PERFORMANCE AND ENVIRONMENTAL IMPACTS OF BIOCONTAINERS IN HORTICULTURAL CROP PRODUCTION SYSTEMS

BY

ANDREW K. KOESER

DISSERTATION

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Doctoral Committee:

Associate Professor J. Ryan Stewart, Chair
Professor Donald Bullock
Associate Professor Richard Hauer, University of Wisconsin-Stevens Point
Associate Professor Gary Kling
Assistant Professor Sarah T. Lovell

ABSTRACT

Market research has help to fuel an increased interest in plant-based biocontainers. Unlike the conventional plastic containers currently favored by greenhouse producers, biocontainers can be direct planted or composted after plant installation. While this effectively reduces landfill waste, biocontainers may influence other aspects of plant performance and production efficiency. Results of this work indicate that biocontainers impact growth both positively and negatively as compared to a conventional plastic control, depending on the plant species grown. Despite differences in aboveground size, plant visual condition remained similar for all containers tested. Containers varied in both strength and their ability to be processed in mechanized horticultural production systems. Injection molded plastic containers were the strongest of the containers tested. Other containers, such as peat, wood fiber, and manure had greatly reduced container strengths – especially when wet. These differences translated into greater damage rates during filling, handling, and shipping experiments. Plantable biocontainers (as compared to compostable) are marketed as a means of reducing labor costs and limiting transplant stress during installation. Outplanting trials showed aboveground plant growth differed by container in two of the three species tested (cleome and lantana). In these species, the conventional plastic control (removed at planting) was always in the top statistical grouping. This suggests direct-plant containers offer little benefit with regard to plant establishment and, in some cases, have the potential to hinder plant growth. When the results of the individual applied trials were combined into an overarching carbon footprint assessment of secondary impacts, little difference existed between the containers tested. While the container itself was a significant component of a final plant's carbon footprint (17%), other factors like lighting played a much more significant role (over 45%) and deserve greater attention.

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CHAPTER 1. THE ROLE OF BIOCONTAINERS IN INCREASING THE SUSTAINABILITY OF THE GREEN INDUSTRY

Sustainability in Ornamental Horticulture

Conventional greenhouse and nursery-production practices in horticulture have been faulted for being unsustainable (Hall et al., 2009; Krug et al., 2008; Lopez et al., 2008). In summarizing the current state of the industry, Hall et al. (2009) noted that greenhouse crop production relies heavily on energy-intensive, non-renewable petroleum-derived products and energy sources for the pesticides, fertilizers, lighting, heating, and packaging needed to produce a uniform, high-quality crop. Beyond its reliance on fossil fuels, the ornamental horticulture industry has also been widely criticized for its contributions to regional solid waste streams and ground and surface water contamination (Dennis et al., 2010; Garthe and Kowal, 1993).

Unlike most traditional agricultural systems, nursery and greenhouse production sites are often located near or within urbanized areas (Dennis et al., 2010). The close proximity allows customers to see much of a business's production and disposal practices firsthand. For environmentally conscious consumers, one of the most visible reminders of horticulture's environmental shortcomings is the ubiquitous plastic container. Serving a variety of functions and found in a multitude of shapes, sizes, and colors, plastic containers are used for propagating, growing, transporting, and marketing ornamental crops (Hall et al., 2010; Helgeson et al., 2009; Evans and Hensley, 2004).

The plastic containers’s consistent performance in production systems removes one of the many possible variables growers must contend with when attempting to produce a uniform crop of high-quality plants. This reliability and flexibility come at a relatively cheap price, which has helped establish the prominence of plastic containers in ornamental production. Unfortunately, this combination of characteristics also creates an overabundance of under-reclaimed plastic waste each production cycle.

Plastic Use in Horticulture

Despite a general consensus that plastic plays a major role in horticultural production, there is an absence of peer-reviewed research that quantifies its use in the industry. Given this void, researchers have relied on reports and surveys from state agencies and university extension offices (Dennis et al., 2010; Evans et al., 2010; Hall et al., 2010; Hall et al., 2009). The most frequently cited of these publications was a non-peer-reviewed extension fact sheet by Garthe and Kowal (1994), which is clearly outdated. At the time of publication, it was estimated that between 145,000 and 222,000 metric tons of plastic were used nationwide each year for greenhouse films, mulch covers, containers, trays, packs, and flats. Greenhouse and nursery containers accounted for between 45 and 67 % of all plastic used in horticultural production with the remainder of plastic being used largely for products like mulches and greenhouse films. While it is difficult to speculate how plastic use in any of the individual categories has changed in comparison to the others over the past couple of decades, it seems reasonable to assume that overall plastic use in horticulture and agriculture has kept pace with increasing national plastic consumption trends (US EPA, 2011; Hall et al., 2010).

In 2010, the United States generated a total of 28 million metric tons of plastic waste (US EPA, 2011). Of this, only 8 % was recaptured through recycling. Recovery rates often vary dramatically given specific plastic type and use. PET bottles and jars and HDPE bottles are the most recycled, with recovery rates of 21 and 28 %, respectively (US EPA, 2011). In contrast, agricultural materials are less likely to be recycled given soil and pesticide contamination and ultraviolet photodegradation (Hall et al., 2010; Helgeson et al., 2009; Garthe and Kowal, 1994). The absence of facilities willing or even able to process these compromised materials leaves many growers, landscapers, and consumers with few options for reliable means of disposing plant container waste. As such, nursery and greenhouse pots from unsold or transplanted materials seem largely destined for the landfill (Kuehny et al., 2011; Hall et al., 2010; Evans and Karcher, 2004; Garthe and Kowal, 1994).

Biocontainers as an Alternative to Plastic: Consumer Perceptions

Bolstered by favorable results from product market testing, biocontainers (biodegradable, plant-based pots) are gaining greater interest among growers, horticultural suppliers, and applied researchers. In studies where various sustainable greenhouse plant attributes were tested, container type was consistently listed as having the greatest impact on consumer product perception (Yue et al., 2011; Dennis et al., 2010; Hall et al., 2010). Yue et al. (2011) identified four key sustainable attributes that were valued by consumers. Three of these traits were directly related to container type (i.e.,plants in biodegradable, compostable, and recycled pots) and were valued equally with locally produced plants. Of the pot types listed, it was found that biodegradable and compostable pots were preferred to pots that were made of recycled plastic.

In contrast, less obvious practices adopted during production failed to generate much consumer interest. No significant advantage was gained by indicating that plants were grown with organic fertilizers and only moderate interest was garnered with the knowledge that plants were grown sustainably or in efficient greenhouse spaces (Yue et al., 2011). Similar results were reported by Hall et al. (2010), who found that container type outweighed all other purchasing considerations, including price and carbon footprint (i.e.,the total set of greenhouse gases – expressed as carbon equivalents – linked to a given product).

These findings have led researchers to conclude that consumers are more interested in the sustainability associated with pot production than in modifications associated with minimizing energy-intensive practices involved in growing plants (Yue et al. 2011). A plant grown in a sustainable setting with reduced inputs is considered a success if it looks identical to its conventionally grown alternative. This leaves much to the imagination of the consumer when trying to envision how a purchase reflects his or her environmental ideals. In contrast, plants in biocontainers are distinctly non-conventional, especially when natural materials like sawdust or straw are used in a relatively unprocessed form to make nursery and greenhouse pots. At some level, the purchase of a plant grown in a biocontainer becomes a symbol of one's commitment (real or perceived) to sustainability.

Biocontainers as an Alternative to Plastic: A Practical Surrogate?

While some of the more familiar peat and paper pots have been on the market for over half a century (Jiffy Group, 2011), biocontainers as whole have yet to be widely embraced by the greenhouse and nursery industry. Hall et al. (2009) found that over 22 % of growers surveyed indicated that they had used biocontainers in their operations. Of the remaining 78 % that participated in the study, only 6 % noted that they would like to add biocontainers to their current nursery processes (Hall et al., 2009). Other researchers reported that 12 % of greenhouse growers acknowledged prior use of peat pots in their operations (Dennis et al., 2010). Most telling in this study was that respondents who used these containers estimated that peat pots made up less than 3% of their total container consumption (Dennis et al. 2010). These figures support a general consensus that the widespread use of biocontainers has been largely limited given their higher cost and perceived limitations (Kuehny et al., 2011; Helgeson et al. 2009).

Maintaining a consistent level of quality is of paramount importance in ornamental horticulture where products are sold primarily for aesthetic purposes. The stakes can be high, as consumers have shown an unwillingness to purchase green alternatives if they prove to be less-effective or lower-quality than the conventional standards they replace (Hall et al., 2010). This unforgiving tendency may make it hard for growers to deviate from energy-intensive, conventional strategies that deliver reliable results.

The hesitation of the industry to experiment with more environmentally friendly production methods was characterized by Hall et al. (2009) in a broad survey of greenhouse and nursery growers. In this report, researchers found that the majority of respondents (65.5%) felt sustainable growing practices were very important in regard to the environment. Furthermore, holding this belief increased the likelihood of a grower initiating sustainable initiatives in their businesses. However, potential risks associated with both yield loss (i.e.,a decrease in plant quality) and difficulties incorporating sustainable processes into existing production methods were found to be significant deterrents limiting the widespread adoption of green practices.

However, with the potential risks associated with adopting new sustainable technologies and practices come rewards. Market research has shown that customers do notice and support environmentally friendly business practices. Customers who value local or sustainably grown products will pay a higher price for products that meet these criteria (Yue et al., 2011; Dennis et al., 2010; Krug et al., 2008). Additionally, consumers have acknowledged being loyal to businesses that offered sustainable goods and services (Yue et al., 2011; Dennis et al., 2010; Krug et al., 2008).

Truly sustainable products must be environmental feasible, economically sound, and socially acceptable. While market research has shown biocontainers meet the latter requirement, they have yet to be fully assessed with regard to environmental and economic viability. If found less sustainable than their conventional plastic counterparts, the green marketing appeal behind biocontainers will essentially turn into *greenwashing* or the misrepresentation of a product or business as being environmentally friendly. With the notable exception of irrigation demand (Evans and Karcher, 2004; Evans et al., 2010), little or no peer-reviewed literature exists which attempts to assess if biocontainers are more environmental friendly than their plastic counterparts. What is present in the current literature is a small, but growing collection of studies aimed at determining the economic implications associated with biocontainer use in greenhouse and nursery production. These works cover a range of topics from yield performance to wet- and dry-pot strength (Evans and Hensley, 2004; Evans and Karcher, 2004; Evans et al., 2010; Keuhny et al., 2011).

A major factor contributing to the success of container production, regardless of pot type, is irrigation. Evans and Hensley (2004) conducted two experiments involving a conventional plastic pot and two biocontainer alternatives (i.e.,a feather-based pot and a peat-based pot). The first was conducted under uniform watering conditions where pots were watered when the media of approximately 25 % of all experimental units – regardless of pot type – were visibly dry. Not surprisingly, plants in pots made from plastic, the only impermeable material tested, performed the best. Plants in peat pots, which dried fastest and were prone to wilting under these watering conditions, had significantly lower rates of growth. Plants grown in poultry feather pots, which were somewhat permeable, tended to fare better than those in peat pots, but did not reach the growth potential of those in conventional plastic containers.

In a second trial, where water was administered based on need, these differences in growth were all but absent (Evans and Hensley, 2004).When comparing these two related studies, the authors acknowledged that water availability appeared to be the key factor for plant success. Subsequent tests by Evans and Karcher (2004) determined that water loss in the peat containers was three times greater than that of the plastic control and 2.5 times greater than that of the feather pot. This water loss translated into a higher irrigation demand and could ultimately diminish the economic and environmental sustainability of the more porous alternatives. Expanding on the protocol established in the uniform watering study above, Keuhny et al. (2011) investigated a wider range of biocontainers in a multi-location greenhouse study. However, in this experiment, the researchers found no clear pattern to indicate any of the pots tested offered a significant advantage across the species investigated (Kuehny et al., 2011).

In addition to plant growth, a major concern with the use of biocontainers is their strength. Automation in pot filling, planting, and movement of containers during production can offer significant cost savings. Any pots that are not rugged enough or are otherwise incompatible with mechanized processing equipment come at an added labor cost to producers. One indirect means of assessing whether a pot can withstand the rigors of production and transport has been to compare various strength properties of biocontainers to similar-sized plastic pots that are currently used in the industry. In 2004, Evans and Karcher evaluated the top-to-bottom crush strength, sideways crush strength, and sidewall puncture resistance for plastic, paper and feather pots. When assessing dry material strength properties, none of the containers consistently out-performed the rest. When wetted, plastic containers were clearly the strongest in all three assessments (Evans and Karcher, 2004). Peat pots had the lowest post strength when wet, making them difficult to handle without breaking. While this research offers a direct comparison of the structural and material strength of pots, the measures are largely meaningless unless one can draw parallels to the forces experienced in production and transport. To date, all published research falls short of this requirement.

Biocontainers in the Landscape

While container wall permeability and degradation can lead to challenges in a production system (i.e.,increased water usage and decreased pot longevity), these two material characteristics are considered beneficial in the landscape. Plantable pots have been marketed as a time- and waste-saving alternative to plastic containers as there is no need to remove and dispose of leftover packaging at planting. Fine roots can easily penetrate many of the more permeable pots (e.g., peat or wood fiber containers) during greenhouse production. As emerging roots are exposed to air, they are effectively air-pruned back toward the container wall. This process helps limit root circling that can slow establishment into the surrounding soil (Kuehny et al., 2011; Evans and Hensley, 2004). With the plant's entire rooting zone left intact at installation, plantable pot use is also commonly believed to limit root damage, reduce transplant shock, and decrease the time needed for plants to establish in the landscape (Kuehny et al., 2011; Hall et al., 2010; Evans and Hensley, 2004; Evans and Karcher, 2004).

In 2011, Keuhny et al. conducted a landscape trial that compared a number of plantable pots to a plastic control (i.e., the pot was removed prior to planting). The results of this experiment indicated that none of the containers tested appeared to have a significant impact on plant growth or establishment in the surrounding landscape. These results suggest that if plants grown in direct-bury pots did experience reduced transplant shock, the difference was not enough to have a lasting effect on plant growth over the course of the season. The findings of this research also suggest that the walls of plantable pots do not serve as a barrier for roots growing out into the surrounding soil.

There is a fine balance between producing pots that degrade too quickly to survive production and producing pots that remain intact too long to be considered plantable. Bio-based plastics can be seen as a compromise between conventional and plantable pots. Bio-plastics provide the consistency of conventional plastic containers in the greenhouse or nursery while also retaining some of the perceived environmental benefits associated with plantable pots (e.g., smaller contribution to landfill waste streams) made from less resilient raw plant materials. Bio-plastic containers are typically labeled as biodegradable or compostable as they will break down naturally in soil or as compost. However, they differ from plantable containers in that their relatively slow rate of degradation can restrict root growth for a growing season or more. Some bioplastic containers have overcome this limitation by incorporating small slits or other openings in their designs that allow for outward root growth.

Research Need and Justification

Recent surveys have shown that there is both industry and public interest in biocontainers as part of a larger effort to increase the sustainability of ornamental horticulture production (Dennis et al., 2010; Hall et al., 2010; Hall et al., 2009). However, biocontainers remain a minor player in the greenhouse and nursery industry. Many obstacles have been identified which are believed to block the widespread use of these products. Some may be real barriers that need to be overcome; however, others may simply be misconceptions bred from an absence of scientific proof. In order to separate actuality from anecdote, this body of research will address the following perceived barriers:

CHAPTER 2: USE OF BIOCONTAINERS FOR LONG- AND SHORT-TERM GREENHOUSE CROP PRODUCTION

- Justification: A key consideration when adopting any new sustainable process is whether or not one can still produce a uniform crop that is of the same quality (or better) as the standard practice. Evans and Hensley (2004) conducted greenhouse trials on a limited selection of pot types under both uniform and prescriptive watering regimes. This work was later expanded to include a broader range of containers, but only under uniform watering conditions (Kuehny et al., 2011). Under this design, any potential effects associated with the containers themselves were confounded with a non-treatment watering effect. There is need for an expanded study that incorporates the newest containers and applies irrigation based on need at the treatment level. This will more closely replicate conditions found in a commercial greenhouse – an environment optimized for vigorous plant growth. Additionally, past work investigating container integrity at the end of production were limited to 4-5 weeks. This project includes a long-term crop cycle (12 wks) to assess which biocontainers are suitable for slower-growing ornamentals.

- Summary: This greenhouse study was designed to investigate the impact of bio-pot type on plant performance for a short-and long-term crop. It also assessed the impact of standard greenhouse production practices on the wall integrity and degradation of biocontainers with a 6-week or 12-week crop cycle.
- Hypotheses:
    - Ho_1: Plant growth parameters (e.g., shoot weight, area) and quality ratings will not differ significantly among treatments (containers).
    - Ho_2: Soil environmental measures (e.g., pH and EC) will not differ by treatment over the duration of the study.

CHAPTER 3: BIOCONTAINER WATER USE IN SHORT-TERM GREENHOUSE CROP PRODUCTION

- Justification: While measurement intensive, water use studies provide per plant estimates of irrigation demand which can be scaled up to larger production systems. Past works investigating this response do not include two of the newer biocontainer alternatives.
- Summary: This greenhouse study investigates the impact of biocontainers on plant growth and water consumption for a short-term (5-week) floriculture crop. Results of the work will be used to assess the overall environmental impact associated with biocontainer adoption in greenhouse production.
- Hypotheses:
    - Ho_1: Plant growth parameters (e.g., shoot weight, area) will not differ significantly among treatments (containers).
    - Ho_2: Total water use will not differ by treatment.

CHAPTER 4: PLANTABLE BIOCONTAINERS IN THE LANDSCAPE: RATE OF DEGRADATION AND IMPACT ON PLANT ESTABLISHMENT

- Justification: Many of the perceived benefits of plantable pots stem from the belief that they outperform non-plantable containers in regard to planting time and plant establishment. A past study investigated how a wide range of direct-bury pots affected plant growth and establishment in the landscape (Kuehny et al., 2011). This work was originally conducted at a single site. We have expanded this past study to include a variety locations in North America that represent a wide range of soil and climate conditions.

- Summary: This study was designed to identify the impact of biocontainers on plant vigor (i.e.,visual rating), plant development (i.e.,height and width growth until planting space reached full stocking/saturation), and pot degradation (i.e.,visual analysis and weight loss) in the landscape. In addition, labor required for planting was recorded for use in the economic analysis.
- Hypotheses:
    - Ho: Measured response variables below (i.e.,plant growth and development metrics, plant appearance rating, pot degradation, and planting time) will not be significantly different among treatments.

CHAPTER 5: BIOCONTAINER USE IN PETUNIA XHYBRIDA GREENHOUSE PRODUCTION – A CRADLE-TO-GATE CARBON FOOTPRINT ASSESSMENT OF SECONDARY IMPACTS.

- Justification: Currently, it is believed that biocontainers are more environmentally sound than their plastic alternatives as they are not derived from oil and are not destined for the landfill. However, these are just two of many considerations which can be used to gauge environmental efficacy. Life-Cycle Analysis of the pots (themselves and as part of a larger greenhouse production system) will account for differences in inputs, waste generation, water usage, and energy associated with greenhouse production using biocontainers. To date, no published work exists which accounts this broader environmental concern.
- Summary: Using a local wholesaler as a case study, a cradle-to-gate life cycle assessment will be conducted. Industry data and data generated through the studies above will be used to gauge the overall sustainability of ornamental crop production systems using the various containers selected for these studies.

APPENDIX 1: COMPATIBILITY OF BIOCONTAINERS IN COMMERCIAL GREENHOUSE CROP PRODUCTION

- Justification: Hall et al. (2009) found that producers were less likely to adopt sustainable practices if they were not compatible with existing production process. However, later work indicated that issues of compatibility were regarded as one of the smallest obstacles greenhouse growers faced when looking to implement new, greener practices (Dennis et al. 2010). This contradiction is rooted in the machinery used for production. While filling and handling devices can be adjusted to accommodate a wide range of containers, trays, and flats, biocontainers may not withstand the rigors faced during processing. Any container incompatible with existing production schemes will be of little interest to growers.
- Summary: This study investigates the impact of several mechanical greenhouse systems (e.g., pot fillers, spacers, and transport systems) on biocontainer integrity. This work determined damage from mechanical systems as well as the speed laborers and machines were able to process them.
- Hypotheses:
  - Ho_1: The time required to prepare pots for mechanized processing will not be significantly different among treatments (pot types; controlling for pot damage).
  - Ho_2: Pot damage ratings associated with the actual mechanized processing will not be significantly different among treatments.

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CHAPTER 2: USE OF BIOCONTAINERS FOR LONG- AND SHORT-TERM GREENHOUSE CROP PRODUCTION

Note: This work was completed as part of a multi-institutional research initiative with additional trials conducted at research facilities associated with the University of Arkansas, University of Kentucky, and West Virginia University. Only work conducted at the University of Illinois Plant Science lab is reported in this chapter. The final revision to be submitted for peer review will include analyses from all four locations.

Summary

While research on the use of biocontainers for greenhouse production is growing, most studies have focused primarily on short-term greenhouse crops. With the recent release of several new bioplastic alternatives, production of longer-rotation ornamental crops may be more feasible. This work investigates ten commercially available biocontainers and their effects on both a short-term (*Impatiens* x*hybrida* ‘Sunpatiens Compact’) and a long-term greenhouse crop (*Lavendula angustifolia* 'Elegans Ice’). Results indicate that plant growth in terms of leaf area and dry shoot mass differed by container. However, the pattern of growth varied by species. Visual yield responses such as plant condition and days after transplanting (DAT) to flowering did not vary with container. Leachate pH and EC varied by container and by week. However, a significant interaction between the two main effects made it difficult to identify any clear trends. Post-harvest container strength varied significantly by container, with the plastic control maintaining the highest puncture resistance after both 6 and 12 weeks. Results show that while some biocontainers were linked to increased growth, this gain should be weighed against potential losses associated with container damage during handling and shipping.

Background

Biocontainers differ from petroleum-based plastic pots in that they are made of plant-derived materials and are plantable or compostable. In order to break down in soil or in a composting environment, biocontainers are essentially designed to degrade over a relatively short period of time. While this design characteristic reduces end-of-use landfill waste, it may also limit biocontainer compatibility with longer-term or multi-season ornamental nursery crop production systems. This potential limitation is reflected both in the market and in recent research. Biocontainers are more readily available in sizes commonly used in commercial greenhouse production, while they are much less prevalent in larger sizes most suitable for woody nursery production. Additionally, a survey of greenhouse professionals and nursery producers found that compatibility with existing equipment and production practices was a minor hindrance for greenhouse professionals but a significant obstacle for nursery producers when adopting sustainable production practices like biocontainers (Dennis et al., 2010).

The integrity and longevity of biocontainers are impacted by the specific conditions of the greenhouse. High-input greenhouse production accelerates plant growth and shortens production time. However, the elevated temperature, humidity, and substrate nitrogen levels associated with these controlled environments hasten organic matter degradation as well as plant development. As such, even the comparatively short crop rotations common in greenhouse operations may be too long with respect to container appearance and integrity. Given that unsightly or damaged containers may be largely unsellable to the plant-buying public, both of these measures of container performance may ultimately affect the economic sustainability of biocontainers.

Past research has investigated biocontainer degradation and strength loss after simulated greenhouse production. However, these assessments are generally limited to short-term crop production. In 2004, Evans and Karcher assessed residual pot strength for plastic, peat, and feather pots after a 5-week growing period. Evans et al. (2010) later expanded on this work by measuring pot crush and puncture for eight commercially available biocontainers after four weeks in production. While a longer, 10-week study was conducted by Helgeson et al. (2009), the sole biocontainer tested in the work was a prototype container constructed by hand using a zein-based bioplastic, which is not commercially available to greenhouse producers.

The study reported herein investigates plant growth and residual container strength for nine biocontainers and a plastic control. Beyond the addition of a new container type (bioplastic sleeve), our research expands on the past work of Evans et al. (2010) by investigating two crop lengths, a short-term (6-week) production period and a long-term (12-week) production period. In adding the longer production cycle, this work investigates the feasibility of biocontainer use in the production of slower-growing greenhouse plants. Beyond measures of container performance, this study also investigates impacts on plant growth and quality. The combined results are intended to assist commercial growers interested in adopting biocontainers for their own greenhouse operations.

Materials and Methods

LOCATIONS. The greenhouse trial for this study was conducted at the Plant Science Laboratory facilities at the University of Illinois at Urbana-Champaign, Urbana, IL (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b). Container strength testing and algal growth assessment were conducted at the University of Arkansas, Fayetteville, AR.

CONTAINERS. Ten container types were used in this study (Table 2.1 and Fig. 2.1). One 4-inch (10 cm) plastic standard pot was selected as the study's control. For the nine biocontainer alternatives, the manufacturer's closest substitution (with regard to volume) to the control pot was selected for comparison.

Fig. 2.1. Images of container treatments used to grow a short-term crop of 'Yellow Madness' petunias. Plants were grown under greenhouse conditions for 5 weeks in order to gauge the effect of container type on irrigation demand. Containers used included (A) plastic control, (B) bioplastic, (C) coir, (D) manure, (E) peat, (F) sleeve, (G) slotted rice hull, (H) solid rice hull, (I) straw, and (J) wood fiber.

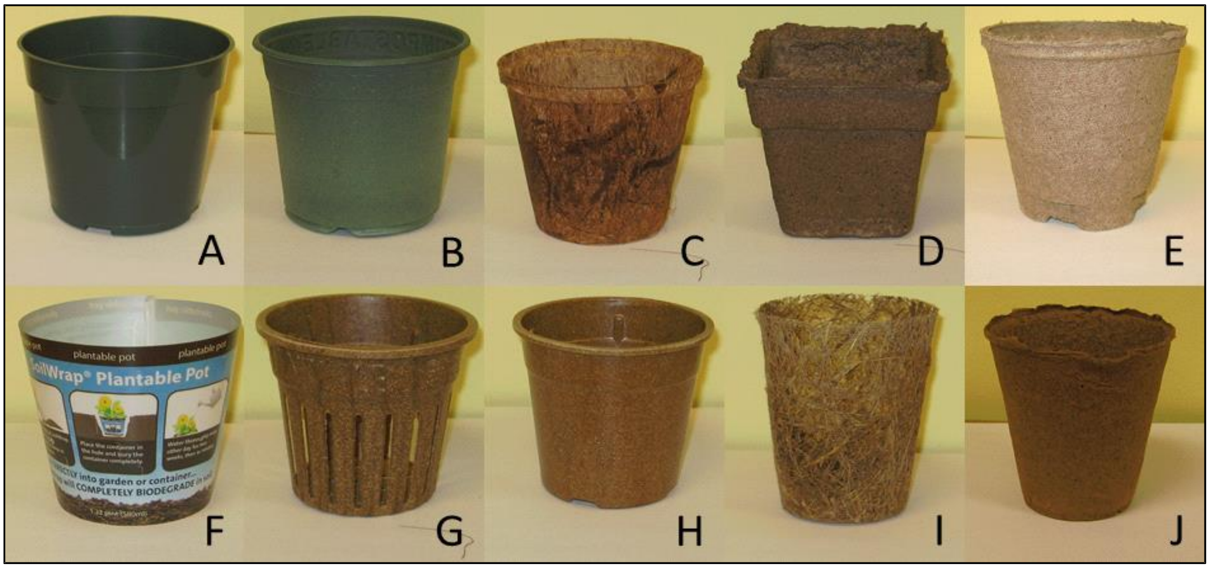


Table 2.1. Container treatments selected for this experiment (including manufacturer information and approximate volume).

