with Schrader et al. (2015) who found that PLA was a better co-polymer with SP.A than PHA for promoting beneficial nutrient functions of SP.A bioplastics. PLA is a better co-polymer with SP.A, and this may be because of
increased degradability of PHA compared to PLA. There is increased availability of carbon (C) supplied from PHA, thus resulting in a low bioavailable C to N ratio. The degradable C in PHA, unlike PLA which is very slow to degrade, can be used as a C source for microbial growth, and a greater demand of nutrients is a possible result of increased microbial activity and reduced leachate nutrient concentrations later in production (Fig. 3).

To solve issues surrounding fertilizer release and species sensitivity to soy-based fertilizers, more evaluations should focus on alternative material formulations and other fertilizer application methods. Future research will evaluate blends that contain varying proportions of SP.A and PLA, blends with and without biochar, and other biorenewable fertilizer sources. Because we only examined a limited range of formulations which included biochar, it will be important for future studies to focus on blends that do not contain biochar for use in container-crop production. Biochar was included in our formulations because various research has shown that it sequesters nutrients (Laird et al., 2010), enhances plant growth and 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 biochar is also hard to disperse and poses an inhalation hazard. The objective of blending biochar with SP.A-based bioplastics were to capitalize on benefits of biochar in the fertilizer mixture and determine if biochar can be stabilized with bioplastic similar to previous research showing success incorporating additives or fillers (Lu et al., 2014a; Lu et al., 2014b; Madbouly et al., 2014; Yang et al., 2015). Although our plant-growth results were variable compared to a commercial fertilizer, our results show that compounding biochar with SP.A-based bioplastics can eliminate hazards associated with application. We theorized that biochar in our formulations would help sequester nutrients and
slowly release them back to plants over time, and this theory may be applicable in other production systems where biochar can be used as a soil amendment.

Research conducted by Schrader et al. (2013) demonstrated that blending SP.A and PLA at equal proportions resulted in a bioplastic that was more durable and provided better functionality than bioplastics made entirely of SP.A, and helped moderate nutrient release to beneficial levels for plant growth. Our results indicate equal blends of SP.A and PLA does not necessarily provide similar plant growth benefits when biochar is included. More evaluations need to be conducted on the proportion of SP.A to PLA when the bioplastic is to be used similar to CRF.

Because of the low nutrient concentrations, specifically N (2.85–5.01% N), in SP.A-based fertilizers, a larger quantity had to be applied to an individual container 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 quantity needed. Reducing the amount of fertilizer applied may be important because treatments that received higher concentrations of SP.A-based fertilizers exhibited extensive microbial growth in the substrate. 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 key role in nutrient conversion and disassociation from the bioplastics. It is highly likely that because bioplastic pellets were under consistently moist conditions in the media, there was excessive microbial growth and rapid nutrient disassociation. Increasing the nutrient concentrations (N, P, or K) of the bioplastics would decrease in the amount (by weight) of fertilizer needed and may
reduce available surface area for microbial growth to occur. Another possibility to achieve favorable nutrient release would be incorporating smaller portions of fertilizer over time by topdressing on a weekly, biweekly, or monthly basis. Incorporating smaller portions would reduce the total amount of bioplastic fertilizer entering the system at any one time, and potentially reduce microbial growth and subsequent nutrient release.

This report shows that pelletized SP.A-based bioplastics have potential as a fertilizer for plants growing in containers, as well as act as an effective means for application of biochar. Even though our results suggest that our formulations don’t match the fertility benefits of a commercial fertilizer, they do show that pelletized SP.A-based bioplastics supply nutrients to plants when incorporated into soilless substrate. If SP.A-based fertilizers are used as a replacement for synthetic fertilizers, they need to match many of the current benefits associated with commercial fertilizers. Although plant growth was variable when supplied with SP.A-based fertilizers at higher concentrations, there was nutrient uptake by plants, and growth was adequate at moderate fertility concentrations. Continued development of pelletized SP.A-based bioplastics for use as a fertilizer should help improve the fertilizing effects of the bioplastics, reduce potential species sensitivity risks, and ensure growers can easily implement the fertilizers into their current production systems.
Literature Cited


