HortScience 60(10):1699–1711. 2025. https://doi.org/10.21273/HORTSCI18780-25

Cultivating Sustainability: Biodegradable Containers in Horticultural Production

Emily R. Stamm, Melanie C. Hill, and Paul C. Bartley III
Department of Horticulture, 101 Funchess Hall, Auburn University, Auburn, AL 36849, USA

Sushil Adhikari
Department of Biosystems Engineering, Auburn University, Auburn, AL 36849, USA

M. Soledad Peresin
Forest Products Development Center, School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL 36849, USA

Keywords. basil, consumer behavior, container performance, degradation, plastic, tensile strength

Abstract. **Plastic containers are the standard in the horticulture industry for the production of live goods. However, the COVID-19 pandemic reshaped consumer perspectives on sustainability and environmental responsibility, fueling a surge in gardening interest and prompting scrutiny of plastic use. With increasing global plastic consumption and mounting regulatory pressure, the need to evaluate viable nonpetroleum-based alternatives is growing. This study assessed the performance, durability, degradation, and marketability of six biodegradable or biobased containers composed of peat, wood fiber, coconut coir, cow manure, tapioca starch, and a biopolymer and compared them with traditional plastic containers. Over an 8-week production cycle, plant growth, container mass loss, and mechanical integrity (including dry and wet tensile strength) were monitored, and a consumer preference survey was conducted. Peat and biopolymer containers produced the largest plants, while starch containers supported the least growth and exhibited rapid degradation under wet conditions. Biopolymer containers maintained structural integrity across all time points and had the highest tensile strength in both dry and wet states, with values approaching those of plastic. In contrast, containers made of starch, peat, and manure were significantly weakened by moisture exposure and became brittle with age. Consumer responses shifted over time, with biopolymer and coir containers receiving the highest preference scores by the end of the trial. These findings highlight key mechanical and horticultural differences among alternative containers and support the biopolymer container as a promising substitute for plastic in short-term production systems.**

Since the invention of synthetic polymers in 1869, more than 9 billion tons of virgin plastics have been produced, leading historians to term the current era the "Plastic Age" (Geyer et al. 2017; Pinto da Costa et al. 2020). In 1960, 390,000 tons of plastic were produced in the United States; by 2018, production increased to more than 35 million tons (Environmental Protection Agency 2023a). Of the estimated 35 million tons, containers and packaging were responsible for 14.5 million tons of plastic (Environmental Protection Agency 2023a). It is estimated that 79% of plastic produced has accumulated in landfills or in the natural environment, while 12% has been incinerated and 9% has been recycled (Geyer et al. 2017).

As plastic use in the United States continues to increase, legislation has been considered and approved in New Jersey, California, Oregon, Colorado, and Maine. California legislature enacted two bills, SB-343 and SB-54, as regulatory provisions that restrict environmental advertising on plastic products as well as require reporting the amount of plastic sold and disposed of by producers (California State Senate 2021, 2022). Colorado, Maine, and Oregon have bills that include regulations similar to California's SB-54 regarding reporting plastic sales and disposal amounts (Colorado State Senate 2022; Maine State Senate 2021; Oregon State Senate 2021). New Jersey legislature enacted bill S2515 in 2024, which requires producers to use 10% postconsumer recycled content in rigid plastic containers; however, by 2035, the rate of 10% postconsumer recycled content will increase to 50% postconsumer recycled content (New Jersey State Senate 2022). In addition to the United States, the United Nations Environment Assembly has been drafting a global treaty to end plastic pollution (United Nations Environment Assembly 2022). This treaty is expected to be enacted by the end of 2024 and supplements the UN Agenda for Sustainable Development, which is projected to be fully implemented by 2030 (United Nations Environment Assembly 2022).

During the last half century, plants grown to be sold in various retail stores have been grown in plastic containers. Plastic containers are the standard in the horticulture industry for the production of plants for retail and landscape use because of their ease of processability, shipping, and marketing, in addition to their durability, low cost, and variety of available sizes, shapes, and types of plastic containers (Chappell and Knox 2012; Evans and Karcher 2004; Hall et al. 2010; Kratsch et al. 2015). As a result, more than 800,000 tons of petroleum-based single-use plastics are consumed each year by the greenhouse and nursery industries in the United States (Schrader 2013).

Typically, recycling of plastic horticulture containers is an uncommon practice because of the presence of adhered particles, microbial growth, grease, vegetation, moisture, and pesticides (Hall et al. 2010; Nambuthiri et al. 2015). Unfortunately, ultraviolet light degradation and heat conditions alter the mechanical properties of the plastic materials, thus rendering them "unrecyclable" and subsequently disincentivizing plant producers and retailers to reuse plastic containers (Conneway 2013; Conneway et al. 2015; Soulliere-Chieppo 2020). Approximately 98% of these petroleum-based, nonrenewable, nonbiodegradable containers are disposed of in the landfills within the United State (Schrader 2013). According to the US Department of Agriculture Census in 2009, the number of plant and container units sold was estimated to be more than 3.4 million units of plants and containers (Schrader 2013). Of the number of plant and container units sold, the estimated total plastic weight of flats or containers was 832,088 tons per year (Schrader 2013).

Sustainability has become an increasingly popular topic after the pandemic, which affected consumers' perceptions of sustainability and the impact they have on the environment, especially in the horticulture industry (Bulgari et al. 2021). During the pandemic, consumers were home more than usual, which granted them newfound freedom to explore their interests, including indoor and outdoor gardening. A study performed at the University of Georgia found that approximately 1400 of the 4200 respondents began hobby gardening in 2020 because the pandemic kept them at home (San Fratello et al. 2022). Recent market research suggests that ornamental plant consumers are willing to pay more for nonplastic and recyclable containers, and an increasing number attempt to avoid the use of plastic or opt for products with packaging that is environmentally friendly (Emmert 2021; Fulcher et al. 2015). Despite the growing demand for biobased containers, Hall et al. (2010) reported that although consumers wanted more sustainable or "green" products, they

Received for publication 26 Jun 2025. Accepted for publication 18 Jul 2025.
Published online 29 Aug 2025.
P.C.B. is the corresponding author. E-mail: pcb0004@auburn.edu.

were reluctant to purchase these products because of their perceived low quality.

Sustainable plant containers are divided into three categories: plantable, compostable, and biopolymer (Soulliere-Chieppo 2020). Containers that fall into the plantable category are typically constructed from materials such as coconut coir, cow manure, peat, paper, hemp, rice hulls, and wood pulp (Fuentes et al. 2021; Harris et al. 2020; Soulliere-Chieppo 2020; Woodske 2015). As the name implies, both the plants and their plantable containers are designed to be planted directly into the soil at the end of their life cycle (Fuentes et al. 2021; Harris et al. 2020; Soulliere-Chieppo 2020; Woodske 2015). Plantable containers are appealing because they allow the plant to be transplanted without removing it from the container, minimizing the risk of damaging the roots (Fuentes et al. 2021; Harris et al. 2020; Soulliere-Chieppo 2020; Woodske 2015). Planting the container and plant is also seen as beneficial because it requires less work for the consumer using plantable containers. The next alternative container type requires composting conditions to degrade. Composting is the practice of collecting organic material in the form of wasted food, dry leaves, or untreated wood and combining the organic materials in a pile to begin the degradation process (Solano et al. 2022; Song et al. 2009; Soulliere-Chieppo 2020). The organic material degrades under composting conditions with the aid of temperature, moisture, and microbes, which results in a nutrient-rich soil amendment (Solano et al. 2022; Song et al. 2009; Soulliere-Chieppo 2020). The compostable containers are produced using materials such as rice hulls, poultry feathers, recycled paper or cardboard, bamboo, or other natural fibers (Conneway et al. 2015; Fuentes et al. 2021; Khachatryan et al. 2014; Soulliere-Chieppo 2020; Yue et al. 2010). Compostable containers require a home or industrial compost system to allow biodegradation of the materials (Bulgari et al. 2021; Environmental Protection Agency 2023b; Harris et al. 2020; Solano et al. 2022; Song et al. 2009; Soulliere-Chieppo 2020). An industrial composting facility is a system that allows large-scale composting of a high volume of organic materials (Borelbach et al. 2023; European Standards (EN) 2005; González et al. 2019; Soulliere-Chieppo 2020). Home composting is performed on a smaller scale and typically consists of yard clippings and food waste (Conneway et al. 2015; Environmental Protection Agency 2023a, 2023b; Harris et al. 2020; Nambuthiri et al. 2015; Soulliere-Chieppo 2020; Woodske 2015). Compostable containers can be easily produced in various sizes that are beneficial for the production of larger nursery crops (Conneway et al. 2015; Harris et al. 2020; Nambuthiri et al. 2015; Soulliere-Chieppo 2020; Woodske 2015). Whether composting is practiced at home or at an industrial composting facility, it requires heat, microbes, water holding content, and enzymes that are specific to degrading compostable materials, such as lipases and proteases (Bher et al. 2023; Borelbach et al. 2023; Pratibha et al. 2022; Solano et al. 2022; Soulliere-Chieppo 2020). Biopolymer containers are made of plastic that is derived from or contains plant constituents rather than petroleum (Conneway et al. 2015; Evans et al. 2010; Pires et al. 2022; Silva et al. 2023; Soulliere-Chieppo 2020). Plant producers prefer biopolymer containers because of their strong similarities to traditional plastic containers relating to the consistency, stability, and durability during handling as well as processing and shipping (Harris et al. 2020; Lopez and Camberato 2011; Schrader et al. 2015; Soulliere-Chieppo 2020).