Container type	Product name[z]	Volume (cm^3)	Manufacturer
Plastic	Dillen 04.00 Standard Thinwall Green	480	Myers Industries Lawn & Garden Group, Middlefield, OH
Bioplastic	TerraShell™ 10cm H Wheat Pot	473	Summit Plastic Company, Akron, OH
Coir	Coir 4.0” Std Fiber Gro Pot	406	Dillen Products, Middlefield, OH
Manure	#4 Square CowPot	450	CowPots Manufacturing and Sales, East Canaan, CT
Peat	4” Jiffy Pot	379[y]	Jiffy Products of America Inc., Lorain, OH
Bioplastic sleeve (Sleeve)	4.5” Standard Assembled SoilWrap®	709[y]	Ball Horticultural Company, West Chicago, IL
Slotted rice hull	4.5” NetPot	591	Summit Plastic Company, Akron, OH
Solid rice hull	Rice Pot 4”	473	Summit Plastic Company, Akron, OH
Straw	n/a	646[y]	Ivy Acres, Baiting Hollow, NY
Wood fiber	10 X 10 cm Round Individual Fertilpot	430[y]	Fertil SAS, Boulogne Billancourt, France

[z] As indicated in manufacturers on-line/print catalog.

[y] Not included in manufacturer specifications. Volume approximated.

EXPERIMENTAL DESIGN, GROWING CONDITIONS, AND PLANT CARE. Two species, *Impatiens* x*hybrida* ‘Sunpatiens Compact’ (impatiens) and *Lavendula angustifolia* 'Elegans Ice’ (lavender) were selected as representative short- and long-term ornamental crops, respectively, for the greenhouse trial. Given differences in production length and watering requirements, each species was assessed separately as its own unique experiment. Trial length for the short-term crop (impatiens) was set at 6 weeks. The trial length for the long-term crop (lavender) was 12 weeks. Both experiments were arranged as completely randomized designs, with trays containing six identical containers serving as the experimental unit (total n=30 trays). Each of the 6 individual pots constituted a pseudo-replicate of its associated tray (total n=180 pots).

All containers were filled with a commercial soil-less growing mix (Fafard 2, Conrad Fafard Inc., Agawam, MA) and planted with either an impatiens or a lavender plug. Trays were arranged tightly together on raised greenhouse benches. A one-plant-wide border row surrounded the outer edge of the experiment.

Both trials were initiated on April 25, 2011. Plants were grown under ambient light conditions with minimum day- and night-time temperatures set at 24ºC and 18ºC, respectively. The median temperature over the course of both experiments was 26.5ºC, with a high of 39.8ºC recorded on May 10, 2011 and low of 21.7ºC recorded on April 27, 2011. Relative humidity during the study period ranged from 19.4% to 89.5%, with a median value of 61.8%.

Irrigation was supplied by hand on an as-needed basis at the experiment (i.e., plant) and treatment (i.e., container type) level. For lavender, this watering threshold was defined as the point when soil moisture levels at or below 30% were detected for a given container type. Similarly, impatiens plants were watered when soil moisture readings of 40% or lower were detected. Soil moisture levels were originally measured with the aid of an electronic soil moisture sensor (ThetaProbe Soil Moisture Sensor – ML2x, Delta-T Devices Ltd, Cambridge, United Kingdom). Once the visual indicators of drying for each of these moisture thresholds were identified (e.g., graying of the substrate surface), watering demand was assessed by sight, as repeated measurements with the sensor in the same soil space can lead to questionable measurements (Evans, personal communication). In addition to this watering, plants were fertigated weekly with a 150 ppm 20N-4.4P-16.6K solution (Plantex® 20-10-20 All Purpose High Nitrate, Plant Products Co. Ltd. Brampton, ON) . This solution was applied to all of the plants on the same day (Wednesday), regardless of any particular container type's watering needs for that day.

MEASUREMENTS. Measurements for this experiment were categorized broadly as plant-focused measurements and container-focused measurements. The former included measures of shoot dry mass, leaf area (using a LI-3100C Area Meter, LI-COR, Lincoln, NE), days after transplant (DAT) to anthesis (full flowering), and a visual ranking of plant quality (Table 2). All measures were conducted at harvest or, in the case of flowering, as it occurred.

Container-focused measurements included bi-weekly electrical conductivity (EC) and pH testing of growing mix leachate, post-harvest container puncture strength, and post-harvest container fungal/algae coverage. EC and pH measurements were taken at the individual tray level from a leachate sample of approximately 50 mL using a portable multi-parameter solution tester (HI 98130 pH/Conductivity/TDS Tester, Hanna Instruments, Woonsocket, RI).

Puncture strength was defined as the amount of pressure required to punch through a container's wall with a 5-mm ball probe. This test was performed using a texture analyzer (TAXT 2I; Texture Technologies, Scarsdale, NY). Algal growth was quantified with a leaf area meter (LI-3100C Area Meter, LI-COR, Lincoln, NE). Patches of algal growth were removed from the container with a razor utility knife and run through the area meter to gauge total area covered.

DATA ANALYSIS. All end-of-harvest measurements (i.e., shoot dry mass, leaf area, and pot strength) were analyzed as a series of one-way Analysis of Variances (ANOVAs). Pseudo-replication in the dry mass and leaf area measurements was averaged away prior to data analysis and analyzed in R (R Development Core Team, 2012). Mean separation was conducted, when appropriate, as a protected Fisher's Least Significant Difference test (de Mendiburu, 2012). End-of-trial, visual plant condition ratings were analyzed using a Kruskal-Wallis rank sum test (de Mendiburu, 2012). DAT to anthesis was modeled as a general linearized model with a gamma distribution in R (R Development Core Team, 2012). As some of the lavender did not flower before the end of the trial, its DAT flowering response was modeled with censoring in the survival package in R (Therneau, 2012).

Both pH and EC were assessed as repeated measures in R (Lawrence, 2012). For both the long- and short-term trials, the data from the puncture strength testing failed to meet two key criteria needed to conduct a one-way analysis of variance through ordinary least squares. Namely, the variances among the containers tested were dissimilar and residuals were non-normal. After investigating several transformations and finding none sufficient, the data were ultimately analyzed via a parametric bootstrap comparison of trimmed means (Wilcox, 2012). Mean separation for puncture strength was conducted using the mcppb20() function (Wilcox, 2012).

Results and Discussion

As noted in Table 2.1, some differences in volume existed among the pots selected for this trial despite our efforts to find the closest comparable surrogate for the plastic control. This variation reflects the realities a commercial grower would face when looking for an alternative to a 4-inch (10 cm) plastic pot. Beyond size, other factors such as pot geometry, material, and the presence/absence of drainage holes are all factors that contribute to overall pot design. The results below are reflective of the combined impact of all of the considerations noted above.

PLANT GROWTH AND APPEARANCE RESULTS. Dry shoot mass varied significantly by pot type for both impatiens (P = 0.0538) and lavender (P = 0.0040). Similarly, final leaf area differed significantly for both impatiens (P = 0.0255) and lavender (P = 0.0430). However, container type did not noticeably impact visual plant condition ratings for either impatiens (P = 0.2750) or lavender (P = 0.7362). Treatment means for these two plant growth measures are displayed below for both impatiens (Fig. 2.2) and lavender (Fig. 2.3). Dry shoot mass and leaf area were analyzed as multiple univariate ANOVAs (as opposed to MANOVA) to allow comparisons between similar analyses seen in past biocontainer work (Evans and Hensley, 2004; Kuehny et al., 2011). In adopting this approach, Huberty and Morris (1989) suggest that authors report the calculated correlation between responses to show no correlation exists (or as a caveat in the event it does). Correlation was calculated and tested using the cor.test function in R. For impatiens, the correlation between dry mass and leaf area was 0.7534 ($P < 0.0001$). For lavender, correlation between these two growth responses was 0.8253 ($P < 0.0001$).

Though plant growth differences in biocontainers appear to be somewhat species specific, a few patterns emerged. For example, the sleeve container was associated with the lowest mean dry shoot for both lavender and impatiens (Figs. 2.2 and 2.3). Similarly, plants in the coir containers were, on average, among the largest in the group (Figs. 2.2 and 2.3). Interestingly, dry shoot mass in the control plants was not among the top group of pots tested (Figs. 2.2 and 2.3).

Fig. 2.2. Dry shoot mass (A) and leaf area (B) for Impatiens xhybrida 'Sunpatiens Compact' grown under greenhouse conditions for six weeks in ten container types (one plastic control and nine biocontainer alternatives). Error bars depict Fisher's Least Significant Difference values (α=0.05).

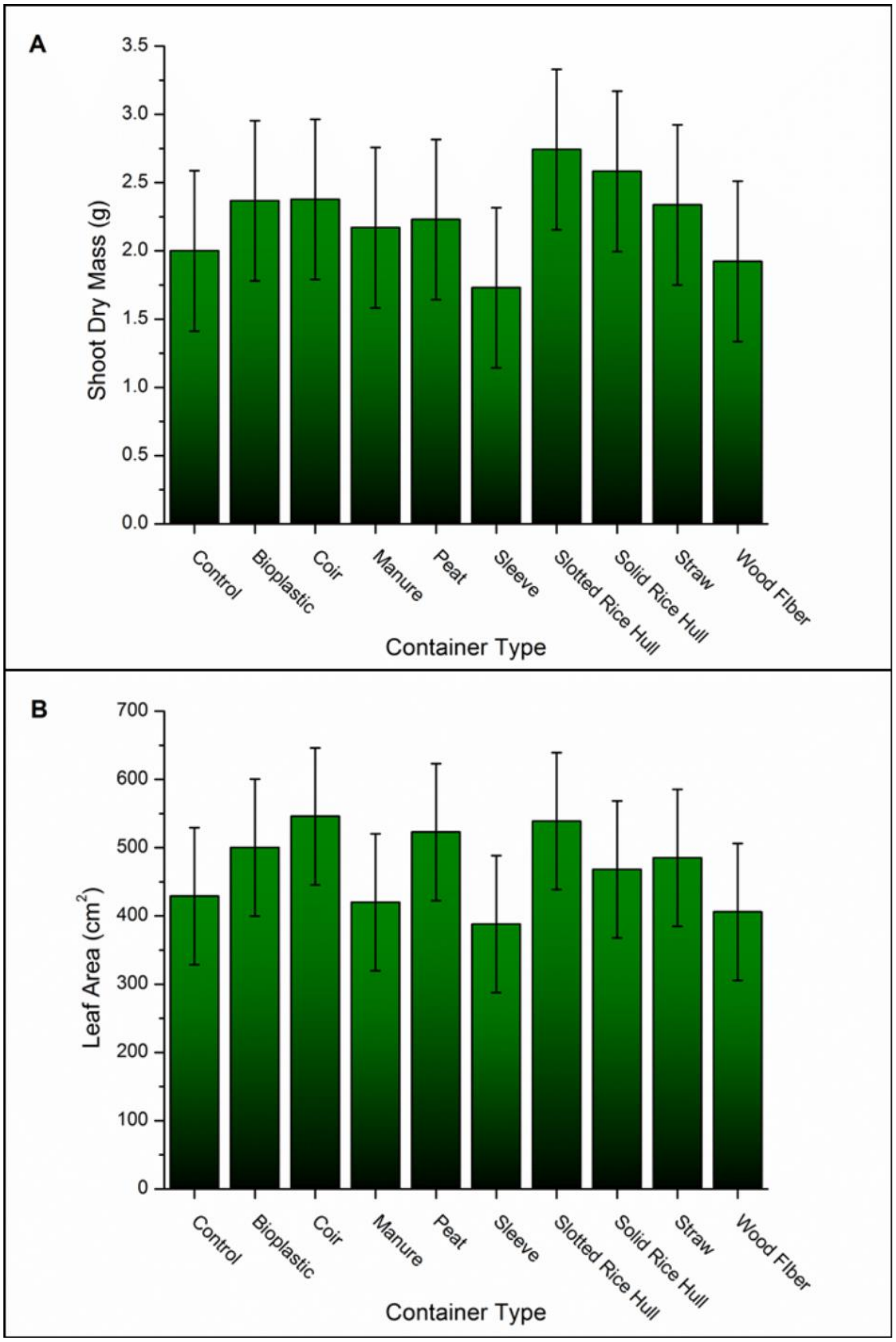
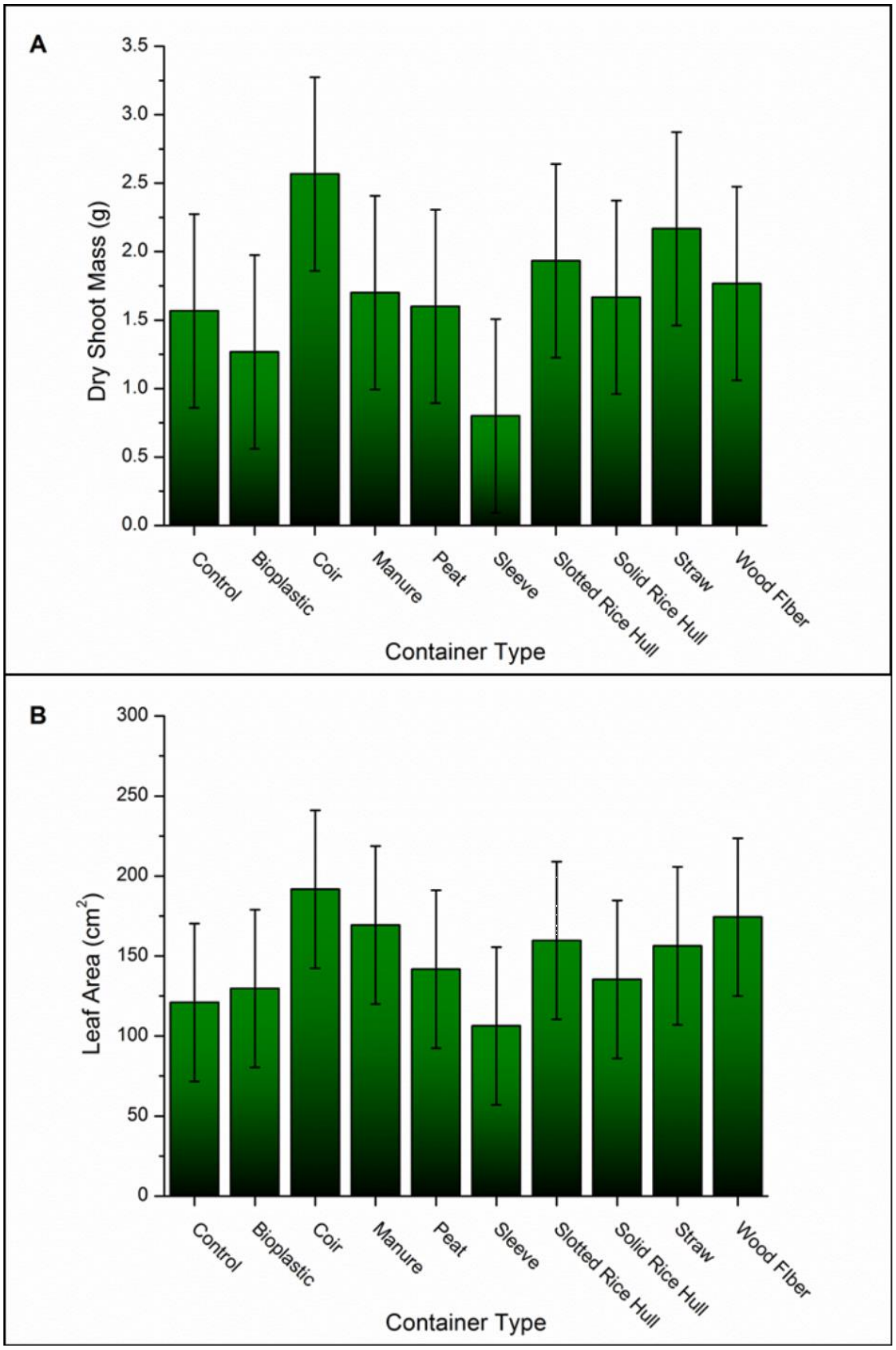


Fig. 2.3. Dry shoot mass (A) and leaf area (B) for Lavendula angustifolia 'Elegans Ice' grown under greenhouse conditions for 12 weeks in 10 container types (1 plastic control and 9 biocontainer alternatives). Error bars depict Fisher's Least Significant Difference values (α=0.05).



Kuehny et al. (2011) also investigated shoot dry mass of impatiens grown in 4-inch biocontainers at three sites. While results for each location differed, dry shoot mass in plastic controls was generally higher than in most of the other containers. For two sites in their study, mean shoot dry weight for plants in coir containers was reduced compared to the other treatments. Our findings are somewhat contrary to these results, but this discrepancy is not too surprising. Plant growth patterns differed even among the three sites featured in the Kuehny paper (2011), showing that despite efforts to replicate watering, fertilization, and environmental conditions through a standardized research protocol, it was difficult to elicit the same response at each site. We suspect that water availability may be the key to these differences. Despite having a set watering threshold, there is some subjectivity associated with the decision to irrigate. A soil moisture probe which continuously monitors rooting conditions and triggers irrigation the moment the threshold is reached may eliminate some variation associated with measurement error. However, these systems are expensive and are not without their own programing and maintenance concerns.

While size and overall quality are commonly associated with ornamental crop yield, DAT to flowering is an often overlooked response variable (Evans, personal communication). Even slightly stunted plants can be shipped off to market once in bloom. For impatiens, DAT to anthesis did not differ by container type ($P = 0.3289$). Similarly, DAT to flowering did not differ significantly by container for the lavender ($P = 0.1866$).These results show that for crops where marketability is driven largely by the presence of flowers, the adoption of a biocontainer will not delay crop availability.

SUBSTRATE CHEMISTRY RESULTS. For impatiens, pH varied by container ($P < 0.0001$), week ($P < 0.0001$), and the container x week interaction ($P < 0.0001$). Leachate EC varied significantly by container ($P = 0.0007$) and week ($P < 0.0001$). Additionally, there was a significant container x week interaction ($P = 0.0002$). For lavender, soil pH for lavender was influenced by container ($P < 0.0001$) and week ($P < 0.0001$), and the c container x week interaction ($P = 0.0017$). EC varied by container type ($P = 0.0315$) and week ($P < 0.0001$); however, the interaction between container x week was marginally insignificant ($P = 0.0577$).

For impatiens, average pH generally increased and EC generally decreased after the first measurement period (Fig. 2.4). From then on, both measures largely plateaued for the remainder of the trial. This pattern was less pronounced in the lavender (Fig. 2.5). For both the long- and short-term trials, average leachate pH for the manure pots was elevated throughout the study periods (Fig. 4 and Fig. 5). This was noted at other sites where the trials were conducted (Renee Conneway and Vicky Anderson, personal communications). While substrate chemistry did not have any noticeable impact of plant condition (e.g., chlorosis), it may be one of several contributing factors behind the growth differences noted above, and should be further investigated.

Fig. 2.4. Bi-weekly leachate pH and Electrical Conductivity (EC) over time for 10 container types. A 6-week trial length was chosen to reflect the production time required for a short-term greenhouse crop (Impatiens xhybrida 'Sunpatiens Compact'). Error bars depict Fisher's Least Significant Difference values (α=0.05).

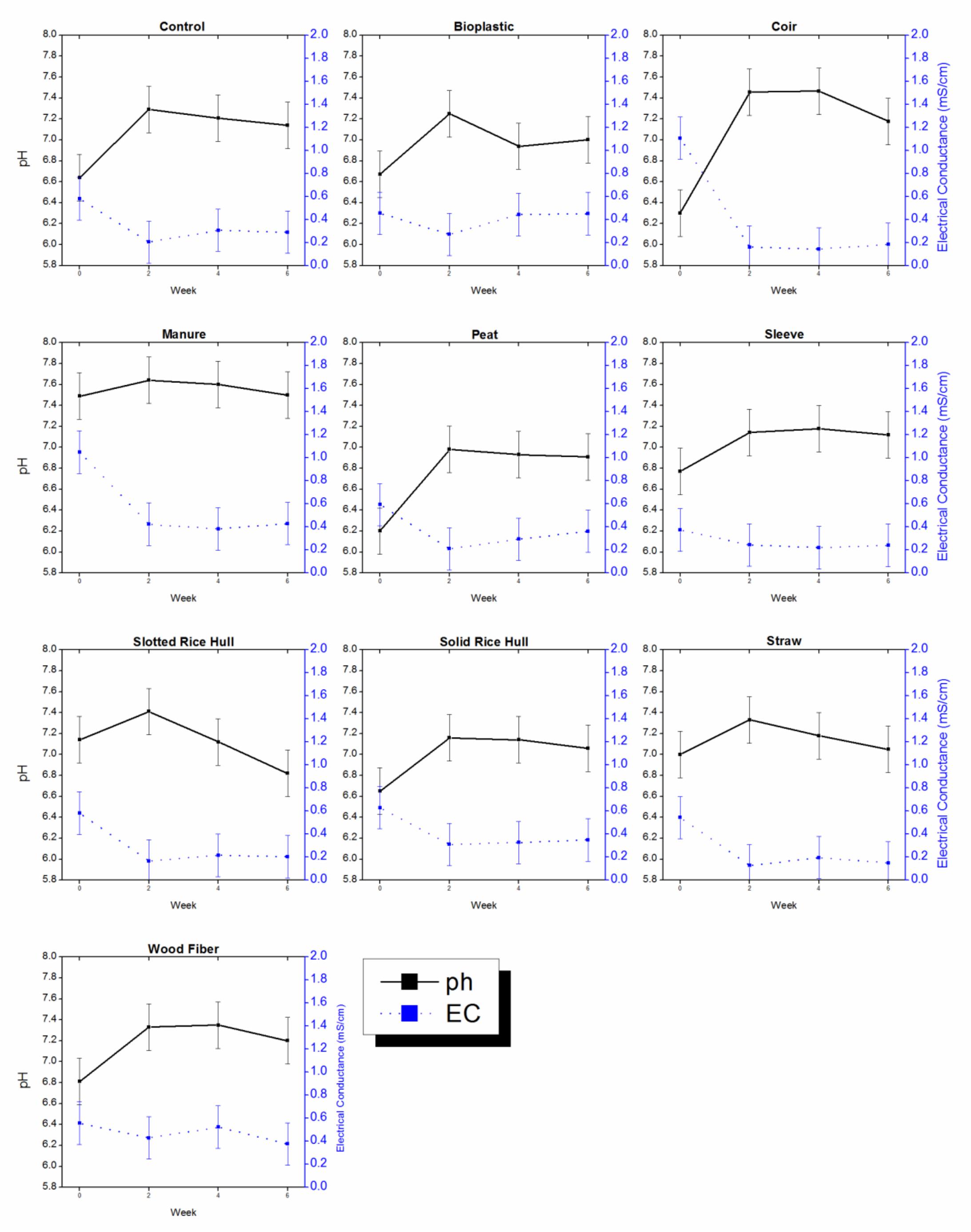
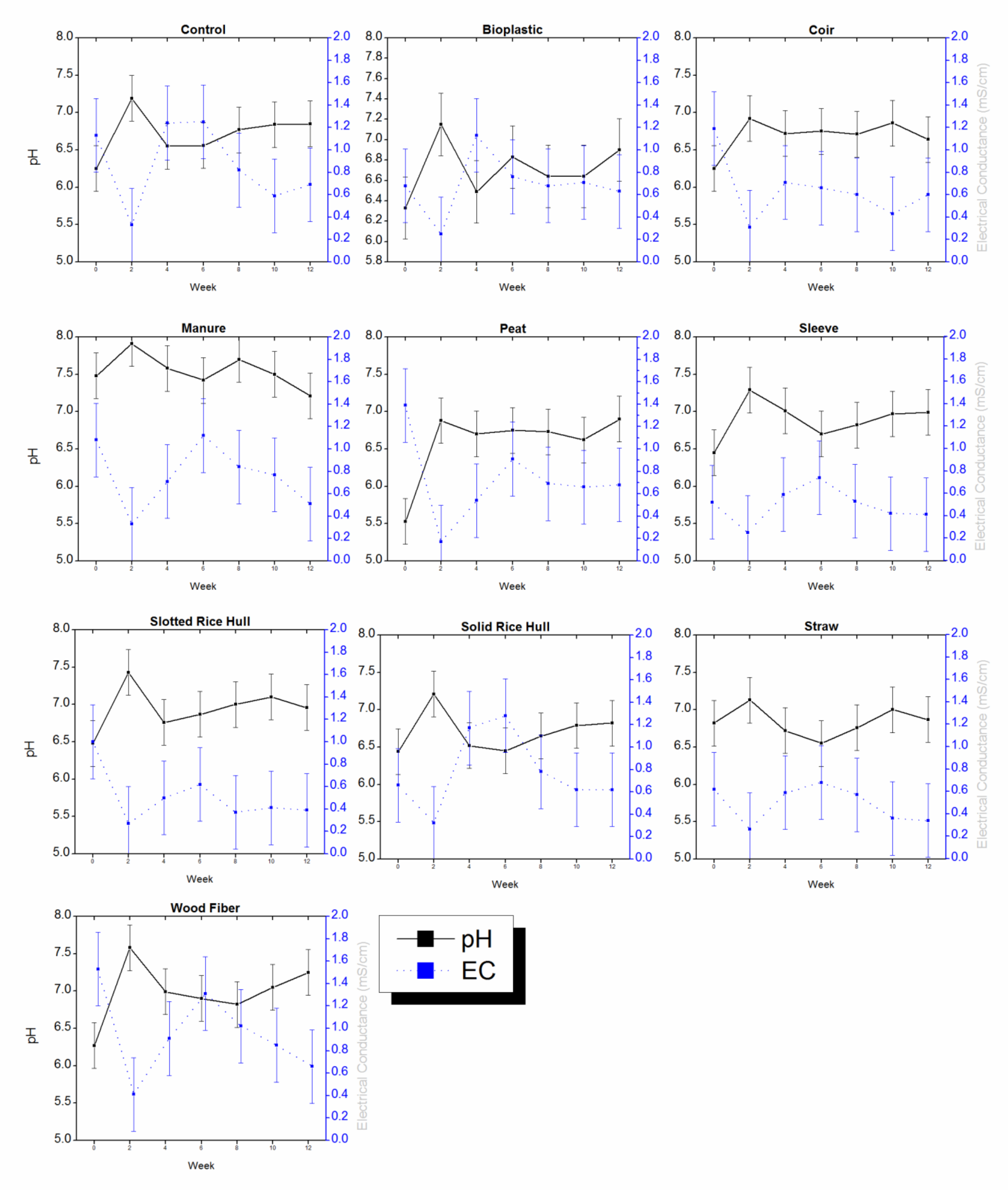


Fig. 2.5. Bi-weekly leachate pH and Electrical Conductivity (EC) over time for 10 container types. A 12-week trial length was chosen to reflect the production time required for a long-term greenhouse crop (Lavendula angustifolia 'Elegans Ice'). Error bars depict Fisher's Least Significant Difference values (α=0.05).