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

<table>
<thead>
<tr>
<th>Fertilizer type</th>
<th>Nutrient concentration (%)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SP.A–PLA–BC (42.5/42.5/15&lt;sup&gt;y&lt;/sup&gt;)</td>
<td>3.33</td>
<td>0.23</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>SP.A–PLA–BC (37.5/37.5/25)</td>
<td>2.85</td>
<td>0.20</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>SP.A–PHA–BC (62.5/22.5/15&lt;sup&gt;y&lt;/sup&gt;)</td>
<td>5.01</td>
<td>0.34</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>SP.A–PHA–BC (37.5/37.5/25)</td>
<td>3.08</td>
<td>0.21</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>CRF (140 d release)</td>
<td>18.00</td>
<td>2.60</td>
<td>6.60</td>
<td></td>
</tr>
</tbody>
</table>

<sup>y</sup>Percentage by weight of material (SP.A, PLA or PHA, and BC) in each fertilizer.

<sup>y</sup>Used during production of marigold, snapdragon, and cyclamen in 11.4-cm diameter containers.

SP.A = soy-based polymer, PLA = poly(lactic) acid, PHA = polyhydroxyalkanoates, and BC = biochar.

CRF was Nutricote (18.0N–2.6P–6.6K) with a 140 d release period (Florikan ESA LLC, Sarasota, FL).
Table 2. Effects of fertilizer type and applied nitrogen (N) on dry weight and nutrient content [N, phosphorus (P), and potassium (K)] of shoots from marigold ‘Honeycomb’ (*Tagetes patula* L.) grown for eight weeks.

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>Applied N (g·pot)</th>
<th>Shoot dry mass (g)</th>
<th>Shoot nutrient content (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated-Pure Water Only</td>
<td>0.00</td>
<td>1.8 D</td>
<td>32 B 7 C 38 C</td>
</tr>
<tr>
<td>CRF</td>
<td>0.72</td>
<td>21.1 ABa</td>
<td>543 Aa 75 ABa 461 ABa</td>
</tr>
<tr>
<td>SP.A–PLA–BC (42.5–42.5–15)^x</td>
<td>0.72</td>
<td>18.1 BCab</td>
<td>300 ABa 79 ABa 417 ABa</td>
</tr>
<tr>
<td>SP.A–PHA–BC (62.5–22.5–15)</td>
<td>0.72</td>
<td>19.1 BCab</td>
<td>447 Aa 60 Ba 353 Ba</td>
</tr>
<tr>
<td>SP.A–PLA–BC (37.5–37.5–25)</td>
<td>0.72</td>
<td>18.3 BCab</td>
<td>390 ABa 69 ABa 405 Ba</td>
</tr>
<tr>
<td>SP.A–PHA–BC (37.5–37.5–25)</td>
<td>0.72</td>
<td>17.0 Cb</td>
<td>421 Aa 57 Ba 337 Ba</td>
</tr>
<tr>
<td>CRF</td>
<td>1.44</td>
<td>24.1 Aa</td>
<td>497 Aa 107 Aa 562 Aa</td>
</tr>
<tr>
<td>SP.A–PLA–BC (42.5–42.5–15)</td>
<td>1.44</td>
<td>17.9 BCb</td>
<td>407 Aa 54 Bb 330 Bb</td>
</tr>
<tr>
<td>SP.A–PHA–BC (62.5–22.5–15)</td>
<td>1.44</td>
<td>18.5 BCb</td>
<td>265 ABa 61 Bb 353 Bb</td>
</tr>
<tr>
<td>SP.A–PLA–BC (37.5–37.5–25)</td>
<td>1.44</td>
<td>21.8 ABab</td>
<td>461 Aa 67 Bab 410 ABab</td>
</tr>
<tr>
<td>SP.A–PHA–BC (37.5–37.5–25)</td>
<td>1.44</td>
<td>20.6 ABCab</td>
<td>424 Aa 77 ABab 429 ABab</td>
</tr>
</tbody>
</table>

^xUppercase letters indicate mean separation across all treatments by Tukey’s honestly significant difference (HSD) test at $P \leq 0.05$ (n = 5 for shoot dry mass and growth index, n = 3 for shoot nutrient content).