Several sustainable containers are already available on the market and have been evaluated during research conducted in greenhouse and landscape settings (Brumfield et al. 2015; Conneway 2013; Hall et al. 2010; Kratsch et al. 2015; Nambuthiri et al. 2013; Sloan et al. 2010; Wang et al. 2015). Containers previously evaluated include rice straw, rice hulls, paper, peat, coconut coir, composted cow manure, and wood fiber (Brumfield et al. 2015; Conneway 2013; Hall et al. 2010; Kratsch et al. 2015; Kuehny et al. 2011; Nambuthiri et al. 2013; Sloan et al. 2010; Wang et al. 2015). The results of these investigations varied, but the overall conclusion was that most container types produced plants of marketable size and quality; they also showed that low container strength can be attributed to containers made of coir, wood fiber, peat, manure, and straw (Conneway 2013; Kuehny et al. 2011). While some of these sustainable containers are commercially available, an online survey conducted by Harris et al. (2020) found that 83% of horticultural producers do not purchase biodegradable containers. Harris et al. (2020) stated that plant producers do not purchase biodegradable containers because of issues relating to the lack of structural integrity during production, shipping, handling, or in the retail environment, which may result in substantial financial losses.

As a result of the pandemic, the demand for horticultural commodities and sustainably sourced products increased by approximately 8% for landscape and gardening items (San Fratello et al. 2022). Considering the variety of plants grown in varying production cycles and changes in consumer perception, a new investigation of sustainable containers was warranted. This study aimed to evaluate commercially available alternatives to traditional plastic containers in biweekly production intervals using crop performance, material testing, and consumer evaluations to determine their viability in floriculture production systems.

Materials and Methods

Six biodegradable or biobased containers were evaluated with an industry-standard plastic container during an 8-week basil production cycle. The product names, material composition, size, and cost per container evaluated in this trial are located in Table 1. Eighteen units of each container type were individually weighed, labeled, and filled with a peat-based substrate (Sunshine Mix #1; SunGro Horticulture, Agawam, MA, USA).

To evaluate the crop performance, each container received a single basil (*Ocimum basilicum* 'Sweet Green Basil') plug transplant (144-plug size) on 28 Mar 2023. The containers were randomly arranged on a greenhouse bench at the Paterson Greenhouse Complex at Auburn University (US Department of Agriculture Hardiness Zone 8b; Auburn, AL, USA). All containers were fertilized once per week with 250 ppm of 15N–2.185P–12.45K (15-5-15; JR Peters, Allentown, PA, USA) and irrigated with clear water every other day. Leachate electrical conductivity (EC) and pH were collected weekly from three reps of each treatment using the pour-through method (Wright et al. 1990) and a portable pH/EC/total dissolved solids/temperature meter (HI9813-6 and HI1285-6; Hanna Instruments, Smithfield, RI, USA).

Four replications from each treatment were randomly selected for a destructive harvest every 2 weeks. Basil vegetation was cut at the substrate surface for each harvest interval and fresh weights were recorded. The separated containers and basil were then dried at 65 °C for 1 week before obtaining dry weights. Once dried, a rubber spatula was used to loosen and remove any substrate or roots connected to the container walls. Any remaining residues were brushed out with a cloth, with special care taken to avoid damaging the containers. The weights of the dried containers were recorded to calculate gravimetric-based degradation, which was expressed as the percentage of weight lost from initiation to the date of harvest.

Before the final destructive harvest (8 weeks after initiation), the containers were irrigated to capacity and weighed; then, time to wilt was recorded. Wilt was determined to have occurred when the third mature leaf from the apical bud lost turgidity and flagged. Once plants wilted, the containers (including substrate and plant material) were weighed again and rehydrated before destructive harvest. The container water loss rate was calculated using Eq. [1]. The net water lost from each container, including plant uptake and evaporative loss, was normalized by the plant dry weight and time to wilt to account for differences in container volume, water holding capacity, and plant size across treatments. This metric is expressed as grams of water lost per gram of plant dry weight per hour.

$$\textit{container water loss rate} = \frac{\dfrac{\textit{container wet weight}\,(g) - \textit{container dry weight}\,(g)}{\textit{plant dry weight}\,(g)}}{\textit{time taken for plant to wilt}\,(\textit{hours})} \qquad [1]$$

Materials testing

Following each harvest date, specimens of each container were subject to tensile strength testing to evaluate changes in material characteristics under dry and wet conditions caused by degradation. Each harvested container was cut into six rectangular test specimens with a width of 1 cm and a length of at least 4 cm. A specimen is defined by American Society for Testing and Materials (ASTM) as "a piece or portion of a sample

Table 1. Physical characteristics, composition, and unit cost of biodegradable, biopolymer, and plastic horticultural containers evaluated in the study.

Product	Composition	Container diam (cm)	Container volume (mL)	Cost per container[i]
CowPot	Composted cow manure	12.7	825	$ 0.51
FertilPot	Wood fiber	10.2	500	$ 0.45
EverEco	Tapioca starch	8.9	270	$ 0.75
PlantBest	Coconut coir	11.4	580	$ 0.12
BioPax	Wood pulp and additives	10.2	600	$ 2.50
Jiffy	Peat	12.7	1,350	$ 0.83
Control	Plastic	10.2	600	$ 0.26

[i] Container costs reflect unit prices at the time of purchase and were sourced directly from manufacturer or distributor websites. Prices may not reflect current market values or wholesale pricing.

used to make a test" (American Society for Testing and Materials 2023). After the specimens were cut, they were conditioned in the testing environment (23 ± 2.0 °C and relative humidity of 50%) for at least 40 h before performing the test.

Horticultural containers must maintain structural integrity throughout the production cycle to support plant growth, withstand handling, and facilitate transplanting. The mechanical properties of these containers determine their durability, resistance to environmental stresses, and overall suitability for greenhouse and nursery production. In this study, the following four key mechanical properties were evaluated: force at max load; tensile strength; modulus of elasticity and elongation at break. Force at max load represents the maximum force a container can withstand before failure, providing insight into its load-bearing capacity. Tensile strength measures a material's resistance to breaking under tension normalized by its cross-sectional area, indicating its ability to withstand handling and external forces. Modulus of elasticity (MOE) describes a material's resistance to elastic deformation, indicating its stiffness and ability to return to its original shape after stress is applied. Elongation at break (EAB) quantifies the material's ability to stretch before failure, providing an indication of its brittleness or ductility. Together, these mechanical properties help determine a container's suitability under production conditions. Containers with high tensile strength and MOE may be more durable but less flexible; however, those with a high EAB can withstand deformation but may be more prone to gradual structural weakening. Evaluating these properties within biodegradable, biopolymer, and plastic containers over time and under varying moisture conditions provides critical insights into their suitability for horticultural use.