CONTAINER PUNCTURE STRENGTH TESTING. Puncture resistance differed by container type for both short-term ($P < 0.0001$) and long-term ($P < 0.0001$) production. For both short- and long-term production, the plastic control offered the greatest resistance to puncturing with mean strength values of 19.5 kg and 20.7 kg, respectively. For both trials, coir containers were the second strongest with regard puncture strength (Figs. 2.6 and 2.7). However, coir puncture strength was 41% of control strength in the short-term trial and 63% of control strength in the long-term trial. Differences in mean puncture strength as compared to the control were even greater for the remaining biocontainers (Figs. 2.6 and 2.7).

Fig. 2.6. Mean puncture strength for 10 container types used in the production of a 6-week greenhouse crop (Impatiens xhybrida 'Sunpatiens Compact'). Letters indicate statistical groupings.

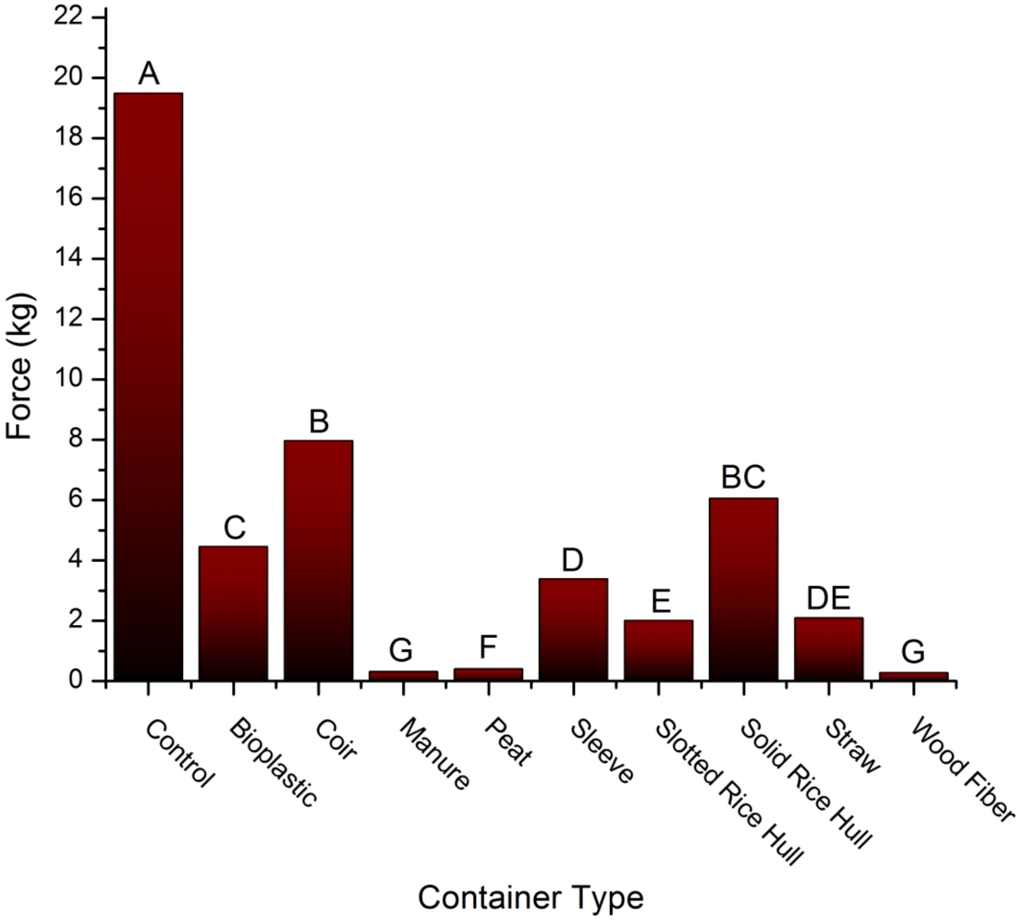
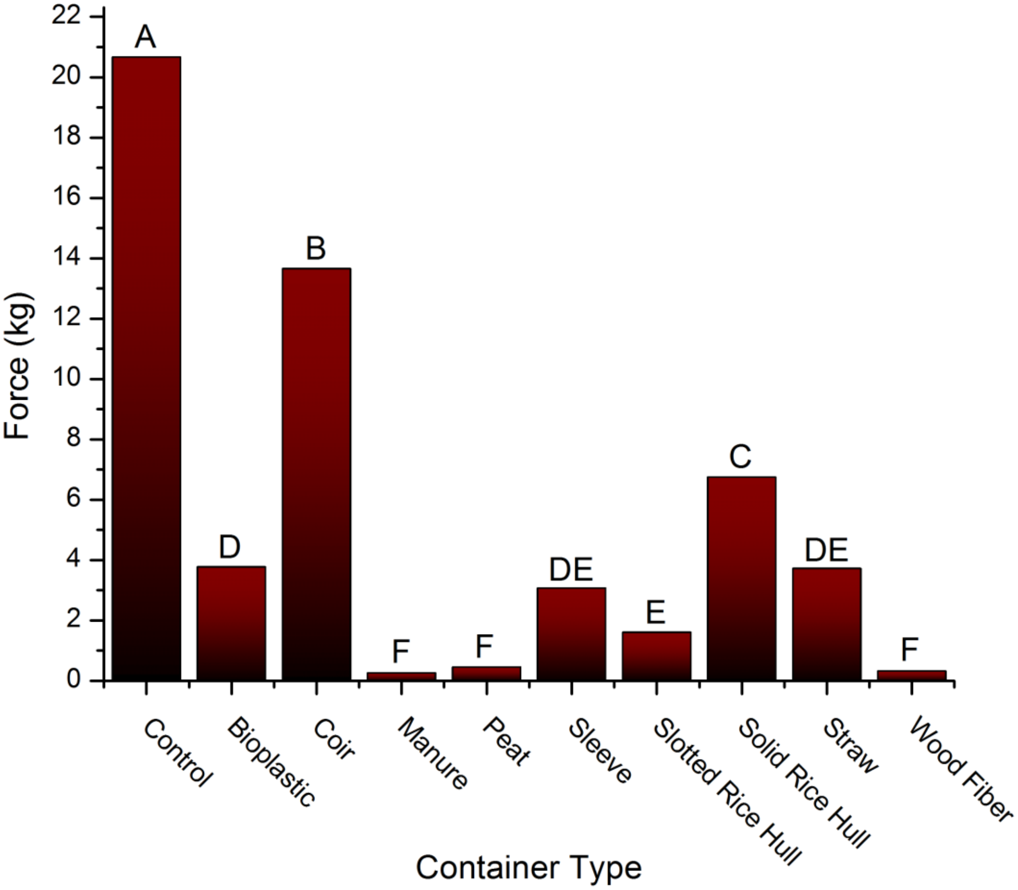


Fig. 2.7. Mean puncture strength for 10 container types used in the production of a 12-week greenhouse crop (Lavendula angustifolia 'Elegans Ice'). Letters indicate statistical groupings.



ALGAL GROWTH. In the short term trial, algal growth was minimal and limited to the peat and wood pulp containers. Average growth in the peat was 5.57 cm^2 and in wood pulp was 0.97 cm^2. Both means were greatly influenced by a large number of containers that contained no algal growth (peat: 11, wood pulp: 17). Algal growth was limited to the manure, peat, and wood pulp containers in the long-term study with mean coverage areas of 15.29 cm^2, 34.97 cm^2, and 37.51 cm^2, respectively. Compared to the short-term trial, algae was much more widespread. Seven cow and four wood pulp containers remained clear of growth by the end of the 12-week period. Every peat container had some level of measurable algae growth.

If algal growth diminishes consumer interest in a potted container, careful consideration must be given before adopting manure, peat, or wood pulp containers – especially for longer-term crops. The discoloration associated with algal growth, combined with their low residual strength, may limit the use of these containers in greenhouse production, especially when growing long-term crops valued for their overall appearance. Those biocontainers not prone to supporting algal growth may be preferred if customers prefer cleaner packaging, yet still have interest in plastic alternatives.

Conclusions

Using biocontainers as replacements for plastic containers is not a clear-cut proposition. The species grown can have a significant impact on how containers perform relative to the conventional plastic container they are intended to replace. In general, plant size seemed to be the main difference with regard to appearance and overall plant quality. Depending on one's tolerance for differences in top growth, container strength and appearance may be more pressing concerns. Several of the less processed containers (manure, peat, wood pulp) supported algae growth. These same containers are also among the most fragile, especially when used for long-term production. As such, they may be best suited for short-term production. When interpreting the findings of this work, it should be noted that the main marketable characteristic of biocontainers is their ability to degrade in soil or compost. The same characteristics that allow them to break down readily also contribute to their limited stability during production. This is the trade-off, but one that waste-conscious producers and consumers may be willing to overlook.

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CHAPTER 3: BIOCONTAINER WATER USE IN SHORT-TERM GREENHOUSE CROP PRODUCTION

Note: This chapter scheduled to print in the April 2013 issue of HortTechnology.

Summary

In recent years, biocontainers have been marketed as sustainable alternatives to petroleum-based containers in the green industry. However, biocontainers constructed with plant materials that are highly porous in nature (e.g., peat, wood fiber, straw, etc.) tend to require more frequent irrigation than conventional plastic products. As irrigation water sources become less abundant and more expensive, growers must consider water consumption in any assessment of their economic and environmental viability. This project evaluated plant growth and total water consumption for nine different biocontainers (seven organic alternatives, and two recently developed bioplastic alternatives) and a plastic control used to produce a short-term greenhouse crop, 'Yellow Madness' petunia (*Petunia* x*hybrida* 'Yellow Madness'). Dry shoot weight and total water consumption differed by container type, with some of the more porous containers (wood fiber, manure, and straw) requiring more water and producing smaller plants by the end of the trial period. Intuitively, the more impervious plastic, bioplastic, and solid rice hull containers required the least irrigation to maintain soil moisture levels, though shoot dry weights varied among this group. Shoot dry weight was highest with the bioplastic sleeve and slotted rice hull containers. However, the latter of these two containers required a greater volume of water to stay above the drying threshold. Findings from this research suggest the new bioplastic sleeve may be a promising alternative to conventional plastic containers given the current production process.

Background

While biocontainers (i.e., plant material-based containers) have emerged as a response to excessive plastic landfill waste, their adoption in the green industry could significantly increase crop watering requirements. Water availability has traditionally been an issue associated with arid and semi-arid production sites (Fereres et al., 2003). However, this issue is quickly becoming a major environmental and economic consideration for all horticultural enterprises, regardless of climate. With demand, regulation, and cost of water all projected to increase (Beeson et al., 2004), growers will be subject to increasing pressure to assess their overall water use and identify areas to improve efficiency and reduce waste.

In their review of irrigation management techniques, Fereres et al. (2003) identified deficit irrigation (i.e., irrigation at a level below the rate of evapotranspiration), irrigation runoff reclamation, and the reduction of evapotranspiration (ET) as the three main strategies for conserving water in horticultural production. Deficit irrigation is largely limited to field-grown crops and large-container production given the ability of the plants to draw upon relatively large soil moisture reserves (Fereres and Soriano, 2007; Fereres et al., 2003). Compared to these production systems, the small volumes of pots and trays commonly used to produce floral and foliage crops limit their overall water-holding capacity and the rooting space available to the plant. Moreover, growers use deficit irrigation in times of limited water supplies to maintain survival rather than maximize growth (Fereres and Soriano, 2007). This loss in yield potential (i.e., biomass) is largely unacceptable when producing high-value ornamental greenhouse crops (Fereres et al., 2003).

While deficit irrigation plays a very limited role in floriculture production, ET reduction and irrigation water reclamation may have important implications for greenhouse growers, especially those intending to adopt biocontainers in their operations. While not the focus of this work, water reclamation in horticulture can be effectively implemented through the adoption of an ebb-and-flood (subirrigation) system which recirculates water and fertilizer runoff (Dole et al., 1994; Dumroese et al., 2006; Morvant et al., 1998). Ebb-and-flood-irrigated 'Florida Sun Jade' coleus (*Solenostemon scutellarioides*) shoot dry weight remained similar among seven different biocontainers (i.e., bioplastic, coir, manure, paper, peat, straw, and wood fiber) and a conventional petroleum-based plastic control (Koeser et al., 2013). However, the study found that the high rate of fertilization and container wetting-drying pattern associated with subirrigation can cause a significant loss of puncture strength in wood fiber and paper biocontainers over time (Koeser et al., 2013). Despite the reduction in container integrity, the use of ebb-and-flood irrigation may still be a viable option for conserving water in biocontainer greenhouse production, especially if containers are supported in plastic shuttle trays.

Though studies on the effects of reclaimed water on biocontainer greenhouse production are limited, the effects of container on ET, as well as drainage, have been more widely documented (Bilderback, and Fonteno,1987; Evans and Karcher, 2004; Evans et al., 2010; Spomer, 1974). In comparing horticulture crops grown in peat, feather, and plastic containers watered uniformly across pot type, Evans and Hensley (2004) found that plants grown in plastic containers, which were impervious to water loss, had higher aboveground biomass than those grown in the peat- and feather-derived containers. However, when all container types were irrigated separately based on need, which resulted in more frequent water application to the peat and feather containers, growth in biocontainers was comparable and even superior to growth in a conventional plastic container depending on species grown (Evans and Hensley, 2004). Evans and Karcher (2004) found the volume of water required to grow a variety of crops was significantly lower in the plastic control as compared to those in the feather and peat containers. Similarly, more frequent watering was required for the peat and feather containers. This increased water demand corresponded with higher rates of water loss through the sides of the containers tested (Evans and Karcher, 2004). Evans et al. (2010) tested an expanded array of biocontainers to assess irrigation frequency and cumulative water demand. In doing so, the authors found that, with the exception of a relatively impermeable solid rice hull container, all biocontainer alternatives required more frequent irrigation and more overall water to maintain the minimum moisture level threshold.

Decreases in ET must coincide with unchanged or even increased plant growth to truly reduce water use in horticulture production (Fereres et al., 2003). As such, this project evaluates both plant dry shoot weight and cumulative water use at the end of the 5-week trial period. Our study expands on past efforts to assess water demand in biocontainers through the inclusion of a pair of newly marketed bioplastic alternatives, a bioplastic container and bioplastic sleeve. In adopting biodegradable, plant-based plastics, container producers hope to emulate the advantages of petroleum-derived products (i.e., durability and imperviousness), while appealing to environmentally conscious consumers and growers. The insights gained from this work will better inform growers who need to reduce water use at their facilities and will ultimately contribute to future water-use models.

Materials and Methods

CONTAINERS. Ten container types (one plastic control, seven organic alternatives, and two bioplastic alternatives) were use in this study (Table 3.1 and Fig. 3.1). A 4-inch (10-cm) standard pot was used as the plastic control. For the biocontainer alternatives, pots with comparable volumes were selected for inclusion in the trial. Variations in volume shown in Table 1 reflect the realities a commercial grower would face when looking for alternatives to standard plastic pots.

EXPERIMENTAL DESIGN, GROWING CONDITIONS, AND PLANT CARE. This study was conducted in a greenhouse setting at the University of Illinois at Urbana-Champaign (lat. 40º6'N, long. 88º13'W, USDA Hardiness Zone 5b). ‘Yellow Madness’ petunia served as a representative short-term floricultural crop for this greenhouse trial. The trial began on 26 May 2012 and concluded after 5 weeks. The experiment was arranged as a completely randomized design, with an individual potted ‘Yellow Madness’ petunia serving as the experimental unit. Each container type was replicated 20 times, for a total of 200 containers used in the design.

Each container (replicate) was filled with a commercial soil-less growing mix (LC1 Mix; Sun Gro Horticulture Canada Ltd., Vancouver, BC, Canada) and one ‘Yellow Madness’ petunia plant. Potted plants were placed on plastic drain trays and spaced widely on greenhouse benches to facilitate the watering of individual experimental units. Given this wide spacing, no border row was deemed necessary. Also, a unique characteristic of the bioplastic sleeves is that they have no bottom. The design relies on the use of a multi-pocket shuttle/carry tray to keep potting mix in place until root growth is sufficient to maintain stability. To account for this, individual pocket bottoms were cut out from a shuttle/carry tray with a 1-cm lip and placed between the containers and the drain tray.

Plants were grown under supplemental light conditions (13 h daily in the absence of natural light/photon flux levels over 600 µmol·m^{-2}·s^{-1}) with minimum day- and nighttime temperatures set at 24 and 18 ºC, respectively. The median temperature over the course of the water use study was 27 ºC, with a maximum of 33 ºC recorded on 28 June 2012 and minimum of 17 ºC recorded on 7 June 2012. Relative humidity during the study period ranged from 24.6% to 90.5%, with a median value of 64.2%. Median photosynthetic photon flux at 1200 HR was 471 µmol·m^{-2}·s^{-1}.

Table 3.1. Container type, product name, approximate volume, and manufacturer information for nine biocontainers and a plastic control used in the trial. 'Yellow Madness' petunias were grown in a greenhouse for 5 weeks to assess the effect of container type on dry shoot weight and watering demand.

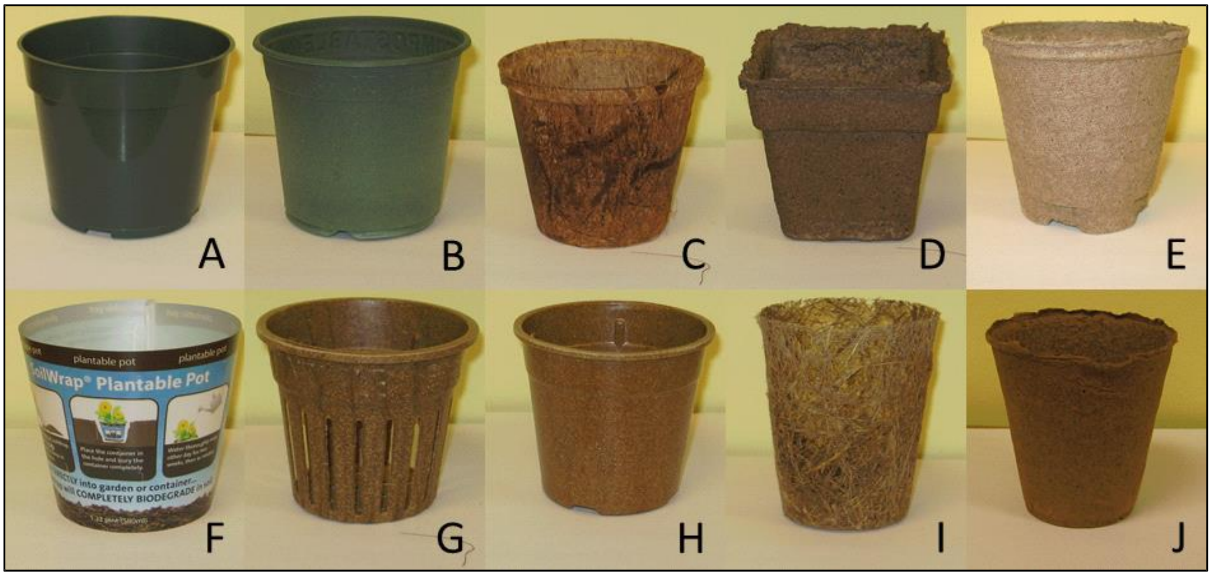
Container type	Product name[z]	Volume (cm^3)	Manufacturer
Plastic	Dillen 04.00 Standard Thinwall Green	480	Myers Industries Lawn & Garden Group, Middlefield, OH
Bioplastic	TerraShell™ 10cm H Wheat Pot	473	Summit Plastic Company, Akron, OH
Coir	Coir 4.0" Std Fiber Gro Pot	406	Dillen Products, Middlefield, OH
Manure	#4 Square CowPot	450	CowPots Manufacturing and Sales, East Canaan, CT
Peat	4" Jiffy Pot	379[y]	Jiffy Products of America Inc., Lorain, OH
Bioplastic sleeve (Sleeve)	4.5" Standard Assembled SoilWrap®	709[y]	Ball Horticultural Company, West Chicago, IL
Slotted rice hull	4.5" NetPot	591	Summit Plastic Company, Akron, OH
Solid rice hull	Rice Pot 4"	473	Summit Plastic Company, Akron, OH
Straw	n/a	646[y]	Ivy Acres, Baiting Hollow, NY
Wood fiber	10 X 10 cm Round Individual Fertilpot	430[y]	Fertil SAS, Boulogne Billancourt , France

[z] As indicated in manufacturers on-line/print catalog.

[y] Not included in manufacturer specifications. Volume approximated.

1 cm^3 = 0.0610 $inch^3$

Fig. 3.1. Images of container treatments used to grow a short-term crop of 'Yellow Madness' petunias. Plants were grown under greenhouse conditions for 5 weeks in order to gauge the effect of container type on irrigation demand. Containers used included (A) plastic control, (B) bioplastic, (C) coir, (D) manure, (E) peat, (F) sleeve, (G) slotted rice hull, (H) solid rice hull, (I) straw, and (J) wood fiber.



Irrigation was supplied by hand using a beaker on an as-needed basis at the treatment (i.e., container type) level. This threshold was defined as the point when soil moisture levels at or below 40% were detected for a given container type. Initially, soil moisture was assessed using an electronic soil moisture sensor (ThetaProbe Soil Moisture Sensor – ML2x, Delta-T Devices Ltd, Cambridge, United Kingdom). However, repeated measurements within the same soil space can lead to questionable measurements as air spaces/channels form in the media. As such, this work followed methods described in past research, relying on visual indicators of drying (e.g., the graying of the soil-less mix surface) to determine water need after the first week (Evans and Hensley, 2004; Evans et al., 2010; Kuehny et al., 2011). Water was applied as needed to saturate the growing mix and container wall and allow for some measurable drainage (approximately 250 mL to 400 mL depending on container volume). Water use was calculated as the difference between the volume of water applied and the volume of water lost through drainage.

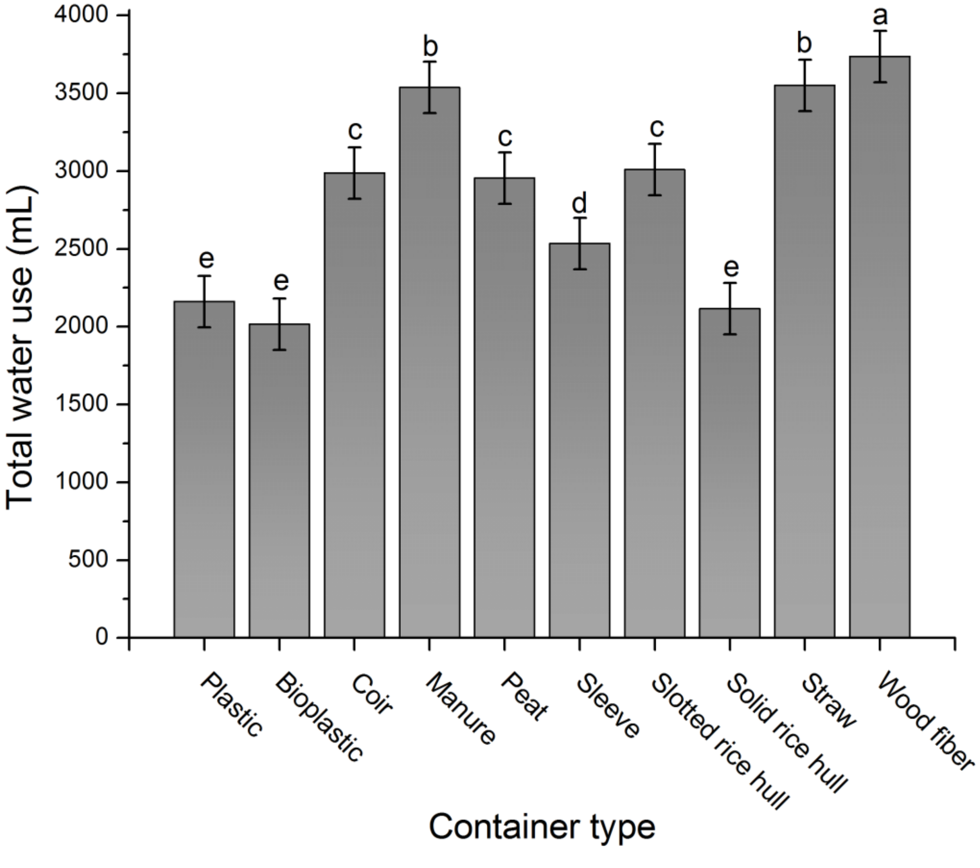
Plants were fertigated weekly with a 150 ppm 10N-6.5P-8.3K fertilizer solution (Schultz 10-15-10 All Purpose Fertilizer; Schultz Co, Bridgeton, MO). The fertilizer solution was applied to each plant weekly when watering was required.