^yLowercase letters indicate mean separation within an applied N treatment across fertilizer type by Tukey’s HSD test at $P \leq 0.05$ (n = 5 for shoot dry mass, n = 3 for shoot nutrient content).
Table 2 continued

\(^a\)Percentage of each material in the fertilizer blend.

SP.A = soy-based polymer, PLA = poly(lactic) acid, PHA = polyhydroxyalkanoates, and BC = biochar.
Table 3. Effect of fertilizer concentration and type on shoot dry mass (g) for marigold ‘Honeycomb’ (*Tagetes patula* L.), snapdragon ‘Montego White’ (*Antirrhinum majus* L.), and cyclamen ‘Laser Synchro Scarlet’ (*Cyclamen persicum* Mill.) grown for five, five, and 10 weeks, respectively.

<table>
<thead>
<tr>
<th>Fertilizer type</th>
<th>0</th>
<th>0.16</th>
<th>0.32</th>
<th>0.62</th>
<th>1.24</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Marigold</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRF</td>
<td>0.6 C&lt;sup&gt;a&lt;/sup&gt;&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.5 Ba</td>
<td>1.9 Ba</td>
<td>2.5 Aa</td>
<td>3.0 Aa</td>
</tr>
<tr>
<td>SP.A–PLA–BC</td>
<td>0.6 Ca</td>
<td>1.2 ABB</td>
<td>1.3 Ab</td>
<td>1.1 Bb</td>
<td>0.4 Cd</td>
</tr>
<tr>
<td>SP.A–PHA–BC</td>
<td>0.6 Ca</td>
<td>1.3 Aab</td>
<td>1.0 Bc</td>
<td>0.7 Cb</td>
<td>---</td>
</tr>
<tr>
<td>Fertilizer (F)</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration (C)</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F × C</td>
<td>****&lt;sup&gt;x&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Snapdragon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRF</td>
<td>0.26 Da</td>
<td>0.89 CDa</td>
<td>1.49 BCa</td>
<td>2.06 B</td>
<td>3.34 A</td>
</tr>
<tr>
<td>SP.A–PLA–BC</td>
<td>0.28 Ba</td>
<td>0.47 ABb</td>
<td>0.51 Ab</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SP.A–PHA–BC</td>
<td>0.26 Aa</td>
<td>0.47 Ab</td>
<td>0.46 Ab</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>F</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F × C</td>
<td>****&lt;sup&gt;x&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cyclamen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRF</td>
<td>0.5 Da</td>
<td>2.5 Ca</td>
<td>3.7 Ba</td>
<td>4.7 Ba</td>
<td>7.5 Aa</td>
</tr>
</tbody>
</table>

---

<sup>a</sup>Means in the same column followed by the same letter do not differ significantly by Tukey’s HSD test at α = 0.05.

<sup>b</sup>Significant difference at α = 0.05.
Table 3 continued

<table>
<thead>
<tr>
<th>Treatment</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP.A–PLA–BC</td>
<td>0.5 Da</td>
<td>2.1 BCab</td>
<td>2.8 ABab</td>
<td>3.3 Ab</td>
<td>1.4 Cb</td>
</tr>
<tr>
<td>SP.A–PHA–BC</td>
<td>0.5 Ca</td>
<td>1.8 Ab</td>
<td>2.0 Ab</td>
<td>1.4 Bc</td>
<td>0.6 Cb</td>
</tr>
</tbody>
</table>

**F**

**C**

**F × C**

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

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

\^Interaction analyses were only performed on concentrations 0, 0.16, and 0.32 for snapdragon and 0, 0.16, 0.32, and 0.62 for marigold across the fertilizer types.

*** Significant at \( P \leq 0.001 \).

--- No means available because plants died.

SP.A = soy-based polymer, PLA = poly(lactic) acid, PHA = polyhydroxyalkanoates, and BC = biochar.
Fig. 1. Concentration (%) of nitrogen (N), phosphorus (P), and potassium (K) in shoots of ‘Honeycomb’ marigold, ‘Montego White’ snapdragon, and ‘Laser Synchro Scarlet’ cyclamen.