Tensile testing of dry specimens was performed after conditioning using an electromechanical tension and compression machine (model 5565; Instron, Norwood, MA, USA). Wet specimens were submerged in water for 105 min before being air-dried for approximately 60 min before testing. Testing began by securing the specimens with clamps (~1.5–2 cm away from the edge of the specimen) to the load frame and concluded when the samples failed (i.e., broke or began to stretch). Each test was performed with the utmost care while handling samples to ensure sample integrity. However, material integrity changed throughout the study, which resulted in inconclusive data from more fragile, degraded materials. For example, the starch containers became more gelatin-like after soaking and could not be tested.

Scanning electron microscopy

The traditional plastic containers and biopolymer containers were examined using a scanning electron microscope (EVO 50; Zeiss Optical, Pleasanton, CA, USA) at weeks 0, 4, and 8 to evaluate the physical characteristics of degradation (Borelbach et al. 2023). The acceleration voltage was 20 kV. Three 1-cm × 1-cm square specimens from each treatment and harvest date were evaluated.

Consumer survey

At each harvest interval, a survey was conducted postharvest (plant and substrate removed) to gauge consumer appeal for each empty container type. Each survey consisted of at least 12 volunteers who were students or employees of Auburn University. The containers were assigned a number, and participants were asked to evaluate each corresponding container based on their likelihood to purchase a plant presented in that container. Participants scored their likeliness to purchase a plant in each container using a Likert scale of 1 to 5, with "1" indicating very unlikely and "5" indicating very likely. To conclude the survey, participants were asked to rank the containers from most to least attractive, with "1" indicating most attractive and "7" indicating least attractive.

Statistical analysis

All data were subject to an analysis of variance (ANOVA) within the PROC GLIMMIX procedure of SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The following metrics were analyzed by harvest date (i.e., week 0, week 2, week 4, week 6, week 8): plant growth metrics; plant dry weight; container degradation by percent of weight loss; and leachate pH and EC. Tensile testing data were analyzed by container type. Means were separated using Tukey's honest significant difference (HSD) at a 5% alpha level.

Results and Discussion

Basil growth

Both plant growth indices and dry weight were affected by an interaction of time × container ($P < 0.0001$), indicating that both harvest week and container type had an impact on basil growth (Figs. 1 and 2). There were no significant differences in growth indices between container types for harvest week 2 (Fig. 1). However, by week 4, the growth index of basil grown in manure, coir, biopolymer, peat, and plastic was higher than that of basil produced in starch containers. Basil growth indices increased significantly from week 4 to week 6. The most significant increases in growth were observed in basil transplanted in peat and manure containers, with increases of 4653.5 cm^3 and 4095.2 cm^3 from week 4 to week 6. Basil grown in coir containers had a mean growth index of 3888.6 cm^3, which was similar to that of plastic and biopolymer containers, which averaged 3190.9 cm^3 and 3169 cm^3, respectively, in week 6. Basil growth indices in starch containers were limited, with an increase of 611.5 cm^3 between week 4 and week 6. A slight numerical decrease in average growth indices was recorded across all

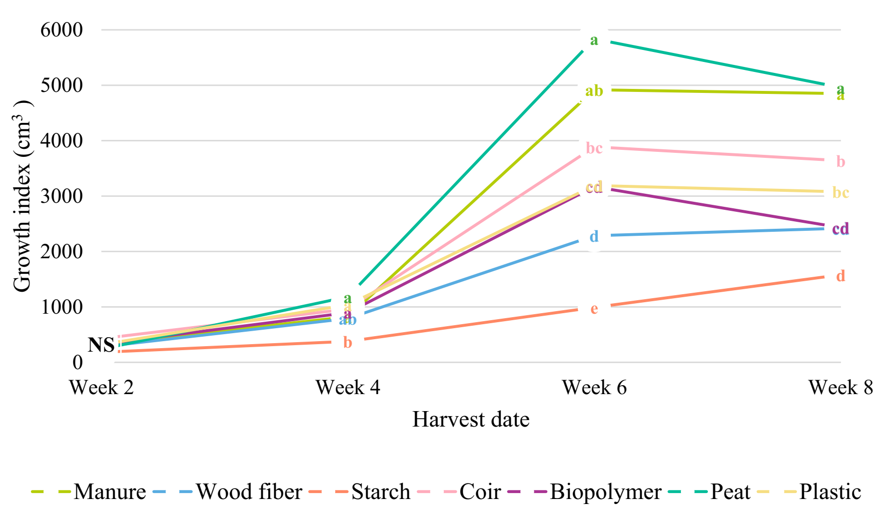

Fig. 1. Average growth indices for plants grown in each container type by harvest week determined by measuring plant height and two perpendicular widths. Means within a harvest week that share a letter are not significantly different ($P > 0.05$).

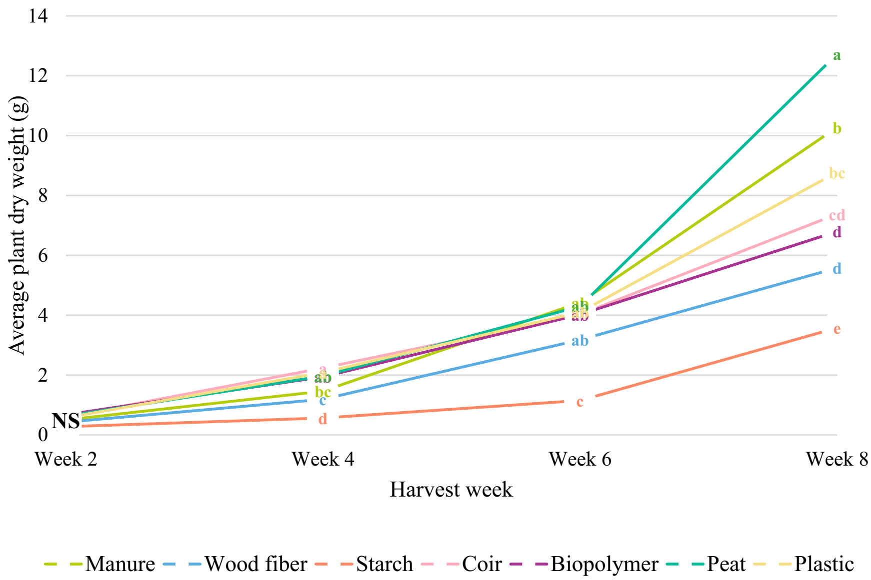

Fig. 2. Average dry weight of the four harvested reps from each container type at each 2-week harvest interval. Means within a harvest week that share a letter are not significantly different ($P > 0.05$).

treatments between week 6 and week 8, except for starch, which increased 590.1 cm^3.

Basil dry weights were similar across all container types 2 weeks after transplant (Fig. 2). Although differences in basil dry weight by container types were recorded at week 4 and week 6, manure, wood fiber, coir, biopolymer, peat, and plastic containers all demonstrated similar positive growth trends, suggesting that each container type provided adequate support for basil growth during this period. By week 8, basil grown in peat containers produced the most biomass (12.5 g). Manure containers produced basil with an average dry weight of 10.2 g, similar to plastic containers, which had an average dry weight of 9.2 g. Coir, biopolymer, and wood fiber containers produced basil with similar dry weights of 7.5 g, 6.8 g, and 5.5 g, respectively. Beyond week 2, basil grown in starch containers were least productive and yielded less biomass compared to basil grown in other container types.