MEASUREMENTS AND DATA ANALYSIS. Cumulative water use and irrigation frequency were recorded as measures of water demand. Final plant growth was measured as shoot dry weight. Water content and dry shoot weight were each analyzed as univariate, one-way analysis of variance (ANOVA) in R [version 2.14.2 (R Core Team, 2012)]. Prior to analysis with ANOVA, correlation between the two response variables was calculated using the COR.TEST function. Correlation was deemed not significant (P = 0.47) with Pearson's correlation coefficient calculated as 0.05. To control experimental-wise error rate, a Bonferroni adjusted α=0.025 was adopted for each of the two ANOVAs. Diagnostic plots confirmed that the residuals for both analyses met the assumptions of normality and equal variances. Mean separation for significant factors was conducted using a protected Fisher's least significant difference test (α=0.05). These comparisons were made using the LSD.TEST function provided in the agricolae package [version 1.1-2. 11 (de Mendiburu, 2012)]

Results and Discussion

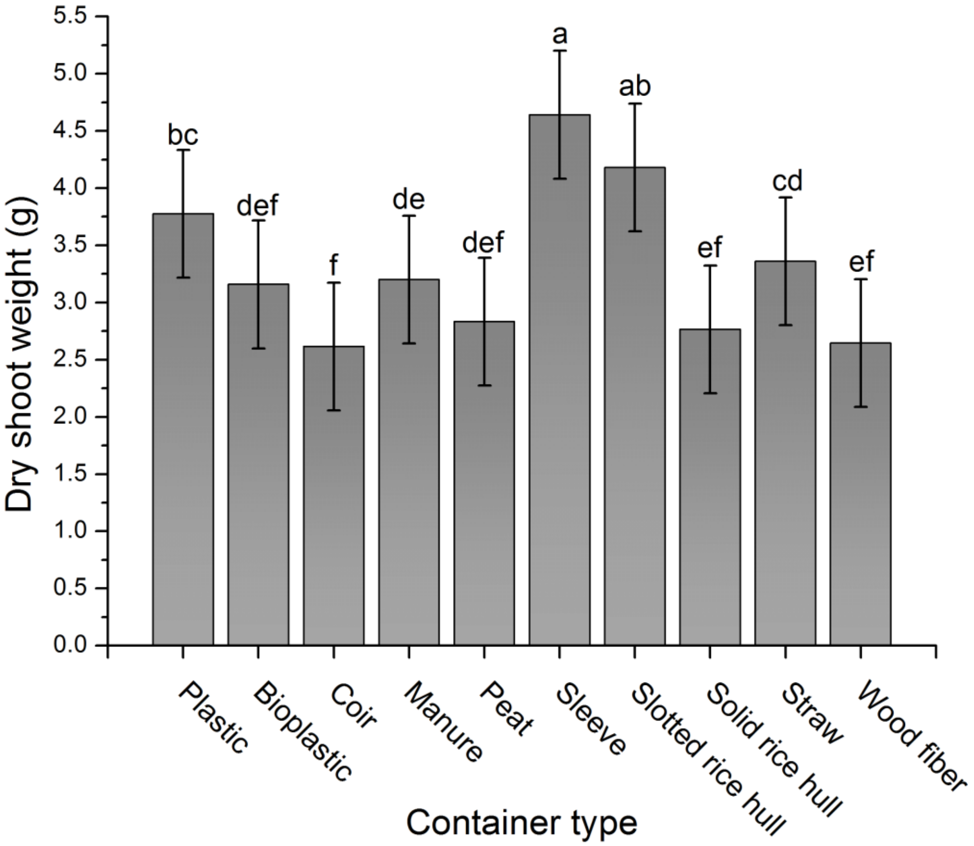
Results indicated that both total water use ($P < 0.0001$) and dry weight ($P < 0.0001$) varied with container type. As expected, containers made from more porous materials used greater volumes of water than the largely impervious plastic, bioplastic, and solid rice hull containers (Fig. 3.2). Among these three containers, differences in water use were not significant.

Fig. 3.2. Average cumulative water used for 'Yellow Madness' petunia plants grown in nine biocontainers and a plastic control. Plants were grown under greenhouse conditions for 5 weeks in order to gauge the effect of container type on irrigation demand. Water was applied when soil moisture levels below a watering threshold of 40% were detected for a given container treatment. Error bars depict Fisher's least significant difference. 1 mL =0.0338 fl oz.



Of the three containers which required the least water (i.e., plastic, bioplastic, and solid rice hull containers), plants grown in the plastic control had the highest dry shoot weight. Within this group, mean shoot dry weight was similarly diminished for the bioplastic and solid rice hull containers (Fig. 3). Mean shoot dry weight in the bioplastic container fell midway between the other two containers, performing slightly, though not significantly, greater than plants in the solid rice hull containers, but significantly less than those in the control.

Fig. 3.3. Average final dry weight for 'Yellow Madness' petunia plants grown in nine biocontainers and a plastic control. Plants were grown under greenhouse conditions for 5 weeks in order to gauge the effect of container type on irrigation demand. Water was applied when soil moisture levels below a watering threshold of 40% were detected for a given container treatment. Error bars depict Fisher's least significant difference. 1 g =0.0353 oz.



The wood fiber pot treatment required the highest amount of water to stay above the drying threshold, yet was among the group of containers with plants having the lowest shoot dry weights. As soil moisture was measured manually each morning, there were some days when readings dipped below the 40% threshold. Containers like the coir, peat, manure, and wood fiber pot, which dried quickly and required more frequent watering, had more opportunities to drop below this ideal lower limit (Table 3.2). In contrast, containers with longer irrigation intervals (lower irrigation frequencies) were spared from more frequent periods of saturated or water-limiting conditions.

Table 3.2. Average irrigation frequency (per wk) by container type. 'Yellow Madness' petunias were grown in a greenhouse for 5 weeks to assess the effect of container type on dry shoot weight and watering demand.

	Avg Irrigation Frequency (per wk)	
Container type	Avg	SD
Plastic	2.8	0.49
Bioplastic	2.6	0.80
Coir	3.6	0.49
Manure	3.0	0.63
Peat	3.4	0.49
Sleeve	2.2	0.40
Slotted rice hull	2.4	0.49
Solid rice hull	2.6	0.49
Straw	2.8	0.40
Wood fiber	3.0	0.00

Our work highlights a major advantage of the bioplastic and rice hull containers and marks the first investigation into the performance of a new biocontainer design, the bioplastic sleeve. With performance comparable to conventional plastic, the bioplastic and rice hull products offer an alternative to petroleum-derived pots with an additional benefit of appealing to environmentally conscious consumers (Hall et al., 2010). Specifically, the bioplastic sleeve appeared to balance water demand and growth in our trial. With the highest shoot dry weight and moderate water use, this container should be tested further using a wider variety of floral and foliage crops.

Any environmental benefits intrinsic to the containers and their production must not be negated by additional environmental impacts in greenhouse production. A true assessment of a container's overall impact on sustainable greenhouse production must account for both water use and yield. This work suggests that more frequent irrigation may be needed for peat, manure, and wood pulp containers to match the levels of growth seen in some of the more impervious alternatives. Future work should address this concern.

Additionally, containers of this size are often arranged in plastic shuttle trays during production, as trays make handling and spacing of small potted plants more manageable. These trays typically surround the majority of a container in impervious plastic. When watered, small amounts of irrigation drainage generally accumulate in the base of the tray. This water may be reabsorbed over time if in contact with roots, growing mix, or porous container surfaces. In addition, this water likely contributes to the production of a boundary layer of humid air trapped between the container and tray. Noting these potential benefits, it is likely that some of the differences in water consumption and irrigation frequency documented in past research can be at least partially mitigated with shuttle trays. Research should quantify what benefits, if any, shuttle trays offer with respect to water use and plant growth.

We and others (Evans and Hensley, 2004; Evans and Karcher; 2004; Evans et al., 2010) used standard soilless growing mixes optimized for plastic container usage. However, porous biocontainers likely perform more like unglazed clay pots, which were traditionally filled using potting mixes with a slower-draining topsoil and/or sand component. Future testing should investigate biocontainer performance using alternative growing mixes, including mixes with wetting agents and hydrogels designed specifically for use in terra cotta containers (Terracotta Pot & Planter Mix, Osmocote®, Bella Vista, NSW, Australia).

Conclusion

In summary, both water use and plant growth differed by container type. The more impervious containers (i.e., control, bioplastic, and solid rice hull) were among the best performing containers with regard to total water consumption. These three container types, while not linked to the largest mean dry shoot weights, did not under-perform with regard to plant growth either. In contrast, reduced shoot dry weight was associated with some of the fastest drying containers like wood fiber, straw, and manure. Though these results may be a source of concern for growers looking to adopt biocontainers, growing system and potting mix optimization may negate some of the differences observed here. Until such innovation occurs, the relatively new bioplastic sleeve may be a promising option for growers looking to maximize growth and limit water consumption.

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CHAPTER 4: PLANTABLE BIOCONTAINERS IN THE LANDSCAPE: RATE OF DEGRADATION AND IMPACT ON PLANT ESTABLISHMENT

Note: This work was completed as part of a multi-institutional research initiative with additional trials conducted at research facilities associated with the University of Kentucky, Mississippi State University, Texas A&M University, and West Virginia University. Only work conducted at the University of Illinois research plots is reported in this chapter. The final publication to be submitted for peer review will include analysis from all five locations.

Summary

Manufacturers and retailers of containers designed for direct-planting market them as reducing transplant stress, labor, and landfill waste. However, some professionals worry that any container, even one designed to break down and allow roots to penetrate into the surrounding soil, may hinder timely plant establishment in the landscape. This study investigated above-ground growth for three floral bedding plants [cleome (*Cleome hybrid* 'Inncleosr'), impatiens (*Impatiens* x*hybrida* 'SAKimp016'), and lantana (*Lantana camara* '2003301')] produced and outplanted in one of eight containers (i.e., one plastic control removed at transplanting, six plantable organic alternatives, and one plantable bioplastic sleeve) over two sequential growing seasons. Above ground dry shoot weight differed by container type for cleome ($P = 0.02109$) and lantana ($P = 0.0093$), but not for impatiens ($P = 0.3254$). In contrast, two other plant responses, above ground volume and a visual condition rating, varied significantly by container type only in the impatiens trial plots ($P = 0.0030$ and $P = 0.0242$ for volume and condition, respectively). Plantable containers were extracted at the end of the growing season to measure residual dry weight as a means of assessing degradation. Residual dry weight (pooled across species and compared against new container weight) differed significantly by container type for both trial years (both $P < 0.0001$) with the proportions intact ranging from 0.86 (slotted rice hull in 2011) to 0.00 (manure in 2012).

Background

Plants are exposed to many stresses as they transition from the site of production to the landscape. These stresses are often sufficient to temporarily halt growth, a condition known as transplant shock (Dufault and Schultheis, 1994; Koeser et al., 2009; McKay, 1996; Nicola and Cantliffe, 1996; Nitzsche et al., 1991). Temperature extremes, mechanical injury, desiccation of plant materials, and changes in growing environment can all contribute to this developmental stagnation. A significant body of research has amassed that identifies causes of transplant shock and corrective measures to help negate its impact on plant growth and survival (McKay, 1996).

In order to prevent one notable source of transplant stress, direct injury to roots, bedding plants are usually left in the soilless potting mix used for their production and transport (Spomer, 1980). While reducing mechanical stress, this practice ultimately increases the potential for root desiccation and death. Soilless mixes are designed to provide drainage in the shallow soil conditions artificially created by container production. Once the impervious barrier of the container is removed, the coarse, soilless media surrounding a plant's rootball becomes part of a much deeper, highly textured soil system. As a result, once-optimal drainage conditions quickly become excessive in the absence of frequent irrigation or rain.

Directly plantable biocontainers are purported to limit root system disruption and reduce transplant shock when used as an alternative to conventional plastic containers, which must be removed prior to planting (Evans and Hensley, 2004; Evans and Karcher, 2004). However, it is also believed that some biocontainers (e.g., peat) may wick water up out of the root zone if not sufficiently buried (Kuehny et al., 2011). Most plantable containers are made from highly porous materials (e.g., peat, wood fiber, or manure). These containers have been linked to both decreased growth and increased watering in greenhouse production (Evans and Karcher, 2004; Koeser et al. findings accepted for publication). In the landscape, they may provide little resistance to water loss from the rootzone to the surrounding soil, and in some cases even increase dessication.

Unlike the plantable pots mentioned above, two newer plantable containers use more impervious materials (i.e., pressed rice hulls and bioplastic) for their construction. These containers are designed with slits or openings to allow roots to penetrate into the surrounding soils and facilitate decomposition. Despite having gaps that expose soilless mix to air, a past greenhouse trial has shown that the dry weights of petunia plants grown in slotted rice hull and bioplastic sleeve containers match or exceed those of a conventional plastic control (Koeser et al. unpublished data). More importantly, this growth did not come with the added burden of increased water demand. This suggests that soil moisture conditions in plantable slotted rice hull and bioplastic sleeve containers are similar to the conditions associated with plastic containers. Unlike plastic containers, which are discarded at installation, the two former pots remain intact around a plant's roots in the landscape, which may moderate some of the drastic changes to drainage seen in conventional planting practices.

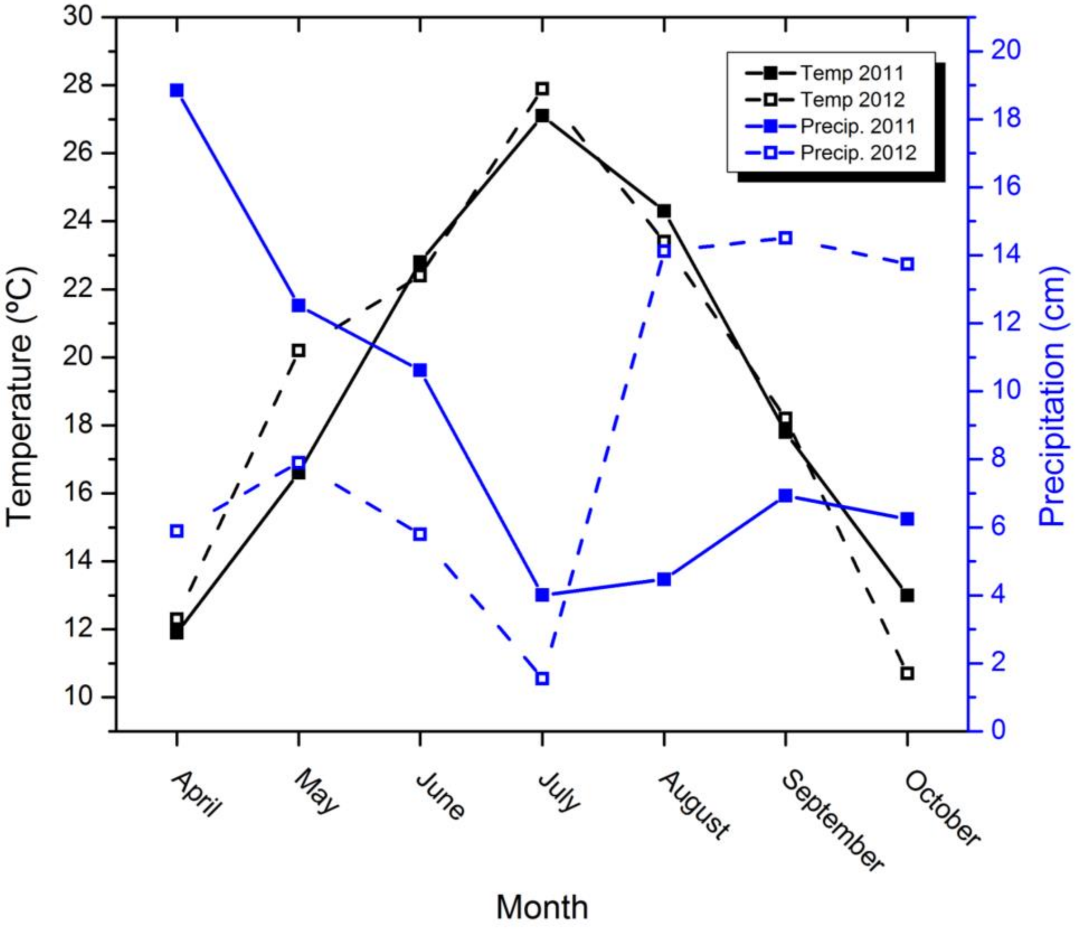
Any benefit offered by direct-plant containers at transplanting will ultimately be undone if root growth into the surrounding soil is hindered. The volumes of containers are limited, and reliance on this soil space alone can cause increased moisture stress when combined with the accelerated drainage conditions noted above (Spomer 1980). Also, though not an issue with annual bedding plants, roots that that circle due to restrictive growth caused by container walls may lead to long-term health and stability issues, especially when combined with excessive, deep planting (Mathers et al., 2007). Plantable biocontainers are designed to degrade in field soil. This rate of degradation must be slow enough to meet the needs of growers, yet not at such a rate as to impede plant establishment and root growth. Few works address the rate at which plantable pots degrade after outplanting (Evans et al., 2010). To date, no studies assess decomposition of the more recently developed slotted rice hull and bioplastic sleeve in field soils.

This landscape trial assesses plant growth and container degradation in seven plantable biocontainers. The work is intended to provide insight into three key research questions: 1) Do direct-plant biocontainers benefit or hinder bedding plant establishment and growth?; 2) If differences exist, are those differences plant specific or applicable to a broader range of bedding plants?; and 3) To what extent do direct-plant biocontainers break down in field soil conditions?

Materials and Methods

LOCATION. This landscape trial was conducted at research field plots at the University of Illinois at Urbana-Champaign (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b) during the 2011 and 2012 summer growing seasons. The soil at the planting site was a Drummer silty clay loam with a 0-2% slope (U.S. Dept. Agr. Natural Resource Conservation Serv., 2013). The first trial began on 17 May 2011 and ended on 19 October 2011. The second trial began on 15 June 2012 and ended on 26 October 2012. Mean monthly temperatures and precipitation for the two trial periods are shown in Fig. 4.1.

Fig. 4.1. Monthly mean temperature and precipitation at the Urbana, IL study site (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b) for the 2011 and 2012 growing seasons.



CONTAINERS. Eight container types (i.e., one plastic control, six organic alternatives, and one bioplastic sleeve) were used in the study (Table 4.1). A 4-inch (10-cm) standard pot (removed at transplanting) served as the control. All biocontainers used in the trial were selected for their direct-plant design and commercial availability. While pots were selected with a volume approximately equal to that of the control, minor variations in volume (Table 4.1) reflect the realities a professional grower would face when looking for alternatives to standard plastic pots. Volume is one of many attributes contributing to the overall design of a container. Differences in geometry, container material, and the presence or absence of drainage holes also varied among the products selected. For this work, the total effect of all these differing attributes is encompassed by our container treatment.

Table 4.1. Container treatments selected for this experiment, including manufacturer information and approximate volume.

Container Type	**Product Name**[z]	**Approximate Volume (cm^3)**	**Manufacturer**
Plastic Control (Control)	Dillen 04.00 Standard Thinwall Green	480	Myers Industries Lawn & Garden Group, Middlefield, OH
Coir	Coir 4.0" Std Fiber Gro Pot	406	Dillen Products, Middlefield, OH
Pressed Manure (Manure)	#4 Square CowPot	450	CowPots Manufacturing and Sales, East Canaan, CT
Peat	4” Jiffy Pot	379[y]	Jiffy Products of America Inc., Lorain, OH
Bioplastic Sleeve (Sleeve)	4.5” Standard Assembled SoilWrap®	709[y]	Ball Horticultural Company, West Chicago, IL
Slotted Rice Hull	4.5” NetPot	591	Summit Plastic Company, Akron, OH
Straw	n/a	646[y]	Ivy Acres, Baiting Hollow, NY
Wood Fiber	10 X 10 cm Round Individual Fertilpot	430[y]	Fertil SAS, Boulogne Billancourt , France

[z] As indicated in manufacturers on-line/print catalog.

[y] Not included in manufacturer specifications. Approximated as a volume of a frustrum of a cone as,

EXPERIMENTAL DESIGN, GROWING CONDITIONS, AND PLANT CARE.

Three species were selected to represent a range of plant water requirements. Impatiens (*Impatiens* x*hybrida* 'SAKimp016') was included in this trial due to its relatively high water-use requirement. Lantana (*Lantana camara* '2003301') was chosen for its low water-use requirement. Cleome (*Cleome hybrid* 'Inncleosr') served as an example of a plant with more moderate watering requirements compared to the first two species.

In the field, plants were grouped by species due to their different watering requirements and in order to prevent the taller species (i.e., cleome) from shading the lower-growing species (i.e., lantana and impatiens). Consequently, each species was designed and analyzed as a separate trial. Each trial was arranged in a completely randomized design with an individual potted plant serving as the experimental unit. Each container type was replicated 10 times per species per year (total n=160 per species over the 2 years).

Plants were grown from plug to market size under conventional greenhouse conditions prior to the start of the trial. A commercial growing mix consisting of peat, perlite, and vermiculite was used for greenhouse production (Fafard 2 Mix, FPM Peat Moss Company, Ltd., Agawam, MA). All plants were transplanted into the landscape at 2-foot intervals. Weeds were controlled with black landscaping fabric (Weed Barrier Pro, DeWitt Company, Sikeston, MO). Irrigation was supplied immediately after installation and as needed via drip tapes in 2011 and by hand in 2012.

MEASUREMENTS. In the 2011 season, bi-weekly measures of plant volume (i.e.,the product of plant height and two perpendicular width measures) were taken until the lantana and cleome reached an average diameter of 0.5 m. A qualitative, 0-5 aesthetic rating was given to each plant in tandem with the plant volume measurements. This rating was conducted throughout the 2011 growing season, even after plant volume measurements ended.

At the end of both seasons, all above-ground biomass was collected, oven dried, and weighed. In addition to dry shoot weight, residual dry pot weight was measured to gauge container degradation in the landscape. Post-harvest dry weights were compared to an average initial dry weight calculated from ten new containers of the same type to determine the proportion remaining.

DATA ANALYSIS. Dry shoot weights for each species were analyzed separately as a series of two-way analysis of variance (ANOVA) in R (R Core Team, 2012). Both trial year and container type served as fixed effects. Diagnostic plots confirmed that the residuals for both analyses met the assumptions of normality and equal variances. In cases where factors and/or interactions were found to be non-significant, model simplification was employed using the methodology described by Crawley (2005) for ease in interpretation. Mean separation for significant factors was conducted using a protected Fisher's Least Significant Difference (LSD) test (α=0.05). These comparisons were made using the Least Significant Difference (LSD).test function provided in the agricolae package (de Mendiburu, 2012).

Volume was assessed as repeated measures using the ezAnova function in the ez package (Lawrence, 2012). Analysis assumptions, including Mauchly's Test for Sphericity, were checked prior to final reporting (Kuehl, 1999). Differences among individual means for the between effect of treatment were determined using Fisher's LSD values calculated using ezStats function in the ez package.

Aesthetic ratings for each plant were averaged prior to analysis to create an overall, season-long rating. This response was analyzed at the species level as a series of one-way ANOVAs. Assumptions were validated as noted above. Mean separation, where appropriate, was conducted as a protected LSD.

Container decomposition was expressed as the ratio of post-harvest container weight over new container weight. The resulting response was a proportion bound between zero and one. As anticipated given this constraint, diagnostic plots indicated that the underlying assumptions required for a standard ANOVA were not met. To address this concern, an arcsine square root and a logit transformation were applied in turn to the response. The former did little to correct issues of residual non-normality or heterogeneity. The logit transformation alleviated the issue of heterogeneity, though failed to address the concern of non-normality. As such, the logit transformation was used prior to analysis with a Kruskal-Wallis one-way ANOVA test on ranks. This approach is similar to the analysis conducted by Hübner et al. (2008) when faced with similar concerns. Analysis and multiple comparisons were conducted with the kruskal() function in the agricolae package (Mendiburu, 2012). All decisions were made at an $\alpha = 0.05$ level of Type I error.

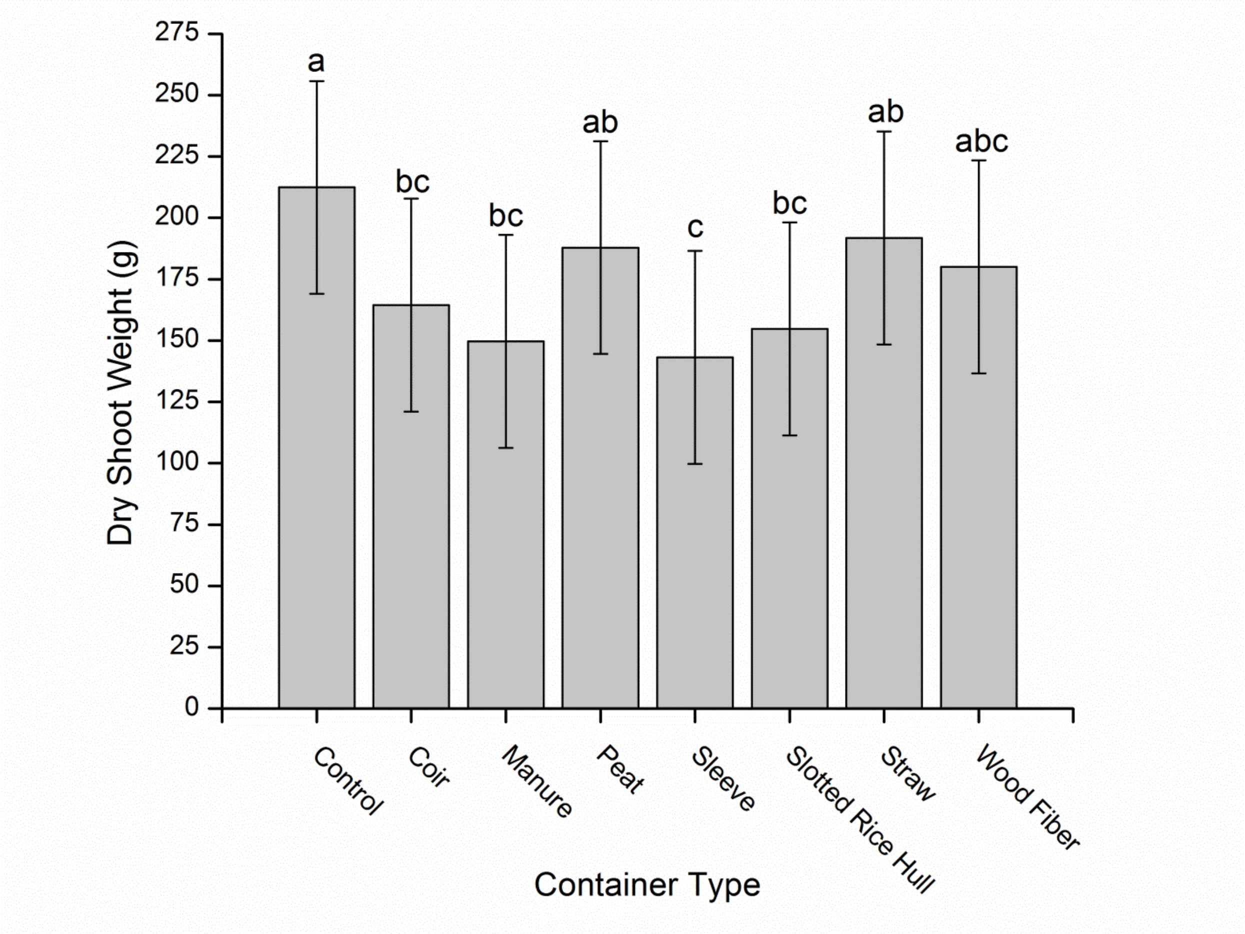
Results and Discussion

DRY SHOOT WEIGHT. With the cleome, the main effect of trial year was not significant (P = 0.1267) and the trial yearXcontainer type interaction was marginally significant/insignificant (P

= 0.0552). In model fitting, testing with the ANOVA function (R Core Team, 2012) showed that removal of the interaction term did not unduly limit the explanatory power of the new reduced model (*P* = 0.0552). This new reduced model was further simplified by removing the trial factor with no significant difference between the two iterations (*P* = 0.1267). In the final, minimally adequate model, data from both trial years was pooled together leaving container type as the lone significant factor (*P* = 0.02109).