Marigolds and snapdragons were grown for five weeks and cyclamen were grown for 10 weeks in 11.4-cm top diameter containers in a glass-glazed greenhouse and supplied with 0, 0.16, 0.32, 0.62, or 1.24 g N from one of three fertilizers sources [SP.A–PLA–BC (3.33N–0.23P–0.57K),...
Figure 1 continued

SP.A–PHA–BC (5.01N–0.34P–0.80K), or 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 N treatment across fertilizer type by Tukey’s HSD test at $P \leq 0.05$ (n = 3).
Fig. 2. Uptake (mg) of nitrogen (N), phosphorus (P), and potassium (K) in shoots of
Marigolds and snapdragons were grown for five weeks and cyclamen were grown for 10 weeks
in 11.4-cm top diameter containers in a glass-glazed greenhouse and supplied with 0, 0.16, 0.32,
Figure 2 continued

0.62, or 1.24 g N 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 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 N treatment across fertilizer type by Tukey’s HSD test at $P \leq 0.05$ (n = 3).
Figure 3 continued

Fig. 3. Concentration (%) 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. Samples were collected from marigolds and snapdragons after five weeks of growth and collected from cyclamen after five and 10 weeks of growth. All plants were grown in a glass-glazed greenhouse and supplied with 0, 0.16, 0.32, 0.62, or 1.24 g N 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 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 N treatment across fertilizer type by Tukey’s HSD test at $P < 0.05$ (n = 3). *‘Laser Synchro Scarlet’
Figure 4 continued

Fig. 4. Plants of marigold, snapdragon, and cyclamen fertilized with 0, 0.16, 0.32, 0.62, or 1.24 g N 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 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.
CHAPTER 4. GENERAL CONCLUSIONS

General Discussion

Implementing bioplastics that provide nutrients will have broad impacts well beyond producers and consumers of plants grown in containers. Numerous areas of the container-crops and horticulture industry will be positively impacted. The industry will reduce dependence on petroleum-based products and synthetic or inorganic fertilizers, thus reducing negative impacts to the environment and accumulation of waste plastics around businesses, and in landfills. Niche markets also expand by using novel products that can be marketed to consumers that may not be a typical customer in garden centers. Plant producers can potentially earn higher profits by charging a premium for plants grown in biocontainers, as well as save money by reducing fertilizer usage during production. Consumers will also be positively impacted by the use of bioplastics in the horticulture industry, and will save money by reducing the amount of waste that goes into the municipal solid waste stream, as well as more options for disposal after use. Biocontainers and bioplastics will be able to “return to the earth,” and fewer pollutants will enter the environment that contaminate our air, landscapes, and waterways.

The main goal of this research was to better understand the fertilizing attributes of soy-based bioplastics and composites when used in container form or as a pelletized fertilizer. Information gleaned from this research suggests that soy-based bioplastics can be an excellent source of nutrients for plants, but more questions arise when looking at the interactions between nutrient release, microbial growth, and plants being grown with the bioplastics. We have learned that mineral nutrients are supplied to plants by soy-based bioplastics, but that nutrient release can vary. Release of nutrients is influenced by moisture and microbes in the environment in which
the bioplastic is used, and the proportion of soy-based bioplastic mixed with other bioplastics (PLA or PHA) in composite formulations.

Compounding PLA with soy-based bioplastics, as compared to PHA, resulted in better nutrient availability to plants, as well as increased structural durability of biocontainers made from the composites. Mixing soy-based bioplastic at equal proportions with PLA also improves nutrient release and plant uptake when the bioplastic composite is used in either container form or as a pelletized fertilizer. This combination is also adequate enough to maintain structural durability of biocontainers for short production-cycle crops (around two months) such as annuals, vegetables, herbs, and some perennials. Bioplastic composites that have smaller proportions of soy-based bioplastic supply some nutrients to plants, but not enough to sustain growth similar to containers manufactured with higher amounts of soy-based bioplastic (≥50% by weight). In regards to nutrient release from pelletized soy-based bioplastics, increased moisture and microbial activity in the substrate can facilitate increased release of nutrients in a shorter period of time. This issue may be resolved by adjusting bioplastic formulations for this specific application, as well as applying the pelletized fertilizers in smaller quantities over time.