The observed differences in basil growth indices and dry weight across container types likely stemmed from volumetric variations (Table 1) that limited root development space and restricted water and nutrient availability. In early growth stages, these differences were minimal, indicating that container volume became more impactful as plants matured. The smallest container, starch, produced the smallest plants with the least biomass (Table 1, Figs. 1 and 2), while the largest containers, peat and manure, supported the largest plants with the greatest biomass. Among similarly sized containers (plastic, biopolymer, and coir), basil grown in coir containers was slightly larger than basil grown in plastic or biopolymer at weeks 6 and 8 (Fig. 1). However, despite this slight size advantage, coir-grown plants showed dry weights similar to those in plastic and biopolymer at week 6, with plants in plastic containers surpassing coir in weight by week 8 (Fig. 2). Container volume also affected water retention capacity, necessitating increased irrigation after week 6 to prevent water stress in smaller containers. Plant volume did not significantly increase after week 6; except for starch containers, basil growth indices remained steady or decreased from week 6 to week 8. Despite these size decreases, basil dry weight increased markedly over this period, with some treatments tripling dry weight between weeks 6 and 8, further linking growth trends to container volume. Additionally, water loss through container walls may have influenced growth and weight because porous biodegradable containers allow evaporation that reduces plant-available water, thus affecting plant growth (Evans et al. 2010).

The rate at which containers lost water was significantly different between container types ($P < 0.0001$). Wood fiber containers had the highest rate of water loss, with an average of 1.07 mL/g plant dry weight/hour (Fig. 3). Manure, peat, and starch containers had similar water loss rates of 0.7 mL/g plant dry weight/hour, 0.65 mL/g plant dry weight/hour, and 0.56 mL/g plant dry weight/hour, respectively. Coir containers lost water at an average rate of 0.46 mL/g plant dry weight/hour, which was statistically similar to that of polymer-based containers. The lowest rate of water loss was observed in biopolymer and plastic containers which had mean water loss rates of 0.32 mL/g plant dry weight/hour and 0.31 mL/g plant dry weight/hour, respectively.

Previous trials that investigate nonplastic containers have yielded similar findings regarding water use efficiency (Evans et al. 2010; Koeser et al. 2013). In these studies, plants such as geraniums, impatiens, and lavender demonstrated the highest water use efficiencies when grown in plastic or plastic-like materials, such as rice hull biopolymer (Evans et al. 2010; Koeser et al. 2013). Wood fiber containers required up to 50% more water to produce similar plant growth compared with that in plastic containers (Koeser et al. 2013), while manure, peat, paper, and coir containers exhibited similarly elevated water

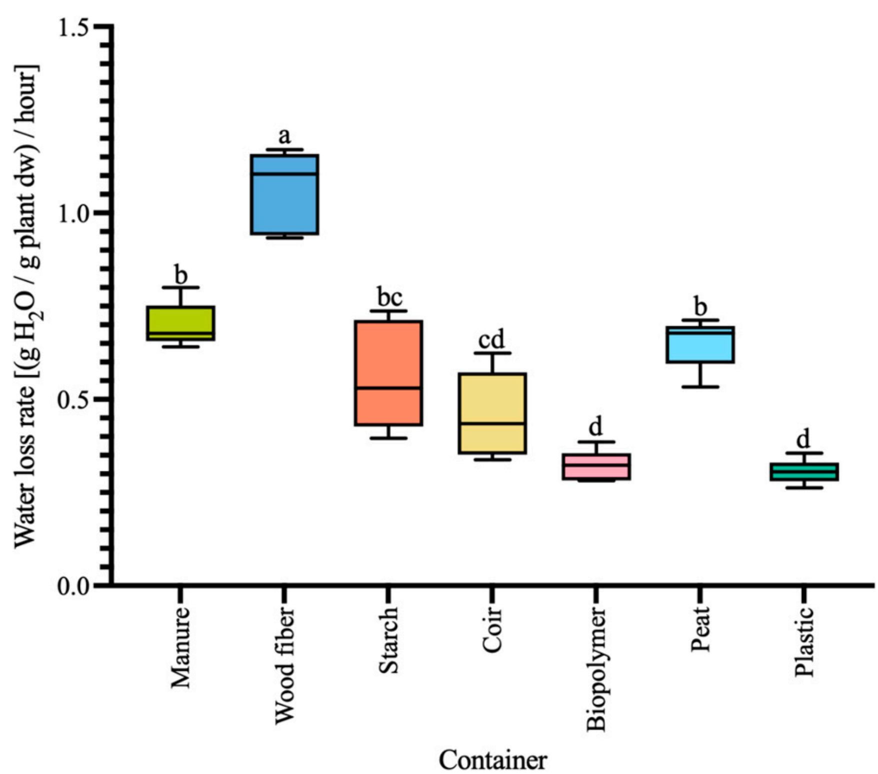

Fig. 3. The total net water lost from each container, including plant uptake and evaporative loss, was normalized by the plant dry weight and time to wilt to account for differences in container volume, water holding capacity, and plant size across treatments. This metric is expressed as grams of water lost per gram of plant dry weight per hour. Container types that share a letter did not have significantly different ($P > 0.05$) water loss rates.

loss rates relative to that of plastic (Evans et al. 2010; Koeser et al. 2013). In this study, water loss rates were even higher than those previously reported, with some containers losing water three-times faster than plastic and biopolymer containers. Notably, coir fiber containers performed comparably to plastic and biopolymer containers in this trial. This variation in the reported water use efficiency of coir fiber containers may be attributed to differences in material sourcing and the thickness of their laminated fiber walls. Overall, these findings support the conclusion that containers made from permeable bio-based materials, such as wood fiber, manure, peat, and coir, tend to exhibit higher evaporative water loss rates than those of impermeable solid polymer-based materials. This distinction in water retention has important implications for container selection in sustainable horticultural practices, particularly when water conservation is a priority.

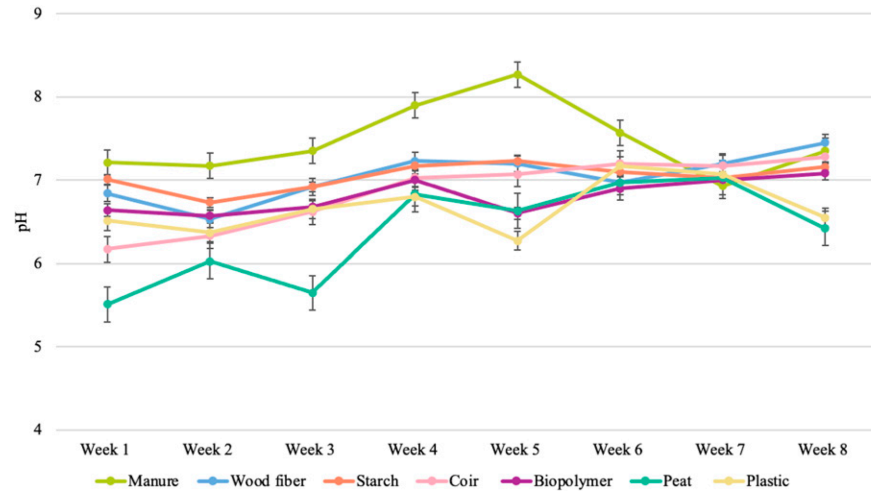

Fig. 4. Changes in leachate pH over an 8-week growing trial. Leachate was collected from three reps per container type via the pour-through method on a weekly basis for the duration of the 8-week trial.

Leachate pH and EC

Significant differences were observed between the average pH of leachates from different container types ($P < 0.0001$). The pH of leachate from manure containers was significantly higher than that of leachate from all other container types for weeks 1 to 6 (Fig. 4). At week 7, there were no significant differences in leachate pH across all container types. All containers except for plastic and peat had similar leachate pH values at week 8. Wood fiber, starch, coir, and biopolymer containers had similar leachate pH ranges throughout the 8-week trial.

Significant differences were observed between the average EC of leachates from different container types ($P < 0.0001$). The EC of leachate from all container types decreased from week 1 to week 8 (Fig. 5). All containers except for manure and wood fiber containers experienced a decline in leachate EC from week 1 to week 2. The highest average leachate EC observed was collected from wood fiber containers at week 2, and the lowest average leachate EC was collected from biopolymer containers at week 5. With the exception of week 4, biopolymer and plastic containers had the lowest EC readings.