Mean dry shoot weights of cleome separated out into three overlapping groups with control, straw, peat and wood fiber being top performers (in order; Fig. 4.2). The second grouping included all but the highest and lowest performing containers (i.e., control and bioplastic sleeve). Finally, the lowest performer for cleome, the bioplastic sleeve, was not significantly different from the wood pulp, coir, slotted rice hull, and manure containers.

Fig. 4.2. Mean dry shoot weight (g) for cleome (Cleome hybrid 'Inncleosr') produced and outplanted in one of 8 container types (i.e., one plastic control removed at transplanting, six plantable organic biocontainer alternatives, and one plantable bioplastic sleeve). Plants were grown at university research plots in Urbana, IL (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b) during the 2011 and 2012 growing seasons. Data from the two growing seasons were pooled as the trial year factor was not significant. Error bars depict Fisher's Least Significant Difference values.



For impatiens, trial year was significant ($P < 0.0001$). However, neither container type ($P = 0.3254$) nor the trial year x container type interaction were significant ($P = 0.7604$). Of the two years, growth was greater in 2011 (Fig. 4.3). Precipitation was largely absent in the spring and early summer of 2012. This situation, coupled with sustained above-average temperatures throughout much of the Midwest (including the study site), under extreme drought conditions (Rippey et al., 2012). Approximately 1.5 in (4 cm) of water was applied weekly to all plots in the absence of sufficient rain. As drought conditions progressed, this level of irrigation, though sufficient to prevent plant death, was not enough to maintain the higher level of growth seen with the impatiens in 2011. Impatiens were included in the trial specifically for their high water demand, so these results do not come as a surprise. More interesting is that no container offered any detectable benefit or hindrance with regard to above-ground biomass of impatiens in either year. Given the species' sensitivity to limiting moisture conditions, any pot which wicked away water or limited root penetration into surrounding soil moisture stores would likely be linked to significant growth reductions, especially in the 2012 growing season. With none detected, it appears other factors (i.e.,environment) play a greater role in plant growth.

For the lantana trial, neither trial year ($P = 0.1662$) nor the trial year x container type interaction ($P = 0.8730$) were significant. These terms were dropped from the final model, effectively combining the data for the two growing seasons. No significant difference in explanatory power was found in comparing the original and reduced models ($P = 0.7512$). As with the original model, shoot dry weight in this final, reduced model varied significantly by container type ($P = 0.0093$).

Fig. 4.3. Mean shoot dry weight (g) for impatiens (Impatiens xhybrida 'SAKimp016') produced and outplanted in one of 8 container types (i.e., one plastic control removed at transplanting, six plantable organic biocontainer alternatives, and one plantable bioplastic sleeve). Plants were grown at university research plots in Urbana, IL (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b) during the 2011 and 2012 growing seasons. Error bars depict Fisher's Least Significant Difference values.

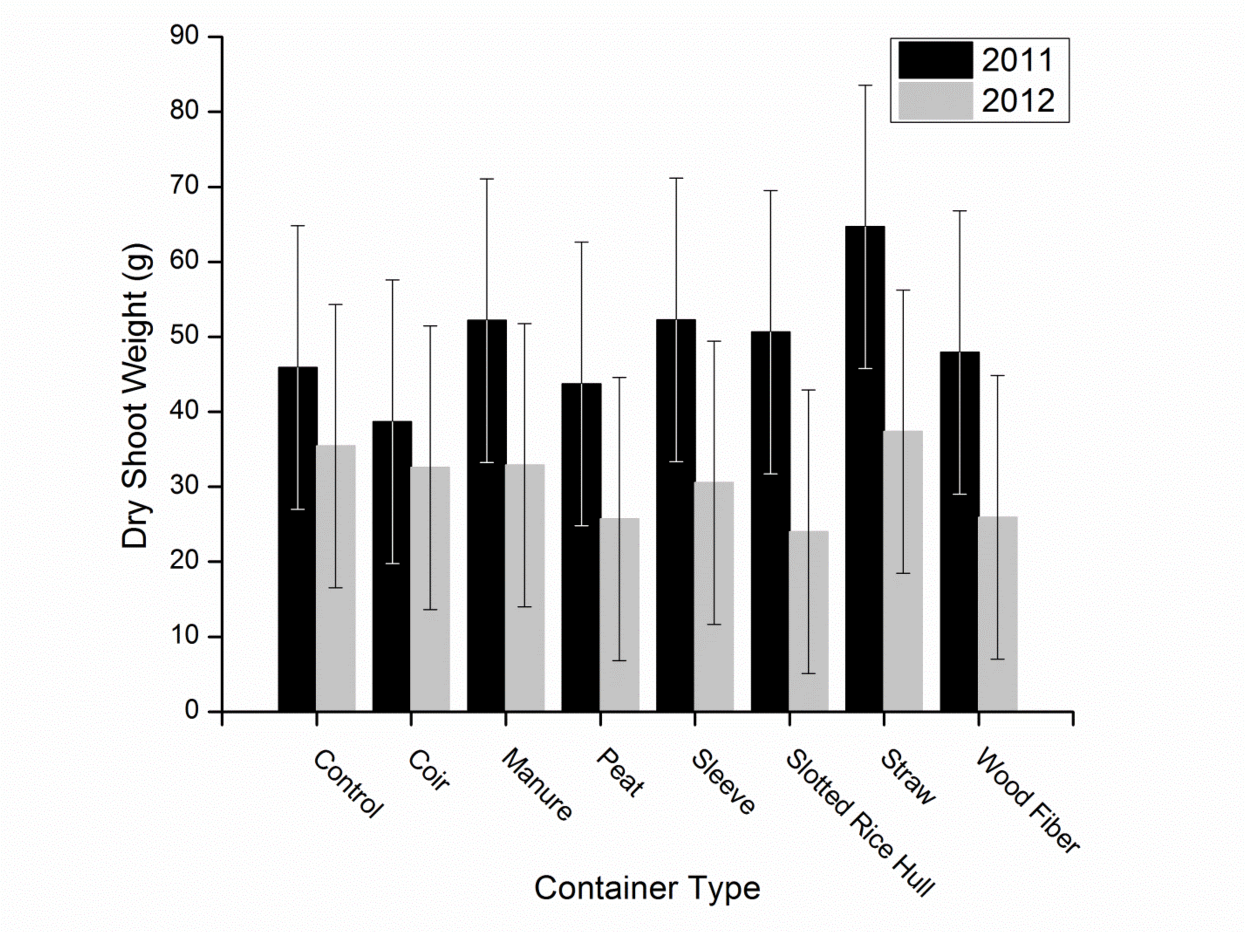
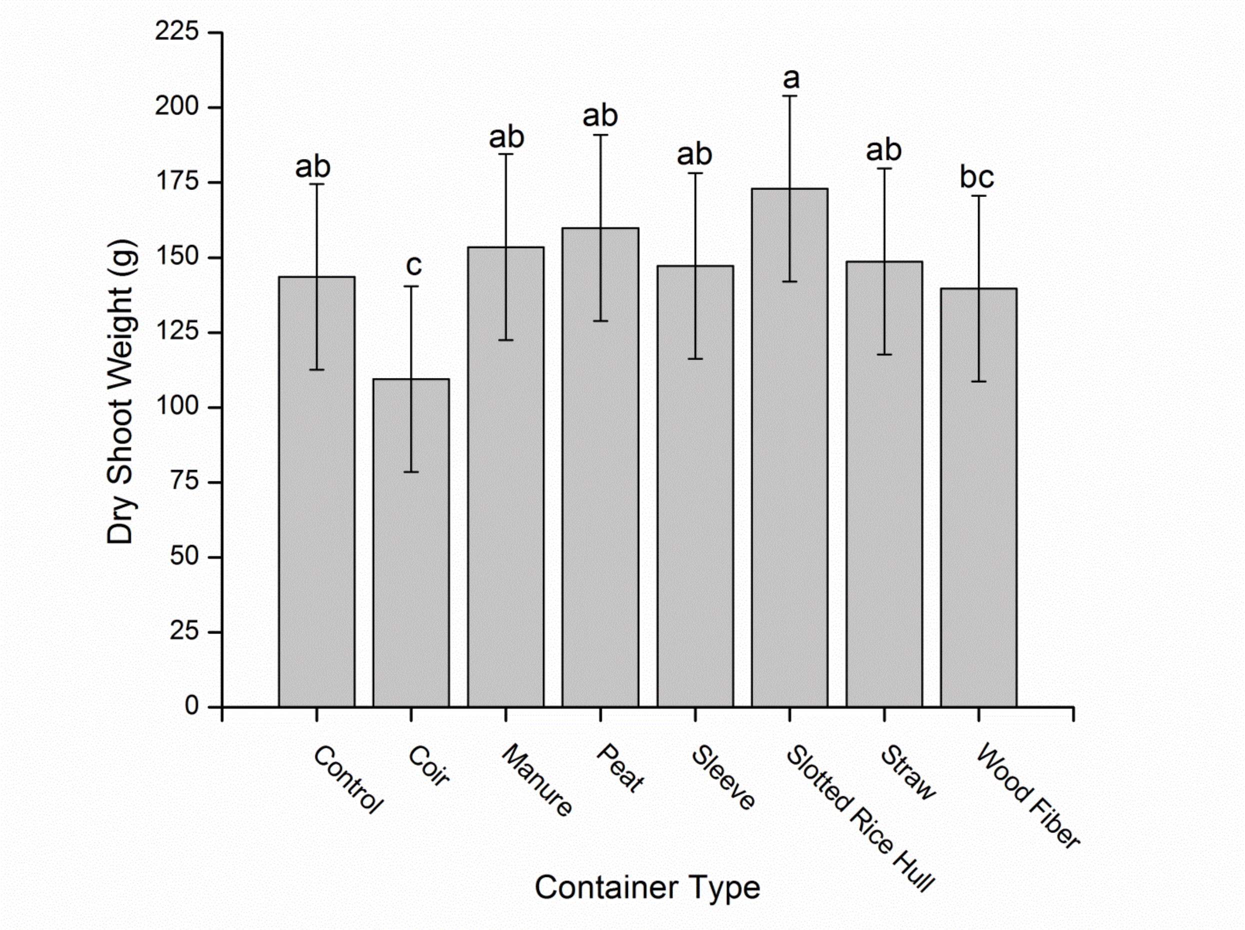


Fig. 4.4. Mean shoot dry weight (g) for lantana (Lantana camara '2003301') produced and outplanted in one of 8 container types (i.e., one plastic control removed at transplanting, six plantable organic biocontainer alternatives, and one plantable bioplastic sleeve). Plants were grown at university research plots in Urbana, IL (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b) during the 2011 and 2012 growing seasons. Data from the two growing seasons were pooled as the trial factor was not significant. Error bars depict Fisher's Least Significant Difference values.



In investigating the effect of container type on lantana dry shoot weight, it appeared that a few key differences among the treatments drove the significance of the factor (Fig. 4.4). Notably, slotted rice hull containers out-performed both wood fiber and coir containers with regard to dry shoot weight. Above-ground growth in wood fiber containers was not significantly different from any of the other containers. Finally, dry shoot weight for plants in coir containers was significantly lower than any of the other containers tested with the exception of wood fiber.

CROWN VOLUME. As expected, crown volume varied significantly over time for cleome, impatiens, and lantana (all $P < 0.0001$). Additionally, container type ($P = 0.0030$) and the container typeXtime interaction ($P = 0.0118$) were significant for impatiens. In contrast, container type was not significant for either lantana ($P = 0.6537$) or cleome ($P = 0.6262$). Additionally, neither lantana ($P = 0.8333$) nor cleome ($P = 0.1418$) had significant container typeXtime interactions.

Despite some variation in mean starting sizes, no significant differences in plant volume were found at planting or at two weeks after planting in the impatiens (Table 4.2). At six weeks after planting (and perhaps earlier), detectable differences were found among the container types. Many of the plants in the containers that would ultimately end up in the top statistical grouping did not experience noticeable stunting as captured in the second measurement period (Table 4.2). The lack of transplant shock may indicate that pots, such as the wood fiber and straw containers, prove no more a barrier to root growth and water than of a plant transplanted from a plastic pot. Early gains in volume seen in the second measurement period were only magnified over time, explaining, in part, the significance of the interaction effect.

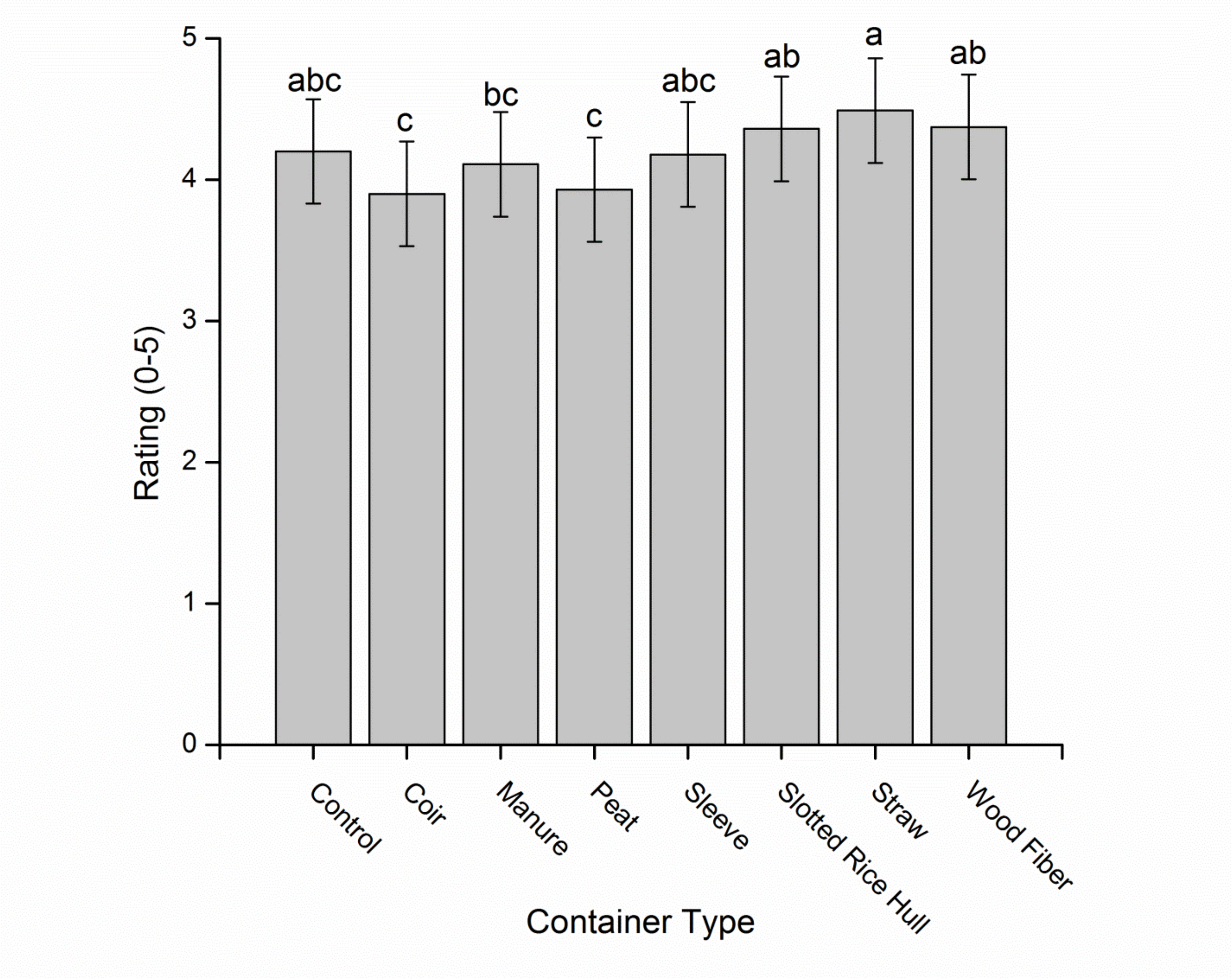
While impatiens volume differed among the treatments, dry weight remained relatively uniform across container type. This discrepancy shows the value of multiple growth metrics. As the product of three measurements, volume is a relatively coarse measurement. However, when differences are detected, they are typically linked to noticeable visual differences. Combined with dry weight, we can infer that plant habit was influenced by container type, with the less voluminous plants being more leggy than those in the other treatments. Based on observation, this reduced leaf area seemed to be linked to water-stress-induced leaf abscission.

Table 4.2. Mean above ground plant volumes (calculated as the product of two perpendicular width and and one height measurement) for over impatiens (Impatiens xhybrida 'SAKimp016') over time. Plants were outplanted in eight container types (i.e., one plastic control removed at transplanting, six plantable organic biocontainer alternatives, and one plantable bioplastic sleeve) at research plots in Urbana, IL (lat. 40º 6' N, long. 88º 13' W, USDA Hardiness Zone 5b).

	Date							
Container Type	19 May 2011	Statistical Grouping[z]	3 June 2011	Statistical Grouping	1 July 2011	Statistical Grouping	13 July 2011	Statistical Grouping
Wood Fiber	6815.9	a	7763.9	a	26724.9	a	35235.2	a
Straw	5931.4	a	7617.0	a	26559.8	a	32003.8	ab
Control	5393.5	a	7176.0	a	22819.2	ab	29746.5	bc
Manure	7622.7	a	7047.6	a	21572.2	bc	27301.3	cd
Sleeve	6514.6	a	5902.4	a	21452.0	bc	26281.2	cd
Slotted Rice Hull	4137.1	a	5977.5	a	19962.7	bcd	23824.9	de
Peat	6978.8	a	6151.1	a	17426.6	cd	20820.3	e
Coir	4817.1	a	3463.1	a	15841.6	d	19609.0	e

AESTHETIC RATING. In comparing the aesthetic condition ratings, neither lantana (*P* = 0.6165) nor cleome (*P* = 0.2355) differed visually by container type. However, rating scores did vary by container type for the impatiens (*P* = 0.0242). As with the dry weights, there was significant overlap in the mean separations, with plants in the straw, wood pulp, slotted rice hull, control, and the bioplastic sleeve all having high visual ratings (Fig. 4.5). Coir, peat, and cow were the lowest rated, though this group was not different from the control and bioplastic mentioned in the previous grouping.

Fig. 4.5. Mean aesthetic ratings (0-5 scale) for impatiens (Impatiens xhybrida 'SAKimp016') produced and outplanted in one of eight container types (i.e., one plastic control removed at transplanting, six plantable organic biocontainer alternatives, and one plantable bioplastic sleeve). Rating used is as follows: 0 – Dead; 1 – Poor; 2-Fair; 3-Okay; 4-Good; 5-Excellent. Error bars depict Fisher's Least Significant Difference values.



POT DEGRADATION. Given the limitations of the Kruskal-Wallis test, each year was analyzed separately. Similarly, data from the three species were pooled together. Pot degradation did vary significantly by container type in both 2011 ($P < 0.0001$) and 2012 ($P < 0.0001$). While not formally tested given the methods of analysis used, both trials exhibited nearly identical ranking orders (Table 4.3). In both years, the slotted rice hull pot, with over 80% of its original dry weight remaining after one growing season, was the most intact container of the products tested. In comparison, the manure container was the least intact, with 5% (median) of its original weight remaining in at the end of the 2011 trial and only rare bits intact in 2012.

While several similarities are noted above, there were two differences in the rankings for the two trials (Table 4.3). First, with regard to proportion of dry mass remaining, the bioplastic sleeve was ranked higher in 2012 than in 2011. Secondly, the order of the straw and wood fiber containers was flipped between years.

With the bioplastic sleeve, the change in ranking appears to be driven primarily by its own level of degradation. In 2011, the median proportion left intact for the bioplastic sleeve was 0.53. In contrast, this proportion was 0.74 in 2012. Two factors may have contributed to this disparity. First, differences in soil temperature and water availability surely influence degradation rate (Donnelly et al., 1990). That noted, for all other containers in the trial, the proportion remaining intact either decreased or remained the same in 2012 as compared to 2011, which is opposite the trend seen with the bioplastic sleeve (Table 4.3). The second factor was the container itself. In 2012, the manufacturer adjusted the design of the bioplastic sleeve. One of the marketed benefits of this container is the ability to custom print logos and branding information on its exterior. However, printing on the earlier iteration of the bioplastic sleeve tested in 2011 would at times melt off prematurely during greenhouse production. In combating this problem, it appears the manufacturer's newest design may not degrade as readily under field conditions.

*Table 4.3. Median, Quartile 1, and Quartile 3 container decomposition levels (i.e.,proportion by weight left intact) for seven plantable biocontainers at the end of the 2011 and 2012 field trials. Values are logit-transformed ratios of post-harvest dry weight over new container dry weight. Raw median levels (i.e.,non-transformed) are included for ease in interpretation. Values are for all three species [cleome (*Cleome hybrid *'Inncleosr'), impatiens (Impatiens xhybrida 'SAKimp016'), and lantana (*Lantana camara *'2003301')] combined.*

Container	Year	Median Proportion Intact **(Raw Proportion)**	Q1	Q3	Statistical Grouping^{z}
Slotted Rice Hull	2011	1.70 **(0.86)**	1.59	1.90	a
Coir	2011	1.20 **(0.78)**	0.61	1.82	b
Peat	2011	1.09 **(0.76)**	-0.19	1.65	bc
Wood Fiber	2011	0.88 **(0.63)**	-0.24	1.35	c
Sleeve	2011	0.10 **(0.53)**	-0.03	0.37	d
Straw	2011	-0.05 **(0.49)**	-0.16	0.23	d
Manure	2011	-2.91 **(0.05)**	-3.66	-2.23	e
Net	2012	1.41 **(0.82)**	1.25	1.59	a
Sleeve	2012	0.98 **(0.74)**	0.86	1.21	b
Coir	2012	0.62 **(0.66)**	0.20	1.07	c
Peat	2012	0.44 **(0.61)**	0.04	0.73	cd
Straw	2012	0.07 **(0.52)**	-0.44	0.59	d
Wood Fiber	2012	0.02 **(0.51)**	-0.35	0.28	e
Manure	2012	-3.66 **(0.00)**	-3.66	-3.16	f

^{Z}Multiple comparisons are for containers within a given year

The differences in degradation that resulted in the ranking differences of the wood fiber and straw pots over the two growing seasons are less pronounced. As compared to 2011, the straw container was marginally more intact in 2012. There was a slightly more dramatic reduction in residual container mass with the wood fiber containers. Without the confounding factor of container design seen with the slotted rice hull pots, differences in soil temperature and moisture variability were likely the primary causes of this change.

Conclusion

With regard to above-ground growth, plantable containers do not appear to offer any significant growth benefit when compared to plastic container-grown bedding plants. Rather, there are indications some containers can actually limit growth, though this varies by species and conditions. While size is an important consideration, plant appearance is likely the most important response from a homeowner or property manager perspective. In this regard, only our most sensitive plant, impatiens, was impacted by the use of a plantable pot. As such, plantable biocontainers may be most appropriate for waste conscious consumers or landscapers looking for labor savings during installation and cleanup. Finally, while some containers readily degrade, others may remain for more than one growing season. Rototilling and other bed preparation activities in subsequent years will likely hasten degradation and limit buildup of residual container materials.

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CHAPTER 5: BIOCONTAINER USE IN *PETUNIA* x*HYBRIDA* GREENHOUSE PRODUCTION – A CRADLE-TO-GATE CARBON FOOTPRINT ASSESSMENT OF SECONDARY IMPACTS.

Summary

While biocontainers (i.e., biodegradable, plant-based containers) are marketed as being more sustainable than conventional plastic pots, little scientific literature exists to substantiate these claims. Past research has instead shown that adoption of plant-derived containers under current greenhouse production practices often leads to greater use of irrigation water, increased damage and waste during filling and shipping, and differences in plant growth. Life cycle assessment (LCA) serves as a holistic accounting of all the material/energy inputs and waste/pollution outflows associated with a given product. This paper draws on LCA methods to assess how secondary production impacts (e.g., irrigation demand) differ as container type changes. The basis for these comparisons is cradle-to-gate assessment of all of the inputs and outflows associated with production of a common annual ornamental plant (e.g., *Petunia xhybrida*) in a plastic container. This work does not consider the inputs and outputs of manufacturing the containers themselves, since that information is propriety in many cases. Container-specific secondary impacts derived from controlled studies were then incorporated as model parameters to assess differences in overall production global warming potential (GWP). Results show that the container itself accounts for approximately 17% of overall CO_2e (i.e.,carbon dioxide equivalent) emissions during petunia production using a conventional plastic pot. Though container was a significant contributor to GWP, electrical consumption for supplemental lighting during plug production and irrigation throughout the production process proved to be the leading sources of CO_2e emissions (over 44%). Differences in GWP were only minor in comparing the use of various biocontainers with standard plastic containers for secondary production impacts. Results demonstrate that biocontainers compete with plastic pots for secondary impacts, suggesting they could potentially be more sustainable than plastic pots once pot manufacturing data are considered. Use of more efficient supplemental lighting sources, however, may ultimately have the greatest impact on overall GWP.