**Recommendation for Future Research**

Even though favorable results were seen when using soy-based bioplastics for horticultural applications, more research needs to focus on the fertilizing properties and nutrient-release dynamics. It is apparent that the bioplastic formulation and intended use of the bioplastic for specific products (ex. containers, fertilizers, etc.) has an influence on nutrient release and species sensitivity. Superior formulations used for manufacturing containers, which contain equal parts soy bioplastic and PLA, may not be the best choice when manufacturing pelletized
fertilizers or other products. It will be important to evaluate bioplastic blends that contain varying amounts of soy bioplastic with other stable bioplastics, as well as the incorporation of fillers or additives for various product applications.

Another area that needs to be examined is the influence that microbes have on nutrient-release dynamics of soy bioplastics. More research should help address macronutrient and micronutrient fertilizer applications, and fertilization of numerous plant species in soy-based containers, as well as impacts of various pesticide treatments that are commonly performed in the industry. The added fertilizer function over conventional plastics translates to production changes needed to produce high quality plant material. Reluctance to change among growers may be mitigated once they understand how nutrients are liberated from soy-composite biocontainers, the fertilizer reductions achieved during production, and the effects of common pest and disease treatments on nutrient release.

When comparing fertilizer release from containers made from soy bioplastic composites with fertilizer release from pelletized soy bioplastic composites, it is apparent that the environment and associated microbial population in which the bioplastic is used can have a large impact on nutrient release. Rapid fertilizer release was observed when incorporating soy bioplastic pellets as a fertilizer, but this was not the case when soy bioplastic composites were used for containers. This may have resulted from the fact that soy bioplastic pellets were incorporated in substrate, and were under consistently moist conditions around the entire surface area of the pellets. This was not the case with containers manufactured with soy-bioplastic composites. The bioplastic material in containers was only exposed to substrate on the inside of the container, thus reducing the surface area exposed to moisture and microbes, and wasn’t as prone to microbial breakdown and nutrient release during plant production. The outside of many
of the containers showed no signs of microbial growth until later in production when containers were degraded from the inside to the outside of the container sidewall, while microbial growth was present on the inside of the containers almost immediately after transplant.

More research should also focus on using soy-bioplastics and composites for other horticultural products. Other products that could potentially be manufactured with soy-bioplastics and composites could include plant labels, cell packs, fertilizing stakes, container inserts, as well as other types of containers in various shapes, sizes, and thicknesses. It will also be important to develop soy-bioplastics and composites that have the ability to be printed on for branding and marketing purposes.

The last area that I would suggest for future research would include examining cultural practices related to irrigation and watering techniques, as well as species sensitivity to containers made from soy-bioplastic composites. More research could focus on watering practices and watering frequency, and how this may impact nutrient release and container breakdown during plant production. Growers vary in how they irrigate crops during plant production, and there may be vast differences in nutrient release and container breakdown when comparing soy-bioplastic composite containers employed by a “wet grower” versus a “dry grower”. Some species of plants may not be able to be produced in soy-bioplastic composite containers because of sensitivity to chemical changes in substrates during production. It will be important to evaluate a wide range of ornamental plant species grown with soy-bioplastic composites to determine potential sensitivity to released nutrients and chemical attributes of the root zone during plant production.
ACKNOWLEDGMENTS

I would like to thank the Department of Horticulture and Iowa State University for being a great working home over the past few years. Iowa State University has been a great educational institution to advance my knowledge of the horticulture industry and beyond. I really appreciate the help and guidance from the departmental faculty and staff, and I hope many more students can have a positive experience similar to what I have had.

I would like to thank Dr. William Graves for your expertise and guidance as my co-major professor and my supervisor. I have had a tremendous time and feel very fortunate to have been able to work on the Bioplastic Container Cropping Systems project, and I appreciate all that you have done to make this happen.

I would also like to thank Dr. Christopher Currey for being a great mentor as my co-major professor and providing a wealth of knowledge related to controlled-environment research. I really appreciate the time spent in the greenhouse looking at crops, and talks about nature and experimentation.

I also want to thank my committee member, Dr. David Grewell, and his graduate student Jake Behrens. Your combined knowledge related to bioplastics, plastic molding, and time spent developing containers and pelletized fertilizers was essential to my research. I would also like to thank Dr. James Schrader. You have been a great colleague to work with in the lab, and very influential in the advancement of my understanding of scientific research and writing.

I also thank and appreciate my family and friends for all of your support in my pursuit of obtaining a higher education. To Ruth, I really appreciate everything. I look forward to the many adventures that await us.