For optimum nutrient availability, container media should have a pH between 5.5 and 6.5 (Mattson n.d.). Basil specifically prefers a substrate pH of 5.8 to 6.2 and an EC of 1.3 to 2.0 mS/cm (Owen et al. 2018). According to the means of container leachate pH by week, only eight of the 56 averages were in the optimum substrate pH range for nutrient availability. Of those eight averages, only two were in basil's preferred substrate pH range. Only two of the average EC readings were in the optimum EC range for basil. While no problems arose from pH and EC values outside of basil's preferred range, nonoptimal pH and EC may lead to nutrient toxicities/deficiencies or salt stress that may impact plant growth and lead to poor plant health.

A previous study using biodegradable containers for greenhouse production demonstrated that the pH collected from all container types decreased from the beginning to the end of the study, whereas the pH in this study slightly increased from the beginning to the end of the study (Conneway 2013). In the previous study, manure containers had the highest leachate pH, while peat and plastic containers had the lowest pH; these findings are similar to the findings of this study. Unlike the EC values of this study that experienced an overall decrease, the previous study observed an increase in leachate EC throughout the study.

Container degradation

Degradation occurred rapidly in the biodegradable containers during the greenhouse experiment (Fig. 6). Significant differences in the amount of weight lost were observed between container types at each harvest week ($P < 0.0001$). All container types, with the exception of plastic, lost at least an average of 2% of their original weight by week 2 (Fig. 7). Despite being the most similar to plastic, the biopolymer containers had lost, on average, 6% of the original weight by week 2, whereas the original weight of plastic containers remained unchanged. Starch containers lost significantly more weight than all other container types by week 2, with an average weight loss of 12.3%. By week 4, starch containers had lost significantly more weight than all other container types except for manure containers. By week 4, plastic containers lost an average of approximately 1.5% of their initial weight, but the average amount of weight lost by plastic containers was not significantly different from the average amount of weight lost by wood fiber, coir, biopolymer, and peat containers. The similarity between wood fiber, biopolymer, peat, and plastic containers continued at week 6. By

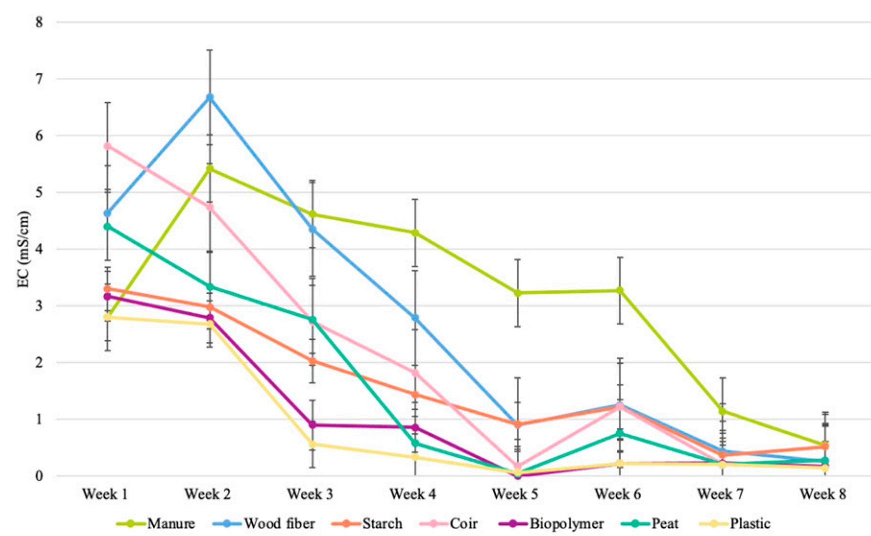

Fig. 5. Changes in leachate electrical conductivity (EC) over an 8-week growing trial. Leachate was collected from three reps per container type via the pour-through method on a weekly basis for the duration of the 8-week trial.

Fig. 6. Progression of plant size and container condition at each harvest interval. Photos were taken of the replicates collected for destructive harvest every 2 weeks. The most representative plant and container from each treatment at each harvest week were cropped and compiled into the figure to illustrate changes in plant growth and container state over the duration of the study.

week 8, starch containers had lost significantly more weight than all other containers, with an average loss of 34.2%. Plastic containers had lost an average of 5.2% of their original weight by the end of the study, but they still were not significantly different from wood fiber, coir, and peat containers.

Five of the seven container types evaluated in this study are classified as biodegradable, meaning they can decompose through physical or chemical processes facilitated by microorganisms within 1 year (American Society for Testing and Materials 2012). The rate and extent of degradation are influenced by environmental factors such as moisture, heat, and light (Wojnowska-Baryła et al. 2022). Horticultural containers are consistently exposed to these elements throughout production cycles, leading to material degradation over time. While previous studies of nonplastic containers have focused on biodegradation following field planting, limited research has examined the structural changes that occur during the greenhouse production phase (Evans et al. 2010). Understanding these changes is essential because premature degradation could affect container integrity, water retention, and overall plant health during production.

Polypropylene, one of the primary plastics used in horticultural containers, is susceptible to thermal degradation under typical greenhouse conditions. Prolonged exposure to heat, light, and moisture can trigger chain scission, reducing polymer molecular weight and ultimately leading to structural weakening (Zeus Inc. 2005). This degradation can affect the performance of plastic containers, potentially making them more brittle over time and influencing their durability in extended

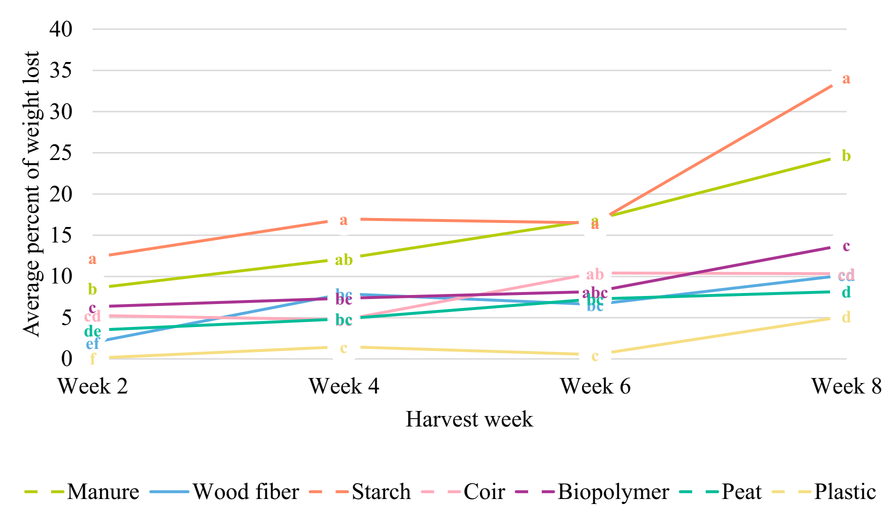

Fig. 7. Average percent of weight lost from containers at each harvest date to estimate container degradation. Each container was weighed before planting and again after being dried and cleaned out after destructive harvest. Percent of weight loss was calculated by subtracting the end weight from the initial weight and dividing by the initial weight.

production cycles or reuse scenarios. Additionally, fragmentation resulting from plastic degradation can produce microplastics, which may be released into soil or water systems (Wei et al. 2021). The environmental impact of microplastic accumulation is an area of growing concern because of their ability to adsorb contaminants such as heavy metals, pesticides, and pharmaceutical residues (Wojnowska-Baryła et al. 2022). Once introduced into the environment, microplastics can be taken up by plants and transferred through the food chain, with potential implications for human and animal health (Mohamed et al. 2021; Yu et al. 2021).

Mechanical properties

Maximum force. The maximum force or stress that a material can withstand may vary by its composition, condition, and structural dimensions. These values most accurately reflect the true strength of a container when lifted by its lip from a single point of contact (i.e., lipping a container). Across most container types, strength declined with age, particularly under wet conditions. Age was a significant factor for all containers except those made of manure and coir (Table 2). Moisture condition (dry vs. wet) significantly affected all container types except plastic ($P = 0.4862$). The age × condition interaction was significant for all containers except manure, coir, and plastic, indicating that material failure did not uniformly worsen with age and moisture for several container types.