Introduction

Environmentally conscious consumers are generally willing to pay higher prices for sustainably-produced goods and demonstrate loyalty to the retailers supplying them (Yue et al., 2011; Dennis et al., 2010; Krug et al., 2008). In the field of horticulture, however, not all efforts to reduce the environmental impacts associated with production have resulted in positive perceptions by the plant-buying public. For example, a recent study demonstrated that the adoption of organic fertilizers offered no significant marketing advantage for floriculture crops (Yue et al., 2011). In this same study, plants labeled as “organic” were actually viewed unfavorably by trial participants, though no explanation was given for this finding.

In contrast to organic labeling, the adoption of biocontainers (plant material-based, biodegradable pots) as an alternative to conventional plastic containers use can be a significant driver of consumer interest. Yue et al. (2011) found that biodegradable, compostable, and recycled pots had the greatest impact on consumer preference – outranking other sustainable production practices not seen directly at the garden retail center (e.g., efficient use of wholesale production space). Similar conclusions were drawn by Hall et al. (2010), who found container type contributed most to consumers' interest in sustainably produced plants – outranking other highly influential considerations such as price and carbon-footprint.

Despite their perceived environmental benefits and appeal as alternatives to petroleum-based plastic pots, biocontainers have not been assessed to determine their overall impact on commercial greenhouse sustainability. In this regard, biocontainers have one obvious advantage over conventional plastic pots – they are not discarded and transported to a landfill after use. Rather, most biocontainers are designed to be planted directly into the landscape or composted in a home compost bin. Some bioplastics, however, may require commercial composting conditions to fully break down (David Evans, personal communication).

While recycling of plastic pots is an option for some consumers with access to collection facilities, containers used for greenhouse and nursery production are less likely to be reclaimed given the potential for chemical contamination and photodegradation (Garthe and Kowal, 1994).

In the United States, overall, plastic recycling rates are estimated to be only 8% (US EPA, 2011). Within this aggregation, not all plastics and plastic products are recycled equally. More ubiquitous and desirable products like bottles and jars have recycling rates ranging from 21% to 28% (US EPA, 2011). Lesser-valued agricultural plastics are generally buried or burned and are likely reclaimed at rates much lower than the overall average (Garthe and Kowal, 1994).

Beyond end-of-life considerations, container selection can have a number of impacts on the overall sustainability of greenhouse production. Biocontainers vary in their material and overall strength, and they can be less resilient to the rigors of mechanization and transport (Koeser et al., 2013a). As such, overall production efficiency may decline due to losses linked to unacceptable container damage. For potted plants that successfully navigate through mechanized transplanting and handling processes, plant growth rate and water use in greenhouse growing spaces can vary given differences in container design and porosity (Koeser et al. 2013b). Moving beyond issues associated with production, purchased plants introduced into the landscape may have different establishment and growth rates depending on whether a plantable pot is used or not.

This study offers a first look at the overall sustainability of biocontainers as part of a greenhouse production system. Hall et al. (2009) noted in their survey work that greenhouse growers believed sustainability in their operations was important. Additionally, the researchers found that decisions regarding sustainable practices were largely based on this belief and not an expectation of economic reward from environmentally-conscious consumers. As such, our work adopts a grower's perspective and focuses on the environmental impacts of container use during the plant production phase (cradle-to-gate).

One of the main difficulties in any life cycle assessment is the collection of quality data from manufacturers and contractors (Boustead, 1996). While this is true even for in-house assessments, the transparency and potential scrutiny that come with publishing one's results in the peer-reviewed literature can be an added barrier to full cooperation. In this assessment, only the secondary impacts occurring during the greenhouse production of plants (e.g., differences in irrigation demand, peat use, etc.) associated with each container are compared. These secondary impacts were directly measured through a series of applied research trials, and represent differences in inputs growers would note in their operations. The results of this work can be used to guide future research by identifying promising containers that should be assessed more thoroughly (i.e., determining their own intrinsic carbon footprints). Furthermore, providing container manufacturers with preliminary results may reduce apprehension and encourage participation by providing a relevant example of the life cycle assessment process.

Biocontainers as a whole are marketed as a means of making the horticultural industry more sustainable. This paper aims to provide one piece of the puzzle in evaluating these claims by identifying the extent to which each container impacts the carbon footprint of petunia production. The results of this work will help commercial growers identify secondary environmental impacts associated with their decision to adopt green packaging in their production systems.

Materials and Methods

GOAL, SCOPE, AND FUNCTIONAL UNIT. This paper assesses the inputs and impacts of a short-rotation greenhouse crop, *Petunia* x*hybrida* (petunia), from initial propagation to plant and container delivery at a retail center. This study is the first to establish a baseline, cradle-to-gate life cycle inventory of this annual floral commodity. Additionally, our paper serves as an initial screening of nine commercially available biocontainers (Table 5.1, Fig. 5.1), which may be selected for a more thorough life cycle assessment that includes manufacturing inputs and environmental impacts in future research.

As a model system, our assessment is based on production practices of a large, semi-mechanized wholesale greenhouse that supplies retailers throughout the Midwestern United States (Mid-American Growers, Granville, IL, United States). Global warming potential (GWP) linked to carbon emissions was selected as the primary environmental impact estimated to allow for comparison with past life cycle assessment works in horticultural production (Aldenton, 2002; Ingram, 2012; Ingram, 2013, Kendall and McPherson, 2012). The functional unit is a single petunia plant and its container (approximately 450 cm^3 volume, though volume was somewhat variable because of size availability for the containers assessed).

Fig. 5.1. Images of container used in life cycle assessment. Containers used included (A) plastic control, (B) bioplastic, (C) coir, (D) manure, (E) peat, (F) sleeve, (G) slotted rice hull, (H) solid rice hull, (I) straw, and (J) wood fiber.

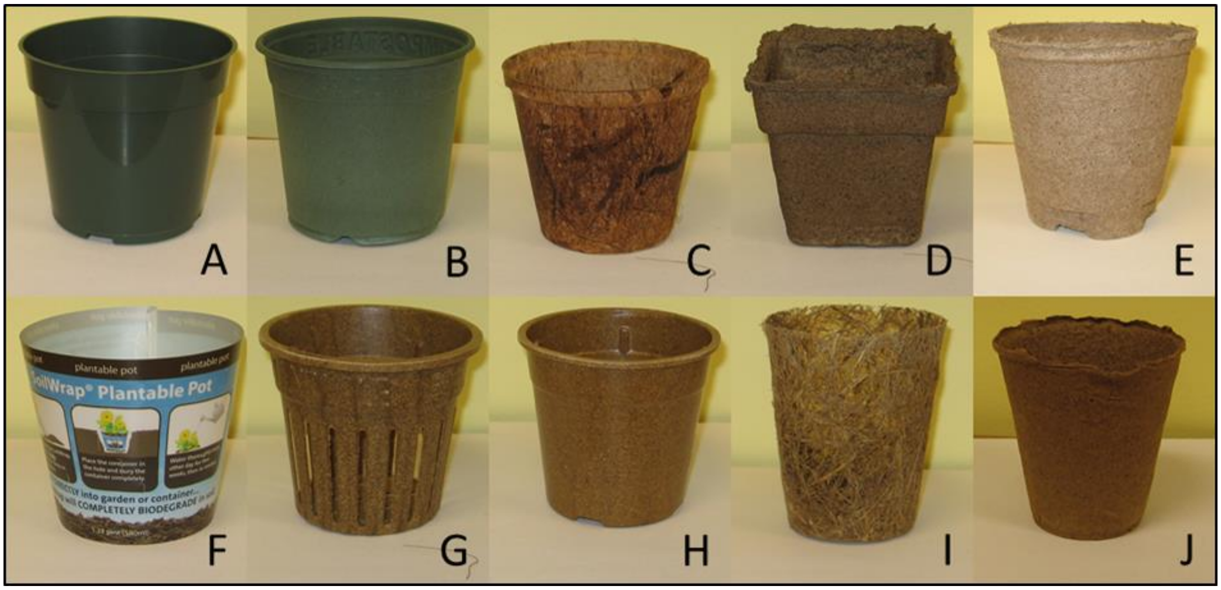


Table 5.1. Container type, product name, approximate volume, and manufacturer information for nine biocontainers and a conventional plastic container use for this life cycle assessment.

Container type	Product name[z]	Volume (cm^3)	Manufacturer
Plastic	Dillen 04.00 Standard Thinwall Green	480	Myers Industries Lawn & Garden Group, Middlefield, OH
Bioplastic	TerraShell™ 10cm H Wheat Pot	473	Summit Plastic Company, Akron, OH
Coir	Coir 4.0” Std Fiber Gro Pot	406	Dillen Products, Middlefield, OH
Manure	#4 Square CowPot	450	CowPots Manufacturing and Sales, East Canaan, CT
Peat	4” Jiffy Pot	379[y]	Jiffy Products of America Inc., Lorain, OH
Bioplastic sleeve (Sleeve)	4.5” Standard Assembled SoilWrap®	709[y]	Ball Horticultural Company, West Chicago, IL
Slotted rice hull	4.5” NetPot	591	Summit Plastic Company, Akron, OH
Solid rice hull	Rice Pot 4”	473	Summit Plastic Company, Akron, OH
Straw	n/a	646[y]	Ivy Acres, Baiting Hollow, NY
Wood fiber	10 X 10 cm Round Individual Fertilpot	430[y]	Fertil SAS, Boulogne Billancourt , France

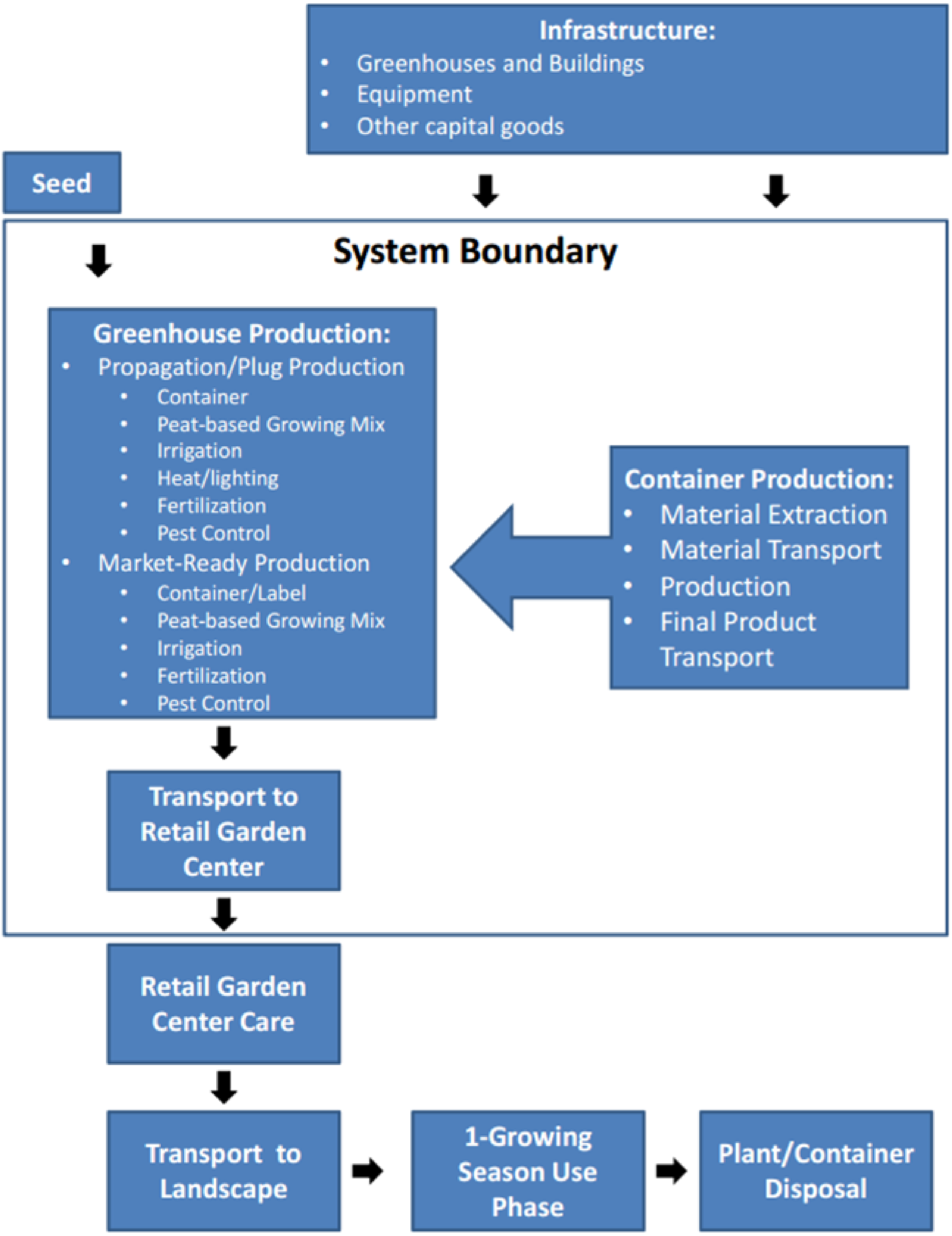
[z] As indicated in manufacturers on-line/print catalog.

[y] Not included in manufacturer specifications. Volume approximated.

SYSTEM BOUNDARIES AND ASSUMPTIONS. The boundary for this cradle-to-gate life cycle assessment begins with propagation via seed at the commercial greenhouse (Fig. 5.2). Actual seed production and transport were not included within the system boundary given limitations of available data and because past work has shown this process contributes very little to the overall impacts of production (rounded to 0%; Kendall and McPherson, 2012), After germination, seedlings are grown in indoor greenhouse space until they are large enough to be transplanted from their initial plug tray cell to a larger, final container for outdoor production. Once plants are market ready (i.e., a point at which a plant is in flower and above-ground growth is sufficiently filling the container), they are transported to a garden retail center for sale.

Following the methods adopted by recent LCA of ornamental nursery crops, the scope of this assessment does not consider emissions associated with the production of capital goods (e.g., the greenhouses facilities and mechanized equipment) used to produce the functional unit (Ingram, 2012; Kendall and McPherson, 2012).

Fig. 5.2. Life cycle of a greenhouse-produced petunia plant. The system boundary for this cradle-to-gate assessment is outlined below.



LIFE CYCLE INVENTORY AND DATA COLLECTION. Data for this life cycle assessment came from a variety of sources. General production practices for plug and final plant production were identified through a series of telephone and email interviews with six growers at Mid-American Growers. These communications were supported by direct meter readings from the greenhouse's boiler system, information from product labels, and interviews with horticultural equipment manufacturers. Direct experimentation from a series of independent greenhouse trials provided container-specific growing requirements. Basic material data came from past literature, the U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory, 2012), and a North American-adapted version of the Ecoinvent Database (US-EI version 2.2, Earthshift Inc, Huntington, VT, United States). Electricity source information specific to the study area was obtained from the United States Environmental Protection Agency's Emissions and Generation Resource Integrated Database (eGRID) model (EPA, 2009). All processes and data sources for the life cycle inventory were managed through the SimaPro life cycle assessment software tool (SimaPro 7.3.3, PRé Consultants bv, Amersfoort, The Netherlands) and are listed in Table 5.2.

INPUTS AND ASSUMPTIONS ASSOCIATED WITH PROPAGATION AND PLUG PRODUCTION. The growers interviewed in the study estimated overall waste during plug production at 10%, given non-germination or poor seedling quality. All input values for plug production have been adjusted to account for this waste. Petunia plants are typically started from seed and grown for 4 weeks in a 200-cell polystyrene plug tray. Each cell is filled with approximately 2.45 g of a 65:35 peat:perlite growing mix (Fafard 2, Conrad Fafard Inc., Agawam, MA, United States). Irrigation occurs every other day for the first 14 days. For the last two weeks, watering occurs daily. The total volume of water applied to a given plant is 52.2 mL. All water used is pumped from on-site surface water sources.

Plants are fertilized at each watering with a 14-2-20 N-P-K fertilizer mixed at a rate of 100 ppm. A fungicide spray/drench (Pageant, BASF, Research Triangle Park, NC, United States) is applied as needed, typically once per crop at a rate of 0.45 mL of stock solution per liter of water. About 2 weeks into the production process, plants are sprayed with 500 ppm solution of the plant growth regulator, ethephon (Florel, Lawn and Garden Products, Inc., Fresno, CA, United States), to promote secondary branching and create a bushier appearance. Around this same time, a 1-3 ppm solution of paclobutrazol (Piccolo, Fine Agrochemicals, Ltd, Walnut Creek, CA , United States) is sprayed on the plants to reduce stem elongation and limit legginess.

Plug plants are grown in an enclosed greenhouse space. Supplemental lighting is provided by 1000 W high-intensity-discharge grow lamps covering an area of 10.5 m^2 each. Lamps are set to run during early mornings and weekends for a total run-time of 73 hours per week. Three wood boilers utilizing chipped industrial wood scrap maintain minimum greenhouse temperatures of 22 to 24 °C.

INPUTS AND ASSUMPTIONS ASSOCIATED WITH FINAL GREENHOUSE PRODUCTION (PLASTIC CONTAINER SCENARIO). Plugs are mechanically transplanted into larger 10-cm polypropylene pots after the initial 4-week plug production process. During transplanting, empty pots are placed in a 10-cell polystyrene filling tray and run through a mechanical potting mix filling machine (KV-L Filler, Agronomix, Oberlin, OH, United States). Each container is filled with approximately 68.4 g of a 85:15 peat:perlite soil-less mix (mixed on site). After filling, plugs are hand-transplanted into the larger containers, and the trays (with pots and plants) are moved outside for the final 5 weeks of production.

Once outside, plants are fertigated every 2-3 days with a 100 ppm 14-2-20 fertilizer solution. Average water use for plants grown in plastic containers (without trays) was calculated to be 2162 mL during an independent growth trial intended to mimic this stage in production (Koeser et al., 2013). This value was adjusted to reflect water savings (6%) associated with tray use (Evans et al., unpublished data).

During the final production stage, petunia plants are typically treated once with a fungicide (Banrot, Scotts-Sierra Crop Protection Company, Marysville, OH, United States) at a rate of 0.60 g of wettable powder per liter of water. They are also sprayed once with the fungal-derived insecticide NoFly (Natural Industries, Inc., Spring, TX, United States) at 2.3 kg per hectare to prevent thrip damage and again with the insecticide Mallet (Nufarm Americas, Inc., Burr Ridge, IL, United States) at a rate of 0.12 g per liter to prevent aphid damage. Finally, the petunia plants are sprayed 1-2 times with a 5-6 ppm paclobutrazol growth regulator solution to maintain a compact, full form. Waste due at this production stage was estimated at 2% by the interviewees.

PRODUCTION INPUTS WHICH VARY GIVEN CONTAINER TYPE (SECONDARY IMPACTS). Secondary impacts of container type fall into one of two general categories: impacts related to container size and impacts related to container-related irrigation demand. Differences in container size directly translate into differences in peat and perlite use during the final production stage and ultimately, shipping weight. A 10-cm diameter container size was chosen as a standard given its wide availability among container types. However, two containers, the bioplastic sleeve and the slotted rice pot, were only available in 11.5-cm sizes. Similarly, the manure pot was available in a 10-cm square only (not a round like the other nine containers). Lastly, the straw pot, though 10-cm in diameter, had a larger volume than most containers given its above-average height.

Water use, while tied in part to container volume, is also influenced by container geometry (i.e., slender vs. stout), absence or presence of drain holes, and container-wall porosity. Differences in water demand influence the amount of electricity required to run irrigation systems. Additionally, all fertilization, pesticide, and growth regulator applications were administered in conjunction with normal irrigation. As such, the amount of chemical applied would vary slightly by container depending on the amount of water dispensed in a given watering.

INPUTS AND ASSUMPTIONS FOR TRANSPORTATION. All pesticides, fertilizers, and the commercially produced plug growing mix were assumed to have come from the nearest major greenhouse supplier (110 km from the study site; BFG Supply Company, Joliet, IL, United States). The horticultural peat material data used for the two growing media mixes included an estimate for average delivery in North America (Cleary et al., 2005). However, the expanded perlite component of this mix did not include a transportation component (US-EI 2.2). As such, perlite was assumed to be sourced and delivered from the nearest processing plant (148 km to study site; Silbrico Corporation, Hodgkins, IL, United States). Finally, transportation for the plastic containers and trays was assumed to be the distance to the manufacturer (740 km to study site; Meyers Industries, Middleton, OH, United States). For all inputs above, transportation via diesel truck was assumed.

Plants are transported only minimally during greenhouse production. Throughout the entire process, plants are moved approximately 0.75 km by lawn tractor or by person (latter assumed). Mid-American Growers provides floral materials to a wide range of major retailers within 480 km of the production site. The largest market in this distribution area is the Chicago, IL (United States) metropolitan area (174 km from Chicago to production site). This was the assumed destination for the final product.

Table 5.2. Life cycle inventory for both the plug and final plant product stages. Data sources included.

Product Stage	Input	Per plant	Unit	Source(s)
Plug	Electricity	0.083	MJ	US-EPA eGRID
Plug	Waste wood heat	0.240	MJ	US-EI 2.2 – heat, hardwood chips from industry
Plug	Growing mix (65:35 peat:perlite)	0.002	kg	Cleary et al., 2005 US-EI 2.2 – expanded perlite
Plug	Perlite transport	0.124	kg-km	NERL USLCI – diesel truck transport
Plug	Plug tray	0.001	kg	US-EI 2.2 – polystyrene Industry Data 2.0– polystyrene thermoforming
Plug	Plug tray transport	0.8050	kg-km	NERL USLCI – diesel truck transport
Plug	14-2-20 fertilizer	9.072×10^{-4}	kg	US-EI 2.2 – urea, as N US-EI 2.2 – ammonium nitrate as N US-EI 2.2 – triple superphosphate as P_20_5 US-EI 2.2 – potassium chloride as K_20
Plug	Ethephon (Florel)	1.228×10^{-6}	kg	US-EI 2.2 – growth regulators
Plug	Paclobutrazol (Piccolo)	4.950×10^{-9}	kg	US-EI 2.2 – growth regulators
Plug	Pyraclostrobin/boscalid (Pageant)	3.143×10^{-7}	kg	US-EI 2.2 – fungicides
Plug	Chemical transport	0.001	kg-km	NERL USLCI – diesel truck transport
Plug	Irrigation	0.052	l	US-EI 2.2 – agricultural irrigation
Final	10 cm plastic pot	0.014	kg	US-EI 2.2 – polypropylene US-EI 2.2 – polypropylene injection molding
Final	Plastic pot transport	10.1	kg-km	NERL USLCI – diesel truck transport
Final	Plastic tray	0.013	kg	US-EI 2.2 – polystyrene Industry Data 2.0 – polystyrene thermoforming
Final	Plastic tray transport	9.89	kg-km	NERL USLCI – diesel truck transport
Final	Growing Mix (85:15 peat:perlite)	0.068	kg	Cleary et al., 2005 US-EI 2.2 – expanded perlite
Final	Perlite transport	1.528	kg-km	NERL USLCI – diesel truck transport
Final	Etridiozole/Thiophanate-methyl (Banrot)	0.8×10^{-5}	kg	US-EI 2.2 – fungicides
Final	Paclobutrazol (Piccolo)	8.874×10^{-7}	kg	US-EI 2.2 – growth regulators
Final	(NoFly)	2.360×10^{-6}	kg	US-EI 2.2 – insecticides
Final	(Mallet)	1.885×10^{-5}	kg	US-EI 2.2 – insecticides
Final	Chemical Transport	0.014	kg-km	NERL USLCI – diesel truck transport
Final	Final product transport	60.95	kg-km	NERL USLCI – diesel truck transport
Final	Irrigation	2.073	l	Koeser et al., 2013 Evans et al., unpublished data US-EI 2.2 – agricultural irrigation

IMPACT ASSESSMENT AND LIFE CYCLE ASSESSMENT. In addition to the life cycle inventory, global warming potentials (as a factor of kg CO_2e emitted) were estimated for the 10 different container production scenarios using the United States Environmental Protection Agency's TRACI 2 impact assessment model [version 4.00 (US EPA, 2012)]. Only processes contributing 0.5% or more toward the overall environmental impact of a petunia are included in the results summaries.

Sensitivity or "what-if" analysis was conducted to see how the overall GWP impact results changed with the inclusion of a given container parameter (Björklund, 2002 ; ISO, 2006). Differences of 15 to 30% are typically adopted by LCA practitioners when identifying influential inputs (Harnoor Dhaliwal, personal communication).

Results and Discussion

BASELINE ASSESSMENT OF PETUNIA PRODUCTION. Global warming potential for all of the main contributing inputs are expressed as kilograms of carbon dioxide equivalents (kg CO_2e) in Table 5.3. For plug production, the overwhelming majority of kg CO_2e were linked to electrical consumption. The majority of the electricity used to propagate and grow petunia seedlings was use for supplemental lighting.

Table 5.3. Base level inputs, transportation requirements, and their associated CO2e emissions per petunia plant grown in a plastic container. Only inputs contributing 0.5% or more toward the emissions for a given production stage are included.

Product Stage	Input	kg CO_2e^z	% Contribution to Total GWP^z
Plug	Electricity (lighting and irrigation)	0.233	94.71
Plug	Waste wood heat	0.002	0.81
Plug	Growing mix	0.002	0.81
Plug	Plug Tray	0.009	3.67
	Plug total	**0.246**	**100.00**
Final	Finished plug	0.246	47.67
Final	Transportation - truck	0.017	3.29
Final	Horticultural peat	0.042	8.14
Final	Expanded perlite	0.012	2.32
Final	Fertilizer solution	0.009	1.74
Final	Plastic container	0.087	16.86
Final	Plastic shuttle tray	0.103	19.96
	Plant total (including plug)	**0.516**	**100.00**

^{z}Values may not sum to total given rounding

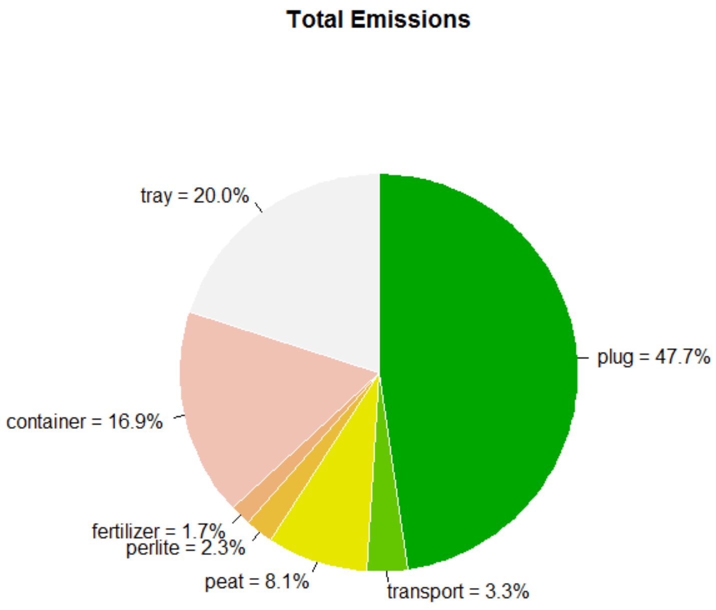
Wood heating was a minimal contribution to GWP. Of the three boilers used, only two were needed intermittently to heat an area of 8 ha. When in operation, the boilers heated a large buffer tank which helped limit temperature fluctuations as nighttime temperatures dropped. The fuel source used by the boilers also served to limit over GWP. All woodchips were sourced locally as industrial byproducts from pallet and other manufacturing processes.