Polymer containers, both plastic and biopolymer, maintained their structural integrity throughout the 8-week trial. Plastic containers showed minimal change over the 8-week trial. The highest force values were recorded at week 4, with a 12% increase in maximum force from week 0, and remained significantly higher at week 8. Biopolymer containers demonstrated the highest maximum force strength of the materials tested, withstanding 404 N to 623 N of tension, which was nearly double that of plastic containers. Significant increases in its load capacity over time under dry conditions were recorded, indicating material hardening. Although wet conditions consistently lowered biopolymer's maximum force strength by approximately 20% to 30%, the overall trend indicated increased durability over time.

In contrast, biodegradable containers showed a consistent and substantial decline in performance. Containers made of wood fiber, peat, coir, starch, and manure all exhibited declining force values with age when dry. Of these biodegradable options, starch containers initially exhibited the highest maximum force, withstanding up to 77 N, followed by peat at 59 N. By week 8, peat containers under dry conditions withstood 36 N of force, while both wood fiber and starch containers withstood 23 N, indicating greater retention of strength in peat over time. All biodegradable containers exhibited losses in strength because of moisture. Starch containers demonstrated complete structural loss under wet conditions and became untestable. Peat containers at week 8 and coir containers at week 4 were capable of withstanding 14 N of force, which was the highest recorded values for biodegradable containers in a hydrated state.

Tensile strength. The tensile strength of a material may vary by its composition, condition, and thickness because it is a value acquired through normalizing the maximum force by cross-sectional area. The average thicknesses of containers (in mm) were as follows: manure, 4.7 ± 0.79; wood fiber, 1.69 ± 0.21; starch, 2.52 ± 0.54; coir, 3.19 ± 1.16; biopolymer, 1.13 ± 0.18; peat, 2.64 ± 0.48; and plastic, 0.64 ± 0.13. Like maximum force, tensile strength decreased with age for most container types. Age was a significant factor for all container types except for manure, coir, and plastic (Table 3). The tensile strengths of all container types except for biopolymer and plastic were significantly ($P \leq 0.05$) impacted by moisture conditions, and all container types except for manure and plastic were significantly impacted by an age × moisture condition interaction.

Plastic containers exhibited no significant changes in tensile strength over time for either moisture condition or in between moisture conditions for any age, with strengths between 24.18 MPa and 29.89 MPa. Biopolymer containers showed an increase in strength over time for both moisture conditions, with strength values between 23.4 MPa and 33.94 MPa. The consistent strength of plastic containers and the increasing strength of biopolymer containers indicated the reliability of these two container types for 8-week production cycles. Biodegradable containers made from manure, wood fiber, starch, coir, and peat had initial strengths between 170% and 197% lower than that of the initial strength of plastic, and they all showed a progressive decline in strength over time as well as when

Table 2. Effects of container age and moisture conditions on the load-bearing capacity of biodegradable, biopolymer, and plastic horticultural containers.[i]

					Force at max load (N)		
					Age (weeks)[ii]		
Container	Week	Effects Condition	Week × condition	Condition[iii]	0	4	8
Manure	$P = 0.1360$	P **< 0.0001**[iv]	$P = 0.8162$	Dry	9.43 a[v]	8.21 a	8.41 a
				Wet	3.57 b	2.92 b	2.32 b
Wood fiber	$P < 0.0001$	$P < 0.0001$	P **< 0.0001**	Dry	40.45 a	17.64 c	22.88 b
				Wet	3.72 d	4.22 d	5.80 d
Starch	P **< 0.0001**	—	—	Dry	76.78 a	49.27 b	22.96 c
				Wet	—	—	—
Coir	$P = 0.3771$	$P =$ **0.0070**	$P = 0.1041$	Dry	26.91 a	21.55 a	12.80 a
				Wet	6.75 b	14.00 b	10.97 b
Biopolymer	$P < 0.0001$	$P < 0.0001$	$P =$ **0.0270**	Dry	404.48 c	542.68 b	622.93 a
				Wet	296.45 d	446.65 c	451.12 c
Peat	$P < 0.0001$	$P < 0.0001$	P **< 0.0001**	Dry	59.38 a	45.53 b	36.48 c
				Wet	16.83 d	10.77 d	14.17 d
Plastic	P **< 0.0001**	$P = 0.4862$	$P = 0.4873$	Dry	230.46 c	260.23 a	245.59 b
				Wet	218.99 c	258.83 a	242.13 b

[i] Each harvested container was cut into six rectangular test specimens (1 in × 4 in) and conditioned at 23 ± 2.0 °C and 50% relative humidity for 40 h before testing. Tensile testing was conducted using an Instron 5565 electromechanical machine (Instron, Norwood, MA, USA).

[ii] Containers were transplanted with a single basil (*Ocimum basilicum* 'Sweet Green Basil') plug (144-plug size) on 28 Mar 2023. They were fertilized weekly with 250 ppm 15N–2.185P–12.45K (JR Peters, Allentown, PA, USA) and irrigated every other day. Four replicates per treatment were destructively harvested every 2 weeks over 8 weeks.

[iii] All samples were conditioned (23 ± 2.0 °C, 50% relative humidity) for 40 h before testing. Dry specimens were tested following conditioning. Wet specimens were submerged for 105 min, air-dried for 60 min, and tested.

[iv] Data were analyzed using an analysis of variance (PROC GLIMMIX; SAS 9.4, SAS Institute Inc., Cary, NC, USA). P values indicate the significance of main effects (week, condition) and their interaction (week × condition) within each container type. Bold P values denote significant effects ($P \leq 0.05$), with corresponding mean separation letters in the subsequent columns. Tukey's honest significant difference (HSD) ($\alpha = 0.05$) was used for mean separation.

[v] Means within a container type with the same letter do not differ significantly ($P > 0.05$). Dashes (–) indicate that tensile testing was not conducted for starch containers under wet conditions because of rapid degradation and structural failure during the trial.

Table 3. Effect of container age and moisture conditions on the tensile strength of biodegradable, biopolymer, and plastic horticultural containers.[i]

	Effects				Tensile strength (Mpa)		
					Age (weeks)[ii]		
Container	Week	Condition	Week × condition	Condition[iii]	0	4	8
Manure	$P = 0.2297$	**$P < 0.0001$**[w]	$P = 0.4888$	Dry	0.16 a[v]	0.22 a	0.15 a
				Wet	0.06 b	0.05 b	0.04 b
Wood fiber	$P < 0.0001$	$P < 0.0001$	**$P < 0.0001$**	Dry	1.93 a	0.92 b	0.89 b
				Wet	0.17 c	0.21 c	0.24 c
Starch	**$P < 0.0001$**	—	—	Dry	1.91 a	1.45 b	0.81 c
				Wet	—	—	—
Coir	$P = 0.0726$	$P = 0.0007$	**$P = 0.0182$**	Dry	1.22 a	0.71 ab	0.34 ab
				Wet	0.18 b	0.37 b	0.25 b
Biopolymer	$P < 0.0001$	$P = 0.5788$	**$P = 0.0066$**	Dry	24.69 bc	29.17 bc	33.94 a
				Wet	23.40 c	31.47 ab	29.72 ab
Peat	$P < 0.0001$	$P < 0.0001$	**$P < 0.0001$**	Dry	1.82 a	1.33 b	1.13 b
				Wet	0.53 c	0.33 c	0.47 c
Plastic	$P = 0.0857$	$P = 0.1583$	$P = 0.2599$	Dry	24.37 ns	28.87	24.18
				Wet	28.89	29.89	29.31

[i] Each harvested container was cut into six rectangular test specimens (1 in × 4 in) and conditioned at 23 ± 2.0 °C and 50% relative humidity for 40 h before testing. Tensile testing was conducted using an Instron 5565 electromechanical machine (Instron, Norwood, MA, USA).

[ii] Containers were transplanted with a single basil (*Ocimum basilicum* 'Sweet Green Basil') plug (144-plug size) on 28 Mar 2023. They were fertilized weekly with 250 ppm 15N–2.185P–12.45K (JR Peters, Allentown, PA, USA) and irrigated every other day. Four replicates per treatment were destructively harvested every 2 weeks over 8 weeks.