The remainder of the inputs had minimal impact given the diminutive size of the plant and plug tray. Only horticultural peat harvesting/processing and polystyrene production/thermoforming (processes noted for their CO_2e admissions) were present in sufficient quantities to register as noteworthy contributors to GWP.

Plug production in the controlled greenhouse space accounted for nearly half of the final plant's carbon footprint (Fig. 5.3). Other notable inputs in petunia production included tray (20.0% of total GWP), container (16.9% of total GWP), and peat (8.1% of total GWP). Lesser contributors to the overall impact included transport (3.3% of total GWP), perlite (2.3% of total GWP), and the fertilizer mix (1.7% of total GWP).

These results are consistent with those documented in a past cradle-to-gate carbon footprint assessment of container woody tree production (Kendall and McPherson, 2012) and tree seedling production (Aldentun, 2002). In the first study, a total of 4.6 kg CO_2e was emitted during the production a typical #5 (13.5 l capacity) container tree. As with petunia production, the researchers noted that inputs were more intensive during propagation and seedling production. While grown over several seasons, the latter stages of tree production, like petunia production, occur outdoors in uncontrolled environments. Kendall and McPherson (2012) also note containers, growing media, and fertilizer as significant material inputs during final production. Aldentun (2002) calculated CO_2e emissions ranging from 0.045 to 0.133 kg per seedling with the variation linked to nursery surveyed. Again, lighting, peat, and tray were identified as significant contributors to overall GWP.

Fig. 5.3. Total emissions associated with container petunia production. Only inputs contributing 0.5% or more are included.

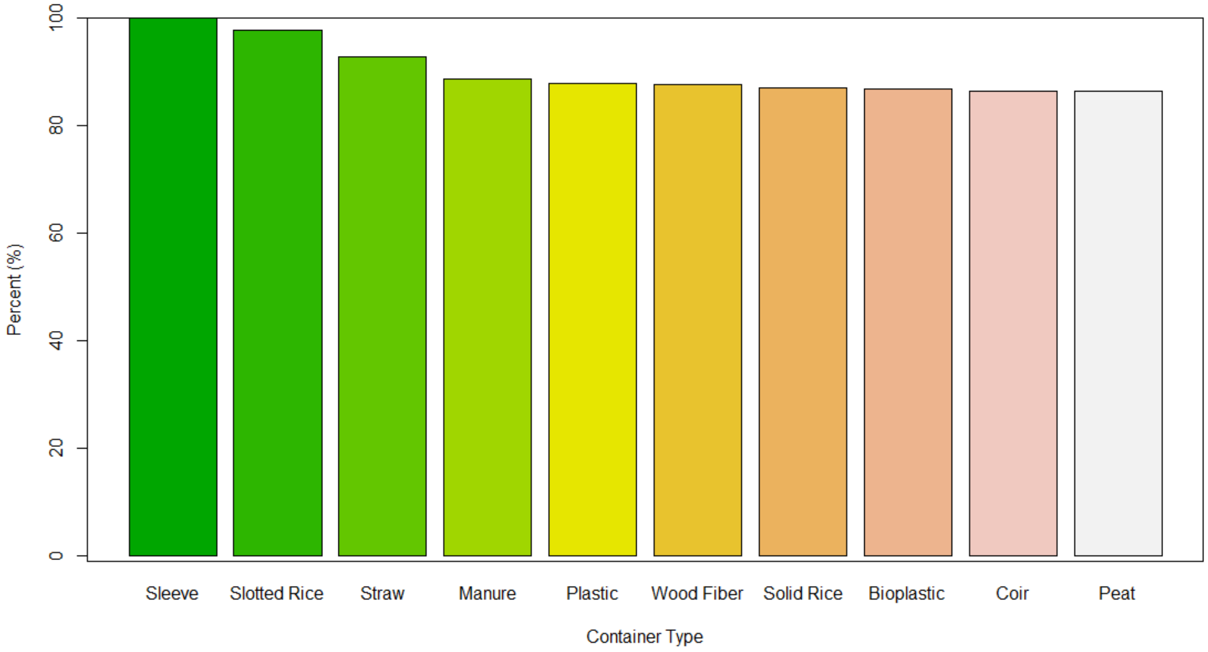


SECONDARY IMPACTS ASSOCIATED WITH BIOCONTAINER USE. While past research has shown biocontainer use can have significant impacts on inputs like irrigation (Koeser et al. 2013), this variability did not translate into significant differences in GWP. In assessing the various container parameters, GWP differed by 14.6% for the lowest and highest ranked container types: sleeve and peat (Fig. 5.4). While close to the more conservative 15% significance level mention in the methods, one could argue this difference is confounded with container size. Petunias grown in six 10-cm diameter biocontainers had nearly identical GWP values as a petunia grown in the conventional plastic pot (also 10-cm in diameter).

The three most visible differences in GWP are seen with the sleeve, slotted rice, and straw containers (Fig. 5.4). These are also the three most voluminous pots (Table 5.1). All containers are filled to capacity by the mechanical filling machine. As such, differences peat use and final shipping weight drive the elevated GWP for these three containers. Other inputs such as irrigation, fertilization, and pesticides appear to have less influence on GWP, as despite being reduced (compared to plastic) in the sleeve and slotted rice containers, overall carbon emission were still elevated for these two pots.

In conducting this assessment, we chose each biocontainer manufacturer's closest alternative to the common 10-cm plastic pot. If a grower switched from this size to one of the three larger biocontainers, the differences noted below could warrant further investigation. However, it seems likely that if all container sizes were identical, the differences in GWP would not have been noted.

Fig 5.4. Comparison of petunia production global warming potential (GWP) when using one of nine biocontainers or a conventional plastic container (CO_2e for Sleeve set at 100%). Differences reflect only secondary impacts and do not include CO_2e emissions associated with the production of the biocontianers themselves.



Conclusions

The results of this work should be encouraging for growers and manufacturers looking to increase sustainability through the use and development of biocontainers. While biocontainers have been linked to reduced performance in plant growth, filling speed, shipping success, and irrigation demand trials, these differences do not have a dramatic effect on production sustainability from a GWP perspective.

Furthermore, for some factors like plant size, variability may be tolerated by consumers and growers, as long as plant appearance remains unaffected. Other factors will likely become less of an issue as biocontainers are fully embraced by the horticultural industry. With widespread use comes innovation and adaptation of conventional greenhouse practices that will overcome past documented pitfalls.

While future life cycle assessment research investigating the impacts of the containers and their production would lead to a more accurate assessment of petunia production GWP, the overall impact may not be very dramatic. In our baseline life cycle inventory, container accounted for approximately 17% of total CO_2e emissions. If a given container was found to have half the GWP of our standard plastic control, the overall reduction in CO2e emissions would be approximately 8 to 9%.

Supplemental lighting, which accounts for nearly 45% of total GWP, is the most important factor contributing to GWP. The use of more energy efficient light sources such as LED lamps, while not as noticeable at the garden retail center, would have the greatest impact on lowering CO_2e emission. Production systems similar to our model site have the potential to reduce both the real and perceived environmental impacts associated with greenhouse grown-petunias by adopting more efficient lighting and biocontainers in their operations.

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APPENDIX A: COMPATIBILITY OF BIOCONTAINERS IN COMMERCIAL GREENHOUSE CROP PRODUCTION

Note: This work originally conducted by Dr. Daniel Warnock prior to leaving the department. It is the preliminary research which led to the larger funding source supporting this dissertation. As such, Dr. Gary Kling and I continued this work – analyzing and reporting the results. This paper is slated for publication in the April 2013 issue of HortTechnology.

Summary

Despite consumer interest in biocontainers, their use in commercial greenhouse production remains limited. Previous research indicates that a perceived incompatibility of biocontainers with current production systems may be a barrier to their widespread adoption. This paper investigates two potential areas of concern for growers looking to adopt biocontainers as part of their production process: 1.) the ability of biocontainers to withstand the rigors of a semi-mechanized commercial production process; and 2.) biocontainer performance under three different irrigation methods (i.e., hand, ebb-and-flood, and drip irrigation). In the two studies presented here, 'Florida Sun Jade' coleus (*Solenostemon scutellarioides*), was evaluated to match measures of container resiliency with plant performance. Results indicate that plants grown in biocontainers were of equal size and quality as those grown in conventional plastic containers within each of the irrigation types tested. However, some biocontainers were more prone to damage during crop production, handling, and shipping.

Background

Market research has shown that environmentally-conscious consumers are willing to pay more for products developed by companies that incorporate sustainable business practices (Blend and van Ravenswaay, 1999; Thompson and Kidwell, 1998; Yue et al., 2011). Beyond the acceptance of premium pricing, green consumers have shown loyalty to businesses that embrace their environmental ideals (Yue and Tong, 2009). When one looks at issues of sustainability and horticultural sales, container type is consistently listed among the top factors having a positive impact on consumer product perception (Dennis et al., 2010; Hall et al., 2010; Yue et al., 2011). As a highly visible symbol of past production processes, container type has generated more interest than "behind the scenes" practices such as organic fertilizer or efficient greenhouse space usage (Yue et al., 2011). Similar results were found in the work by Hall et al. (2010), who found that container type outweighed all other purchasing considerations – including price and carbon footprint. These findings have led researchers to state that consumers are more interested in making the pots sustainable than the plants themselves (Yue et al., 2011).

Despite this consumer interest, biocontainers as a whole have yet to be widely embraced by the greenhouse and nursery industry. Hall et al. (2009) found that over 22% of growers surveyed indicated that they had used biocontainers in their operations. Of the remaining 78% that participated in the study, only 6% noted that they would like to add biocontainers to their current production processes (Hall et al., 2009). Similarly, research by Dennis et al. (2010), reported that 12% of greenhouse growers acknowledged prior use of peat pots in their operations. Within this 12%, respondents estimated that peat pots comprised less than 3% of their total container consumption (Dennis et al., 2010). These figures support a general consensus that the widespread use of biocontainers has been largely limited by their higher cost and perceived limitations (Helgeson et al., 2009; Kuehny et al., 2011).

Conventional plastic containers remain popular given their ability to provide consistent performance (e.g., comparable wet/dry strength, compatibility with equipment) in production systems. This effectively removes one of the many possible variables a grower must contend with when attempting to produce a uniform crop of high-quality plants. The price of plastic still remains relatively inexpensive and economically accessible to ornamental crop growers (Evans and Hensley, 2004; Helgeson et al., 2009). For its cost, plastic is strong, lightweight, and versatile. These properties make it fully compatible with mechanized production processes and ideal for shipping (Evans and Hensley, 2004; Hall et al., 2010; Helgeson et al., 2009).

Given the reliability of plastic, growers – especially growers with large operations – are hesitant to move toward any container that they feel may pose a risk to their crop or be difficult to implement in their existing production practices (Dennis et al., 2010, Hall et al., 2009). Despite this aversion to risk, greenhouse growers (in contrast with nursery growers and nursery/greenhouse growers) ranked issues of compatibility as a minor barrier, indicating that perhaps flexibility in production practices, equipment, and crops may allow for greater adoption of biocontainers (Dennis et al., 2010).

Though some published research has quantified biocontainer resistance to puncturing and crushing as indicators of container resiliency in production processes (Evans and Karcher, 2004; Evans et al., 2010), the current range of biocontainers on the market have yet to be thoroughly tested in the mechanized systems required for high throughput production of crops grown in greenhouses. As shown in this paper, in situ commercial testing is needed to assess impacts on system efficiency beyond container breakage (e.g., time to process).

Furthermore, previous biocontainer growth studies under research greenhouse conditions have focused exclusively on hand irrigation as a means of water delivery (Evans and Hensley, 2004; Evans and Karcher, 2004). However, commercial greenhouses often rely on a variety of irrigation methods beyond overhead watering (e.g., drip irrigation and ebb-and-flood irrigation) – each with its own pattern of initial wetting and saturation that could potentially impact biocontainer durability during crop production.

This work reports findings from two separate, but complimentary studies. The first is a series of interrelated experiments designed to determine whether biocontainers can withstand the rigors of high throughput, commercial greenhouse production – namely semi-mechanized filling, transplanting, handling, and shipping. Additionally, this study includes two successive growth trials (drip irrigation only) intended to determine if container root zone conditions, and ultimately plant shoot growth, are affected by container type. The second study expands on the first set of growth trials, as well as the existing body of biocontainer research, through the inclusion of an irrigation method factor. Measures of plant growth and container strength were conducted to determine the impact of drip irrigation, hand watering, and ebb-and-flood irrigation on crop and container performance. The combined product of these efforts contributes to the growing body of biocontainer research while helping professional growers make more informed decisions on whether these plastic pot alternatives can be incorporated in their own operations.

Materials and Methods

CONTAINERS. Eight container types (one control and seven biocontainer alternatives) were compared in all experiments (Table A.1).

Table A.1 Containers evaluated in all greenhouse and industrial trials in this paper. Greenhouse trials investigated the growth of 'Florida Sun Jade' coleus (Solenostemon scutellarioides) in the containers below when watered using a variety of irrigation methods (i.e., drip irrigation, ebb-and-flood table, and hand watering with a wand). Industrial trials assessed container damage as a result of mechanical filling, lifting, and shipping.

Container type^{z}	Approximate vol (L)	Product name^{y}	Manufacturer
Plastic (control)	1.3	JanorPot® 15cm-L	Summit Plastic Company, Akron, OH
Wheat-based bioplastic (bioplastic)	1.2	15cm-L TerraShell™/OP47	Summit Plastic Company, Akron, OH
Coir	1.3	6” Round Coir Pot	Dillen Products, Middlefield, OH
Pressed manure (manure)	1.2	6” Round	CowPots Manufacturing and Sales, East Canaan, CT
Paper	1.0	5” Kord® Fiber Grow Round Pot	ITML Horticultural Products, Middlefield, OH
Peat	0.7	Jiffy-pots® 5	Jiffy Products of America Inc., Lorain, OH
Straw	0.8	5” Straw Pot	Ivy Acres, Baiting Hollow, NY
Wood fiber	3.9	7X7RD	Western Products Company, Corvallis, OR

[z] Shortened descriptions appearing in parenthesis will be used throughout this paper.

[y] Product names are as listed in their respective company's catalog.

1 L = 0.2642 gal

LOCATIONS. The mechanical filling and spacing experiments were conducted at a wholesale commercial greenhouse facility (Mid-American Growers, Granville, IL). Both greenhouse growth trials were conducted at a university research facility (University of Illinois at Urbana-Champaign Plant Science Laboratory, Urbana, IL). The route for the shipping experiment connected these two locations. Container strength testing was conducted at a university materials testing facility (Advanced Materials Testing & Evaluation Laboratory at the University of Illinois at Urbana-Champaign, Urbana, IL).

MECHANICAL FILLING. This experiment was a randomized complete block design with four separate runs serving as blocks. Within each run, the eight pot types were sent through a gravity-fed pot-filling machine (model PM1100; Agrinomix, Oberlin, OH) in batches of 50 transport trays. Though containers sizes were selected to provide similar rooting volume for the later greenhouse trial, differences in width and height required the use of both six-cell and eight-cell azalea transport trays (Landmark Plastics; Akron, OH) during the filling experiment. As a result, each batch of 50 trays consisted of either 300 or 400 total pots. Four workers were involved in the filling process: one person to load the transport trays onto the conveyor belt; two to un-stack the pots, load them into the transport trays, and ensure that the machinery was running properly; and one person to load the trays onto carts after going through the filling machine. The pot filling machine and conveyors were adjusted between each run to meet various pot height requirements. The calibration time was not included in the total run time. Data gathered during this procedure included: proportion of pots damaged by machinery (e.g., crushed, torn, or punctured pots), proportion of pots unfilled (defined as more than 33% of pot volume devoid of soil), and total elapsed pot filling time (starting with placement of the first tray at the beginning of the line and ending with the removal of the last tray at the end of the line).

MECHANICAL SPACING. Lifter bars were used in a simulated spacing trial to assess compatibility with the biocontainers tested. As with the filling trial, individual differences in container dimensions influenced sample size. To account for differences in pot widths, one of three lifter bars was selected for each pot type in this trial: a 4-inch, 15-pot spacer bar; a 6-inch (15.2 cm), 10-pot spacer bar spacer; and an 8-inch (20.3 cm), 7-pot spacer bar (FW Systems, Bergschenhoek, The Netherlands). In addition to the eight container types, two different levels of a “shelf life” factor were used during this experiment. The first group in this factor was comprised of pots that had been filled with soil and watered just prior to the lifting test. The second level was comprised of containers under greenhouse conditions 4 weeks after transplanting (WAT). This second set of containers was also watered just prior to lifting.

A simulation of mechanical spacing equipment was used for this trial. The downtime and labor associated with changing pot lifter bars and calibrating the mechanical spacer was prohibitive given the small volume of pots in each treatment. Thus, lifter bars were raised manually to assess whether the biocontainers tested were compatible with mechanical spacing equipment. The appropriate number of pots was lined up across the bench. The pots were lifted with a person on each end of the spacer bar to a height of approximately 1 ft and then set down and released approximately 1 ft away from the original location (similar to the mechanical spacing process). This procedure was replicated a total of four times per pot type in a randomized order for both treatments. After each lift, data were collected on the number of pots damaged during spacing, the number of pots spilled during spacing, and the number of pots that were not picked up by the spacer bar.

SHIPPING. Pots filled with soilless media and arranged in shuttle trays were watered just prior to this trial, loaded onto rolling greenhouse carts, and loaded onto a box truck for transportation to and from the two sites in this trial. At each destination point, pots were unloaded and inspected for fraying, tears, gashes, creasing, crushed areas and other signs of damage. Data from one-way trips (200 km) were used in this analysis to minimize any confounding factors associated with pot handling by mechanized equipment or simulated mechanized handling while at each site. For each container type, 12 groups of five similar containers (total n=60) were used to assess the proportion of pots damaged during transport.

GROWING CONDITIONS (BOTH GREENHOUSE TRIALS). Each of the two greenhouse trials listed below (i.e., drip only and hand, drip, and ebb-and-flood irrigation) were repeated. The first and second iterations of the two experiments began on 28 Apr. 2010 and 28 June 2010, respectively. All pots were mechanically filled with a peat-based substrate (85:15 by volume peat:perlite, Mid-American Growers, Granville, IL) and planted with rooted cuttings of 'Florida

Sun Jade' coleus (*Solenostemon scutellarioides*). These cuttings were grown under ambient light with minimum day and nighttime temperatures set at 24 and 18ºC, respectively. Plants were fertigated weekly (with one key exception detailed below) with a 250 ppm 20N-8.7P-16.6K fertilizer solution (Plantex 20-20-20 All Purpose Fertilizer; Plant Products Co, Brampton, ON, Canada). All plants were pinched in week three after planting to promote branching. Trials were concluded once the plants reached market-ready size (week 7).

GREENHOUSE TRIAL – DRIP IRRIGATION. This experiment was a completely randomized design with groups of five similar containers serving as the experimental unit (n=6 groups for the two trials). Plants were placed on metal mesh greenhouse benches with drip tubes (Chapin Tube Weights; Jain® Irrigation, Fresno, CA). Water was applied uniformly across all container treatments when ≈25% of the potted plants showed visible drying on the surface of the media. Irrigation frequency was recorded, and weekly above-ground plant volume (i.e., the product of two perpendicular diameters and the height to the apical meristem), as well as pH and electrical conductivity (EC) measurements of pot leachate were taken. Container leachate was analyzed with a portable pH and EC meter (HI 98129 pH/Conductivity/TDS Tester; Hannah Instruments, Smithfield, RI) using a pour-through measurement technique. Dry shoot weight and total leaf area were quantified at the end of each trial.

GREENHOUSE TRIAL – HAND, DRIP, AND EBB-AND-FLOOD IRRIGATION. Plants were watered using one of three irrigation methods: ebb-and-flood table (Ebb-Flo Bench, Midwest GROmaster, Inc. Maple Park, IL), drip tubing (Chapin Tube Weights), or hand watering with an irrigation wand. Ebb-and-flood tables were set for slow fill, fast empty with a 20-min, manually-triggered watering cycle. Drip irrigation was set to run for 1 min after being manually set to run. Water was applied uniformly across all container and irrigation method combinations when ≈25% of the potted plants showed visible drying on the surface of the media. As fertilizer was premixed in the ebb-and-flood reservoir tank, plants given this irrigation level were fertilized at every watering, not every week as with the drip and hand irrigated treatments (limitations are discussed below).

The large footprint of the ebb-and-flood tables limited randomization and necessitated a split-plot design. Irrigation was considered the whole-plot factor and container type was designated the subplot. Each whole-plot was replicated three times per trial and contained 40 individual pots arranged by container type in groups of five. Response values for each of the individual pots in these groupings were averaged making sub-plot the experimental unit (total n=144). Watering frequency for each irrigation level was recorded throughout the study period. In addition, substrate pH and EC readings were taken on a weekly basis. Final plant growth was measured as dry shoot weight.

CONTAINER STRENGTH TESTING – HAND, DRIP, AND EBB-AND-FLOOD IRRIGATION. After plant harvest, pots were emptied and allowed to dry. A random selection of used pots representing each container type/irrigation system combination was taken to a materials testing lab to evaluate the crush (n=5) and puncture strength (n=5). All used containers were emptied and dried prior to testing. Additionally, new containers were strength tested as a comparison to pots that had been used in production (n=8). A portion of these new containers were tested dry (n=5). The remaining containers were submerged in water for 24 h and tested while still saturated to assess wet strength (n=3).

STATISTICAL ANALYSIS. Unless otherwise noted, all conclusions are made at an α=0.05 level of type I experimental error. Container damage and filling success data from the pot filling experiment were analyzed via analysis of deviance within the GLM function of R (version 2.14.2, R Development Core Team, 2012). Wood fiber containers were not included in the pot filling analysis, as they did not fit in the transport trays used for testing. The remaining seven container types were fit to a generalized linear model with a quasibinomial distribution specified to account for overdispersion (Crawley, 2005). A left-tailed Dunnett's test (to see if the proportion of undamaged/filled containers decreased as compared to plastic control) was completed using the MULTCOMP function (Hothorn et al., 2008) in R.

Pot filling speed was standardized as the time (in minutes) required to fill 100 containers. These data were analyzed with the analysis of variance within the AOV function of R (version 2.14.2 R Development Core Team, 2012). Means separations were completed using a right-tailed Dunnett multiple comparison test (to see if time increased) with the plastic container designated as the control.

Pot shipping was also analyzed via analysis of deviance. For this data set, neither the wood fiber nor the paper containers experienced any damage. To contend with this lack of variation, these two treatments were removed from the analysis. As with the filling data, a quasibinomial distribution was specified given the presence of overdispersion. A left-tailed Dunnett multiple comparison test was conducted against the plastic control .

The influence of container type on plant volume, potting mix EC, and potting mix pH were analyzed using repeated measures with the MIXED procedure of SAS/STAT (version 9.2; SAS Institute, Cary, NC).

Final leaf area and final dry shoot weight for the greenhouse trials were assessed using analysis of variance (ANOVA) within the MIXED procedure of SAS/STAT. A $\log_{10}$ transformation was applied to the observed dry shoot weights in order to meet the assumptions of normality and homogeneity of variance required for the analysis assumptions.

Crush strength and puncture strength were assessed using ANOVA as part of the GLM procedure for SAS/STAT. Plastic, straw, coir, and bio-plastic containers were not included in the puncture analysis. These materials are very flexible and resisted penetration when tested with the metal probe. A square root transformation was applied to the response variable, load (in kilonewtons), to meet the assumptions (particularly homogeneity of variance) required for the analysis of the crush data. A $\log_{10}$ transformation was applied to the load measurements from the puncture testing for similar reasons.

When making plant growth and container strength comparisons between irrigation types (i.e., hand, drip, and ebb-and-flood), probability values from *post hoc* contrasts have been included to supplement the figures in cases where it may be difficult to make clear separations of means using the confidence interval bars.

Results and Discussion

MECHANICAL FILLING. The proportion of successfully filled pots did not vary by run/block (*P*=0.1998) or by container type (*P*=0.5993). However, the proportion of damaged containers did vary among the containers tested (*P*=0.0679) (Table A.2). In addition, blocking/run was significant (*P*=0.0198) with regard to container damage. Compared to the plastic control, coir (*P*=0.0098), pressed manure (*P*=0.0055), paper (*P*=0.0181), and peat pots (*P*=0.0204) were more likely to be damaged by the filling machine (Table A.2). Despite these statistical differences, none of the containers experienced damage levels greater than 1.5%. As many of the biocontainers had not been used at the facility before, it is conceivable that the proportion of damaged pots could decrease as workers become more familiar with the products.

The differences seen between runs show the impact of initial machine calibration and setup when switching container types. For the potting equipment used in this experiment, the most crucial adjustment involved setting the overhead brushes that sweep excess potting mix from tops of the containers to the appropriate height (Fig. A.1). Brushes were manually adjusted to minimize damage while maintaining effectiveness. Slight inconsistencies in this process or in the containers themselves (i.e., some have irregular rims) may account for the differences seen between runs. The results of the mechanical filling trial suggest that damage to containers is a more pressing concern than filling success given the pots and equipment used. Individual container properties contributed to the differences in damage among the products tested. Containers made from flexible materials (e.g., plastic, bioplastic, and straw) experienced a lower proportion of damage than containers constructed with brittle material (e.g., manure, peat, and paper; Table A.2). Coir pots, though relatively flexible in nature, were prone to fraying as the tops were brushed to remove excess potting mix. If some tearing or chipping of the container top is acceptable, even the level of damage seen among the worst performing containers may be well within the tolerances of a grower.