[iii] All samples were conditioned (23 ± 2.0 °C, 50% relative humidity) for 40 h before testing. Dry specimens were tested following conditioning. Wet specimens were submerged for 105 min, air-dried for 60 min, and tested.

[iv] Data were analyzed using an analysis of variance (ANOVA) (PROC GLIMMIX, SAS 9.4; SAS Institute Inc., Cary, NC, USA). *P* values indicate the significance of main effects (week, condition) and their interaction (week × condition) within each container type. Bold *P* values denote significant effects ($P \leq 0.05$), with corresponding mean separation letters in the subsequent columns. Tukey's honest significant difference (HSD) ($\alpha = 0.05$) was used for mean separation.

[v] Means within a container type with the same letter do not differ significantly ($P > 0.05$). Dashes (–) indicate that tensile testing was not conducted for starch containers under wet conditions because of rapid degradation and structural failure during the trial.

NS = not significant.

moisturized. Because strength declined with age and because of the drastic difference in initial strength between biodegradable and industry standard plastic containers, it can be inferred that manure, wood fiber, starch, coir, and peat containers, as they currently exist, do not have adequate strength or durability for even short-term production cycles.

Containers in this trial were handled with care to avoid breakage during the production window. As a result, all container types survived being handled and used for growing. However, it is important to recognize that this is not representative of a commercial production environment, and that the containers may respond differently. In a commercial production setting, containers would be set in trays, which would reduce the stress on the containers themselves but might allow for the pooling of water at the base of containers in the trays, which would accelerate a loss in tensile strength. Containers with low initial tensile strength have the potential to break during automated denesting caused by the force exerted on the rims or bottoms of containers to pull them apart. Aged materials with low tensile strengths also have the potential to break along the base and/or sidewalls if their holding trays are handled roughly or if a single container is pulled from the holding tray.

Modulus of elasticity. The MOE describes a container's stiffness by reflecting how resistant it is to bending or flexing when handled. Container elasticity varied across container types and was influenced by both moisture condition and age (Table 4). The MOEs of manure and wood fiber containers were influenced by moisture conditions, but not by age. In contrast, the MOEs of starch and coir containers were impacted by age, but not by moisture condition. Peat, biopolymer, and plastic containers indicated changes in stiffness over time depending on the hydration condition of the material.

Plastic and biopolymer containers maintained consistent elasticity over the 8-week trial. Initial MOE values under dry conditions were not significantly different from those recorded after 8 weeks in either moisture condition. The MOE for these polymer containers ranged from approximately 1200 MPa to more than 2000 MPa, with the highest recorded values for biopolymer recorded in week 4 (2086 MPa) and for plastic in week 0 and week 4 (2125 MPa and 2112 MPa, respectively). Overall, polymer containers were three-times to 50-times more resistant to deformation than the biodegradable alternatives evaluated in this study.

Containers made of starch, wood fiber, peat, coir, and manure demonstrated decreased elasticity over time or when exposed to moisture. The MOE of starch containers declined steadily from week 0 to week 8, indicative of the gradual degradation of the material. Manure and wood fiber containers exhibited a significant decrease in MOE when hydrated, declining by more than 90%. Peat containers also experienced significantly lower MOE values under wet conditions compared with dry conditions, thus underlining the susceptibility of biodegradable materials to moisture-induced softening. Coir containers were the exception to this susceptibility. However, age alone significantly reduced their stiffness, which was visibly apparent as the fibers delaminated over the course of the trial.

Elongation at break. The EAB depicts the ability of a material to elongate or stretch without fracturing or failing. Specifically, the percentage of elongation or stretch of the material before breakage is recorded. The ability of container types to resist deformation without breaking was impacted by age and moisture condition (Table 5). Age alone did not impact the EAB of wood fiber or plastic containers, and moisture condition alone did not impact the EAB for biopolymer or plastic containers. The EAB of all container types, except for manure, was impacted by an age × moisture condition interaction.

New dry plastic containers were less ductile than those after 8 weeks, and they were capable of stretching only 24.85% of their original length before breaking compared with 47.16% for older containers. The opposite trend was observed in hydrated plastic containers: EAB decreased from 46.36% in new containers to 24.58% by week 8. Biopolymer and biodegradable containers are brittle relative to petroleum-based plastic. However, among the alternatives, biopolymer containers were the most ductile, with an EAB of 13.51% at week 8 under wet conditions. All biodegradable containers exhibited an EAB less than 9%, with starch containers stretching the least (0.76%) at week 8.

As with many of the metrics evaluated, biodegradable materials were incapable of withstanding significant force without failure. Biopolymer containers, however, performed comparably to plastic containers in terms of force at max load, tensile strength, and MOE. Despite their similarities, biopolymer containers

Table 4. Effect of container age and moisture conditions on the modulus of elasticity of biodegradable, biopolymer, and plastic horticultural containers.[i]

Container	Effects Week	Effects Condition	Effects Week × condition	Condition[iii]	Modulus of elasticity (Mpa) Age (weeks)[ii] 0	4	8
Manure	$P = 0.1024$	P **< 0.0001**[iv]	$P = 0.2218$	Dry	37.93 a[v]	46.87 a	23.09 a
				Wet	4.53 b	3.35 b	1.49 b
Wood fiber	$P = 0.1640$	$P =$ **0.0012**	$P = 0.1956$	Dry	94.62 a	238.93 a	82.57 a
				Wet	10.55 b	15.41 b	11.84 b
Starch	$P =$ **0.0054**	—	—	Dry	420.83 a	337.69 ab	292.00 b
				Wet	—	—	—
Coir	$P =$ **0.0006**	$P = 0.4433$	$P = 0.3406$	Dry	100.86 a	27.70 b	11.89 b
				Wet	180.18 a	11.54 b	15.73 b
Biopolymer	$P < 0.0001$	$P = 0.3547$	$P =$ **0.0002**	Dry	1,418.33 bc	1,692.50 ab	1,283.89 c
				Wet	1,242.92 c	2,082.50 a	1,383.72 bc
Peat	$P < 0.0001$	$P < 0.0001$	P **< 0.0001**	Dry	168.33 a	112.87 b	123.27 b
				Wet	21.04 c	15.59 c	20.27 c
Plastic	$P < 0.0001$	$P = 0.0366$	$P =$ **0.0240**	Dry	1,394.17 c	2,019.17 ab	1,194.44 c
				Wet	2,125.33 a	2,112.50 a	1,655.00 bc

[i] Each harvested container was cut into six rectangular test specimens (1 in × 4 in) and conditioned at 23 ± 2.0 °C and 50% relative humidity for 40 h before testing. Tensile testing was conducted using an Instron 5565 electromechanical machine (Instron, Norwood, MA, USA).
[ii] Containers were transplanted with a single basil (*Ocimum basilicum* 'Sweet Green Basil') plug (144-plug size) on 28 Mar 2023. They were fertilized weekly with 250 ppm 15N–2.185P–12.45K (JR Peters, Allentown, PA, USA) and irrigated every other day. Four replicates per treatment were destructively harvested every 2 weeks over 8 weeks.
[iii] All samples were conditioned (23 ± 2.0 °C, 50% relative humidity) for 40 h before testing. Dry specimens were tested following conditioning. Wet specimens were submerged for 105 min, air-dried for 60 min, and tested.
[iv] Data were analyzed using an analysis of variance (ANOVA) (PROC GLIMMIX, SAS 9.4; SAS Institute Inc., Cary, NC, USA). *P* values indicate the significance of main effects (week, condition) and their interaction (week × condition) within each container type. Bold *P* values denote significant effects ($P \leq 0.05$), with corresponding mean separation letters in the subsequent columns. Tukey's honest significant difference (HSD) ($\alpha = 0.05$) was used for mean separation.
[v] Means within a container type with the same letter do not differ significantly ($P > 0.05$). Dashes (–) indicate that tensile testing was not conducted for starch containers under wet conditions because of rapid degradation and structural failure during the trial.

were not as ductile as plastic containers. During mechanical properties testing, biopolymer specimens consistently failed, with a crisp snap, whereas few plastic container specimens fractured and often deformed without breaking. The reduced ductility and increased brittleness of most biodegradable materials, particularly under dry conditions, suggest a higher risk of cracking or breaking during mechanical handling, denesting, and transporting.