Table A.2. Proportion of unfilled or damaged containers for mechanical filling and shipping trials. Values are given as the number of unsuccessfully processed pots per 100 pots. Eight container types (one control and seven biocontainer alternatives) were used in both trials. For the filling trial, containers were run through a gravity-fed filling machine (model PM1100, Agrinomix, Oberlin, OH) in trays. For the shipping trial, containers (in trays) were transported approximately 200 km (124.3 miles) in a box truck.

Proportion of unfilled or damaged containers (%)

	Container type							
	Control	Bioplastic	Coir	Paper	Peat	Pressed manure	Wood fiber	Straw
Filling-unfilled	0.29	0.33	0.33	1.25	0.50	0.58	na[y]	0.31
Filling-damaged	0.11	0.33	1.25*[z]	1.08*	0.87	1.42**	na[y]	0.50
Shipping-damaged	1.67	8.33	8.33	0.00	35.00**	26.67**	0.00	6.67

[z] Comparisons are made across rows. Multiple comparisons were not conducted for the filling-unfilled response (first row) as pot type was non-significant. Mean separation was conducted as a left-tailed Dunnett's test with the plastic container designated as "Control". Estimates significant at the 0.05 level are marked with a double asterisk (**). Estimates significant at the 0.1 level are denoted with a single asterisk (*).

[y] Wood fiber containers were not included in the filling analysis as appropriate transport trays were not available for this pot type.

Fig. A.1. As trays of straw pots exit the gravity-fed filling machine (model PM1100, Agrinomix, Oberlin, OH) a rotating brush sweeps off excess potting mix. Proper adjustment of this brush was critical in the prevention of container damage and tipping.

With regard to pot filling speed, both container type (*P*<0.0001) and run (*P*=0.0054) were significant factors. At our particular study site, conveyor belt speed, and therefore run time, was ultimately most affected by the rate at which pots were unstacked and loaded into shuttle trays. As containers were placed in the trays, the worker stationed at the filling machine controls adjusted the belt speed to match the pace of the process. Any container type which resisted separation during unstacking, ultimately increased the time needed to complete a particular run. This was reflected in our calculated times for filling 100 containers (Table A.3). Peat, pressed manure and straw containers were substantially slower to fill than the control or other pot types.

Table A.3. Time in minutes required to fill 100 containers. Filling time included denesting new containers, loading them into shuttle trays, mechanically filling with a potting machine (model PM1100, Agrinomix, Oberlin, OH) and removing shuttle trays from the conveyor.

Filling time (min)

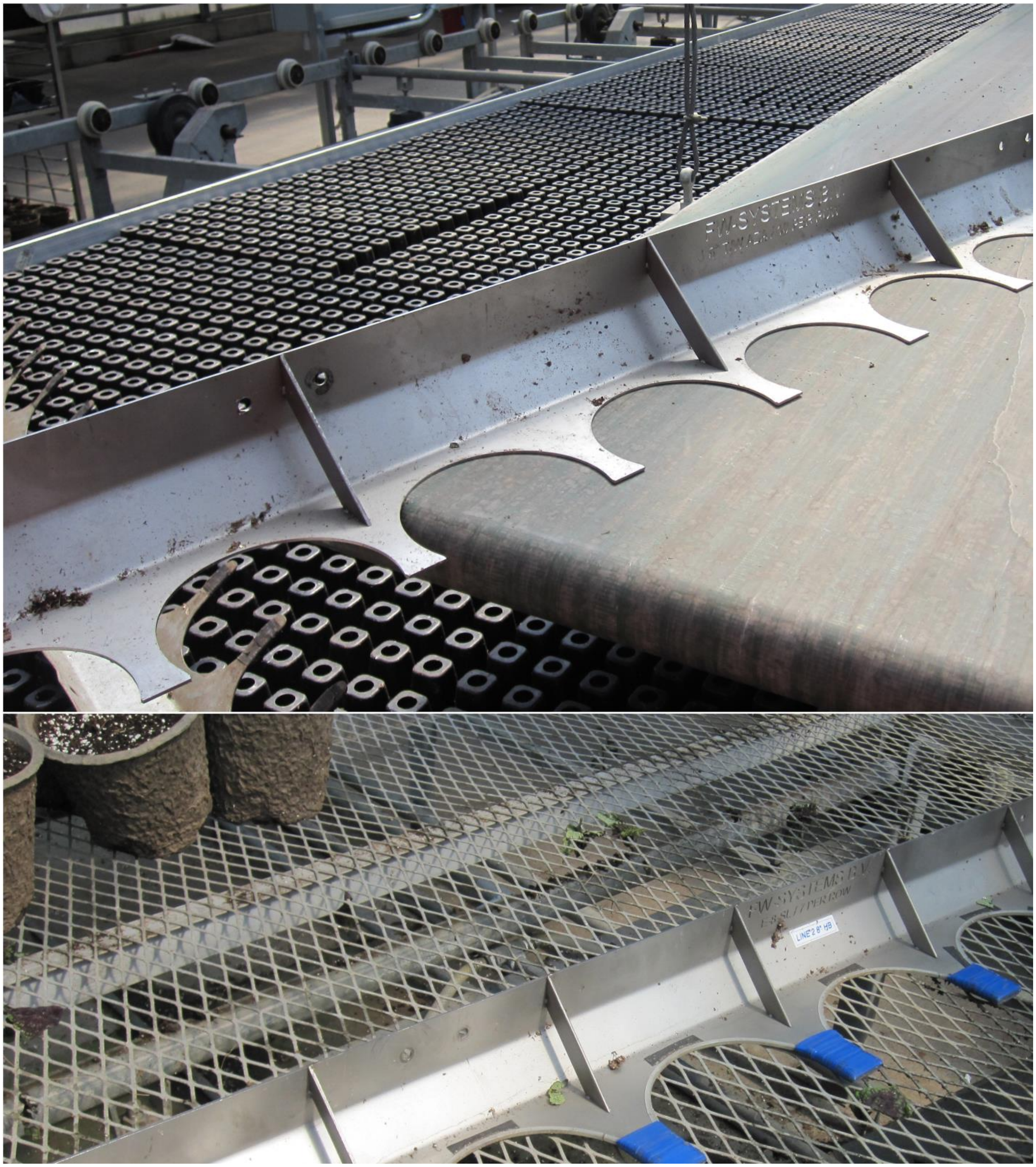
Container type[z]	Avg	SE
Control	1.25	0.047
Bioplastic	1.56**[y]	0.113
Coir	1.30	0.058
Paper	1.32	0.039
Peat	1.81***	0.063
Pressed manure	2.17***	0.095
Straw	2.31***	0.119

[z] Wood fiber containers were not included in the filling analysis as appropriate transport trays were not available for this pot type.

[y] Mean separation was conducted as a left-tailed Dunnett’s test with the plastic container designated as “Control”.

Estimated differences significant at the 0.01 level are denoted with a triple asterisk (***). Estimated differences significant at the 0.05 level are marked with a double asterisk (**).

Fig. A.2. Comparison of (top) 6-inch (15.2 cm) and (bottom) 8 inch (20.3 cm) spacer bars. Incurved tines on the 6" bar made it difficult to achieve clean release of the pressed manure and wood fiber biocontainers after lifting.



MECHANICAL SPACING. Straw and peat containers were excluded from the spacing trial as the proper sized lift bars for these pots were unavailable from the commercial collaborator. This highlights the first of several issues associated with switching to alternate pot types in a commercial facility. Additional capital may be needed to purchase new or modify existing equipment to successfully implement the use of novel pot sizes. Furthermore, the slightly greater than one-half circle slots of many of the metal spacer tines combined with flexibility of the wetted pressed manure and paper containers caused these containers to wedge into slots in the spacer bars, making a clean release after lifting difficult (Fig. A.2). Given some of the complications noted above, no formal statistical analysis is included. However, several insights were gained from this work. In the lifting tests, damage was only seen in the pressed manure containers (2.2%) and occurred as a direct result of the issue with the spacers noted above. Lifting success of the coir containers was 28.8%, paper 69.8%, and wood fiber 91.9%. For the plastic, bio plastic, and pressed manure containers, 99% to 100% of the containers were lifted successfully. For the coir containers, the absence of a lip on the top edge of the pot was a key limitation to lifting success. While paper containers did feature a lip, it was not strong enough to support the container under wetted conditions.

These results show the importance of matching an appropriate spacer bar to the container used in production. Growers are encouraged to work with manufacturers to determine the appropriate spacing equipment for the biocontainer being considered for adoption.

SHIPPING. The proportion of pots damaged during shipping differed with container type (P=0.0002). The overall significance of this factor was driven largely by differences in pressed manure (P=0.0317) and peat pots (P=0.0153) compared to the plastic control. Both of these biocontainers experienced significant losses in shipping, with the former experiencing damage in 27% of the pots measured and the latter recording damage in 35% of the pots measured. Care should be taken when handling and transporting well-watered peat and pressed manure containers, especially after they have been in production several weeks. As such, these containers may be best suited for shorter rotation crops (B. Hayes, personal communication). Damage rates across flexible pots, such as coir, bioplastic, and straw, were higher than expected compared to the control pot treatment (Table A.2). The only containers that outperformed the plastic control in shipping were the paper and wood fiber pots.

GREENHOUSE TRIAL – DRIP IRRIGATION. Neither final leaf area (*P*=0.2804) nor final shoot dry weight (*P*=0.1068) varied significantly by container type. Similarly, above-ground plant volume, a relatively coarse plant growth metric compared to the other two measures, was found to be insignificant (*P*=0.6708). As expected, plant volume increased each week (*P*=0.0003). However, the interaction between week and pot type was non-significant (*P*=0.9632).

Potting mix pH did differ with container type (*P*=0.0515; marginally significant), but was insignificant given week *(P*=0.0895). There was no significant interaction between these two factors (*P*=0.1073). With the exception of the straw containers, which generally had a higher media pH than the plastic control, no clear trends were present in the weekly pH data. Furthermore, while pH was found to be different among containers, the growth data above suggests any alterations to the rooting environment were not of biological significance for the species tested (coleus). EC did vary with week (*P*=0.0316), but not among container types (*P*=0.2284).

The findings from this greenhouse experiment contrast somewhat with published work. Evans and Hensley (2004), found dry shoot weight in plastic containers was generally greater than similar measures for peat- and feather-based pots in a variety of species. Our findings suggest that the biocontainers tested had no impact on coleus growth and development compared with petroleum-based plastic containers. Thus, these biocontainers are suitable replacements for plastic containers from a plant-growth perspective for coleus.

GREENHOUSE TRIAL – HAND, DRIP, AND EBB-AND-FLOOD IRRIGATION. In analyzing the container type and irrigation main effects on above-ground dry weight, only the latter was found to be significant (*P* = 0.033; Table A.4). Neither container type (*P* = 0.268) nor the interaction between irrigation method and container type were significant (*P* = 0.072). *Post hoc* analysis of the dry weight means showed that ebb-and-flood plants were significantly different from drip irrigated plants (P = 0.025) and hand watered plants (P = 0.019). These comparisons were made at a Bonferroni-adjusted, α=0.025 level of type I experimental error.

Table A.4. Mean dry shoot weight (g) with (SE) for 'Florida Sun Jade' coleus (Solenostemon scutellarioides) plants harvested 7 weeks after planting. Plants in each of eight container types (one control and seven biocontainer alternatives) were watered using one of three irrigation methods (i.e., ebb-and-flood, drip, and hand).

Avg dry shoot wt [mean ± SE (g)]

	Irrigation method			
Container type	Ebb-and-flood	Drip	Hand	Avg over method
Control	17.6 ± 6.4	8.0 ± 2.9	8.4 ± 2.6	11.3a^{z} ± 6.1
Bioplastic	18.7 ± 4.3	10.3 ± 4.0	8.8 ± 3.0	12.5a ± 5.8
Coir	15.5 ± 5.7	7.8 ± 2.4	8.2 ± 2.4	10.5a ± 5.2
Pressed manure	19.0 ± 5.2	6.7 ± 2.4	7.3 ± 2.8	10.9a ± 6.7
Paper	12.6 ± 4.0	6.5 ± 2.9	6.9 ± 2.8	8.7a ± 4.3
Peat	13.0 ± 3.9	6.2 ± 2.9	3.9 ± 2.7	7.7a ± 5.0
Straw	12.5 ± 4.1	7.2 ± 2.4	6.3 ± 1.7	8.6a ± 4.0
Wood fiber	17.2 ± 6.9	10.7 ± 4.2	8.2 ± 3.8	12.1a ± 6.4
Avg over container type	15.7a^{z} ± 5.7	7.91b ± 3.4	7.3b ± 3.1	

^{z}Non-significant differences for combined values (at an α=0.05 level of Type I error) are denoted with the same letter.

1 g = 0.0352 oz

While the ebb-and-flood irrigated plants outperformed both their drip- and hand-irrigated counterparts, the effect of irrigation level is admittedly confounded with rate of fertilization (see methods). Fertilization is likely a significant – if not the most significant – contributing factor behind the increased dry shoot weight. As such, it is inappropriate to claim that ebb-and-flood is superior to hand watering and drip irrigation. This said, many meaningful insights can be gleaned from this experiment with regard to container performance within each of the irrigation type. Furthermore, direct comparisons can be made between hand and drip irrigation.

When comparing hand to drip irrigation, neither method offered any significant growth advantage for the species tested. Thus, other considerations such as cost, water consumption, and grower preference should take precedence over concerns of plant performance when choosing either of these two systems for biocontainer-based greenhouse production of coleus. Within any given irrigation method, plant growth (i.e., dry weight) in biocontainers was no different than growth in the conventional plastic control. These results offer further evidence that, from a plant growth perspective, biocontainers can be suitable substitutes for plastic pots. Beyond growth, we did not observe any noticeable deviations in plant coloration or fullness. As such, growers can put more emphasis on considerations like container price and appeal when working to make an informed decision on the costs and benefits of biocontainer adoption.

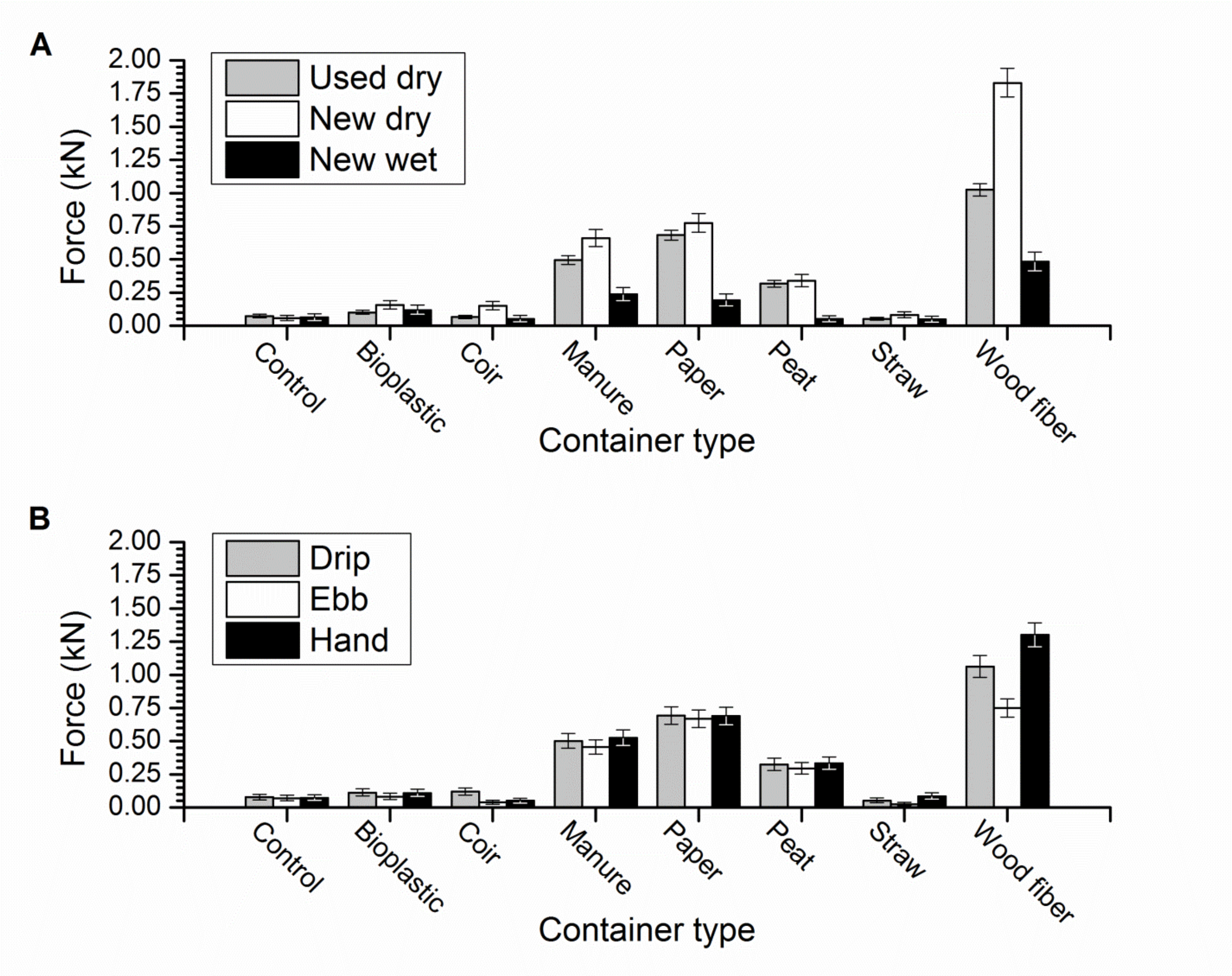
Potting mix pH was significantly impacted by container type (P=0.0009), irrigation method (P = 0.0364), and week (P = 0.0160). However, none of the interactions among these fixed effects were found to be significant. EC did not vary significantly by irrigation method (P = 0.5158), container-type (P = 0.4983), or week (P = 0.5930).

The rise in substrate pH in the ebb-and-flood plants is likely linked to the additional fertilization received prior to leachate collection. Furthermore, fertilization likely masked any container influence for this irrigation level. In this trial, measures of pH were consistently lower in the manure-based containers and higher for straw containers compared with the plastic control. Despite the statistical significance of these differences, it appears that the changes in soil chemistry did not significantly impact coleus growth as quantified with dry shoot weight.

CONTAINER STRENGTH TESTING – HAND, DRIP, AND EBB-AND-FLOOD IRRIGATION. For crush load, the main effects of container type, irrigation method, and the container type X irrigation method interaction were all significant with probability values <0.0001 (Fig. A.3). When looking solely at conventional plastic containers, no significant difference in crush load was found in comparing ebb-and-flood to hand irrigation ($P = 0.7998$) or ebb-and-flood to drip irrigation ($P = 0.6471$). Similarly, post hoc analysis found no significant difference in crush load for bioplastic containers when comparing ebb-and-flood to hand irrigation ($P = 0.1354$) or when comparing ebb-and-flood to drip irrigation ($P = 0.1048$). In contrast, the peak crush load for non-plastic biocontainers (assessed as a group that included coir, manure, paper, peat, straw, and wood fiber) differed given irrigation method. Both hand irrigation ($P < 0.0001$) and drip irrigation ($P < 0.0001$) had significantly higher recorded crush loads than ebb-and-flood containers. Differences in used dry, new dry, and new wet crush strength are noted in Figure A.3. New wet crush strength appears to be significantly diminished (compared to new dry crush strength) in coir, manure, paper, peat and wood fiber pots.

Mean peak puncture loads differed significantly given container type ($P < 0.0001$), irrigation method ($P < 0.0001$), and the container type X irrigation method interaction ($P < 0.0001$; Figure A.4). In *post hoc* comparisons for peat containers, ebb-and-flood irrigation did not significantly impact mean peak puncture load as compared to drip irrigation ($P = 0.1830$) or hand watering ($P = 0.1617$). In contrast, ebb-and-flood watering did significantly (at a Bonferroni-adjusted, $\alpha = 0.0125$) lower puncture resistance in ebb-and-flood manure-based containers when compared to drip irrigation ($P = 0.0125$) and hand watering ($P < 0.0001$). The reduction in puncture strength related to ebb-and-flood irrigation was even more dramatic in paper and wood fiber containers.

Fig. A.3. (A) Mean peak crush load in kilonewtons (with 95% confidence interval bars) for new dry (n=5), new wet (n=3), and used dry (n=15) containers. The used dry category below includes the combined mean and 95% confidence interval for the three different irrigation methods assessed (i.e., drip irrigation, ebb-and-flood table, and hand watering with a wand). (B) Mean peak crush load in kilonewtons (with 95% confidence interval bars; n=5) for a thermoformed plastic control and biocontainer alternatives used to produce a 7-week greenhouse crop under three different irrigation methods (i.e., drip irrigation, ebb-and-flood table, and hand watering with a wand). 1 kN = 224.8089 lbf



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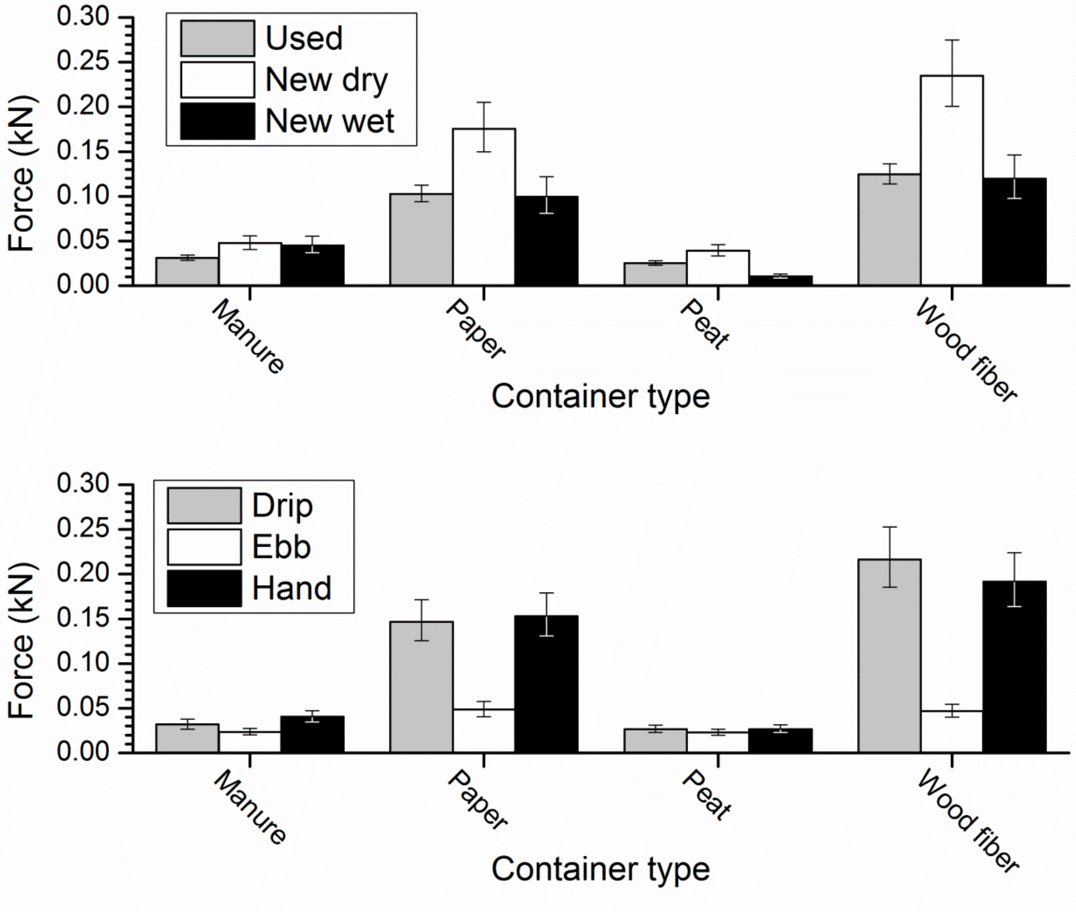

Looking at the strength testing data, it may come as a surprise that the plastic control and bioplastic containers were consistently found to be among the weakest pots. Both were made of thermoformed plastic (control selected as such for the sake of comparison). If a direct-injected plastic container of the same size had been selected as an alternative/second control, it would likely be more resistant to crushing and puncturing. While not as strong with regard to vertical loading as the manure, paper, peat, or wood fiber containers, the plastic, coir, and straw containers were generally more resilient given their flexibility. These properties made them less prone to tearing or rupturing – a notable concern with saturated manure, paper, peat, and wood fiber containers. Instead, plastic, coir, and straw containers tended to invert or fold under pressure. Often, these containers could be re-formed with minimal visible damage.

As mentioned above, plastic, bioplastic, coir, and straw pots were not included in the puncture testing given their resistance to puncturing. For the remaining pots, this test (and the low mean loads it garnered) appears to at least partially justify concerns raised with use of some biocontainers in mechanized production (Fig. A.4). Some production machinery and equipment (i.e., lifters and spacers) concentrate pressure on relatively localized portions of the container wall. Pots prone to puncturing would be less desirable in these settings without workarounds such as the use of shuttle trays during production.

Drip irrigation and hand watering had similar impacts on container structural integrity within the time frame of this study. Accelerated degradation was noted in the ebb-and-flood containers. This may be linked to both the relative abundance of nitrogen and differences in water availability associated with the ebb-and-flood system. As the ebb-and-flood fertilization strategy employed in the study closely mirrors current industry norms, this advanced degradation is noteworthy. Though not assessed in this study, similar degradation may have occurred in the hand-watered and drip-irrigated pots if a constant-feed fertigation strategy had been adopted. These results show that in addition to production cycle length, growers should factor in level of supplemental fertilization when selecting an appropriate biocontainer for their operation.

Conclusion

Despite some statistical differences in the mechanical filling experiment, the biocontainers tested were generally compatible with the machinery used at the study site. Mechanical lifting did prove problematic for both coir and paper containers compared with the plastic control. However, the differences may be at least partially negated though careful selection or development of appropriate spacing equipment. Alternatively, the use of transport/shuttle trays in production may altogether avoid the issues noted in the lifting trial. Finally, the levels of shipping damage seen in some of the containers (e.g., pressed manure and peat) during this study would be a major concern for growers if the damaged containers proved unsellable. From a plant growth perspective, biocontainers appear to be suitable replacements for plastic pots across a variety of irrigation methods. Though not addressed specifically, results suggest that future work should identify what factors, such as fertilization, lead to hastened degradation in some of the containers.

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