Degradation can be quantified in many ways, including mass reduction, strength properties, and physical observations through the use of electron microscopy (Baidurah 2022). As materials degrade, reductions in weight and strength are expected (Eckel et al. 2024). All container types, with the exception of biopolymer and plastic, aligned with the expectation presented by Eckel et al. (2024), whose work suggested that materials lose strength as they age and degrade. Studies of biodegradable containers in floriculture production have suggested that containers with compression and puncture strengths less than 2 kg (19.61 N) are prone to damage during handling and transport (Evans et al. 2010). While compression and puncture strength are not interchangeable with tensile strength, it could be extrapolated that containers with tensile strength below 2 kg (19.61 N) may be unsuitable for horticultural production systems. Containers made of biopolymer, peat, and plastic exhibited adequate tensile strength for handling and transport during the entire 8-week production window as both dry and wet containers.

Scanning electron microscopy

Imaging using a scanning electron microscope revealed surface degradation in both plastic and biopolymer containers over time (Fig. 8). The exterior surface of plastic containers remained largely unchanged between weeks 0, 4, and 8, with the exception of deeper surface scratches observed at week 8. In contrast, the exterior of biopolymer containers exhibited a rough texture that masked some surface abrasions and adhered particles, such as soil debris and fungal mycelium.

Interior surfaces of the biopolymer containers showed more pronounced physical damage and adhesions compared with plastic containers. Progressive surface degradation was evident in plastic containers, with increasing occurrences of cracks, crazing, pits, and adhered particles at each assessment interval. By week 8, plastic containers displayed widespread surface imperfections, including numerous craters, extensive crazing, and deep fractures. The most pronounced degradation was observed in biopolymer containers at week 8, with prominent large adhered particles, deep cracks, and extensive crazing, indicating advanced material breakdown.

These findings suggest that while both plastic and biopolymer containers undergo surface degradation over time, the extent and nature of deterioration differ between materials. Plastic containers exhibited progressive surface damage, whereas biopolymer containers showed more extensive adhesions and structural breakdown by week 8. The accelerated degradation observed in biopolymer containers may impact their durability and suitability for extended production cycles, highlighting the need for further evaluation of their structural integrity and performance under varying environmental conditions, such as those encountered in a nursery production setting.

Consumer opinion

A total of 64 survey responses were collected between Apr 2023 and Jun 2023. Responses with missing data were excluded from the analysis. Among the participants, 7.8% purchased plants weekly, 18.8% purchased monthly, 48.4% purchased seasonally, 14.1% purchased once per year, and 10.9% purchased less than once per year. Consumer likelihood to purchase plants grown in the evaluated containers did not vary by harvest week ($P > 0.5612$), suggesting that changes in container appearance throughout the 8-week production period did not influence purchasing intent. However, differences in container preferences were observed (Fig. 9). Starch containers received the lowest average purchase likelihood score (2.2 out of 5), with 67% of participants rating them as 1 or 2. Wood fiber and manure containers received an average score of 3.3 out of 5, with manure containers having the highest percentage (33%) of neutral responses (score of 3). Peat and plastic containers were rated slightly higher, with scores of 3.7 and 3.8 out of 5, respectively. Consumers were most likely to purchase plants grown in biopolymer and coir containers, with both receiving an average score of 3.9 out of 5. Coir containers were particularly favored, with 69% of participants rating them as 4 or 5. Plastic and biopolymer containers received similar support, with 66% and 68% of respondents, respectively, indicating they were likely or very likely to purchase plants grown in these containers.

During postsubmission discussions, many participants expressed a preference for coir containers and described their textured appearance in later weeks as resembling "bird

Table 5. Effects of container age and moisture conditions on the elongation at break of biodegradable, biopolymer, and plastic horticultural containers.[i]

Container	Effects: Week	Effects: Condition	Effects: Week × Condition	Condition[iii]	Elongation at break (%) Age (weeks)[ii]: 0	4	8
Manure	$P = 0.0406$	$P =$ **0.0067**[iv]	$P = 0.2305$	Dry	4.17 b[v]	4.04 b	2.76 b
				Wet	4.34 a	6.25 a	4.45 a
Wood fiber	$P = 0.8250$	$P < 0.0001$	$P =$ **0.0111**	Dry	5.65 abc	4.33 bc	3.78 c
				Wet	5.96 abc	6.70 ab	8.02 a
Starch	$P =$ **0.0011**	—	—	Dry	1.71 b	3.30 a	0.76 b
				Wet	—	—	—
Coir	$P < 0.0001$	$P = 0.0179$	P **< 0.0001**	Dry	5.86 b	5.95 b	6.10 b
				Wet	8.85 a	8.28 a	3.66 c
Biopolymer	$P < 0.0001$	$P = 0.0532$	$P =$ **0.0106**	Dry	9.01 bc	5.14 d	7.57 bcd
				Wet	10.75 ab	6.76 cd	13.51 a
Peat	$P = 0.0043$	$P = 0.0006$	$P =$ **0.0005**	Dry	2.71 b	4.66 a	1.49 b
				Wet	5.95 a	5.71 a	5.98 a
Plastic	$P = 0.3128$	$P = 0.8603$	P **< 0.0001**	Dry	24.85 c	37.05 b	47.16 a
				Wet	46.36 ab	40.20 ab	24.58 c

[i] Each harvested container was cut into six rectangular test specimens (1 in × 4 in) and conditioned at 23 ± 2.0 °C and 50% relative humidity for 40 h before testing. Tensile testing was conducted using an Instron 5565 electromechanical machine (Instron, Norwood, MA, USA).

[ii] Containers were transplanted with a single basil (*Ocimum basilicum* 'Sweet Green Basil') plug (144-plug size) on 28 Mar 2023. They were fertilized weekly with 250 ppm 15N–2.185P–12.45K (JR Peters, Allentown, PA, USA) and irrigated every other day. Four replicates per treatment were destructively harvested every 2 weeks over 8 weeks.

[iii] All samples were conditioned (23 ± 2.0 °C, 50% relative humidity) for 40 h before testing. Dry specimens were tested following conditioning. Wet specimens were submerged for 105 min, air-dried for 60 min, and tested.

[iv] Data were analyzed using an analysis of variance (ANOVA) (PROC GLIMMIX, SAS 9.4; SAS Institute Inc., Cary, NC). *P* values indicate the significance of main effects (week, condition) and their interaction (week × condition) within each container type. Bold *P* values denote significant effects ($P \leq 0.05$), with corresponding mean separation letters in the subsequent columns. Tukey's honest significant difference (HSD) ($\alpha = 0.05$) was used for mean separation.

[v] Means within a container type with the same letter do not differ significantly ($P > 0.05$). Dashes (–) indicate that tensile testing was not conducted for starch containers under wet conditions because of rapid degradation and structural failure during the trial.

nests." Others voiced concerns over plastic waste, with some initially mistaking biopolymer containers for conventional petroleum-based plastics. Upon learning that biopolymer containers were not derived from petroleum, participants responded more favorably. Additionally, the seafoam green color of the biopolymer containers was slightly preferred over the standard black plastic containers.

These findings suggest that while container degradation over time did not significantly impact consumer purchasing intent, material type played a key role in consumer preferences. Biopolymer and coir containers were the most favored, likely because of their aesthetic appeal and perceived sustainability. However, the perception of sustainability can be a double-edged sword because some consumers may misidentify sustainable alternatives because of their resemblance to traditional plastic products. Misconceptions or inadequate marketing of biopolymer containers could result in improper disposal or recycling, potentially undermining their potential benefits. These insights highlight the importance of visual appeal, material composition, and marketing to consumer decision-making, thus presenting opportunities for alternative container materials to gain wider market acceptance.

Conclusion

The adoption of biodegradable containers by plant producers in the horticulture industry is a topic with many points of concern. Plant producers are most concerned that the quality

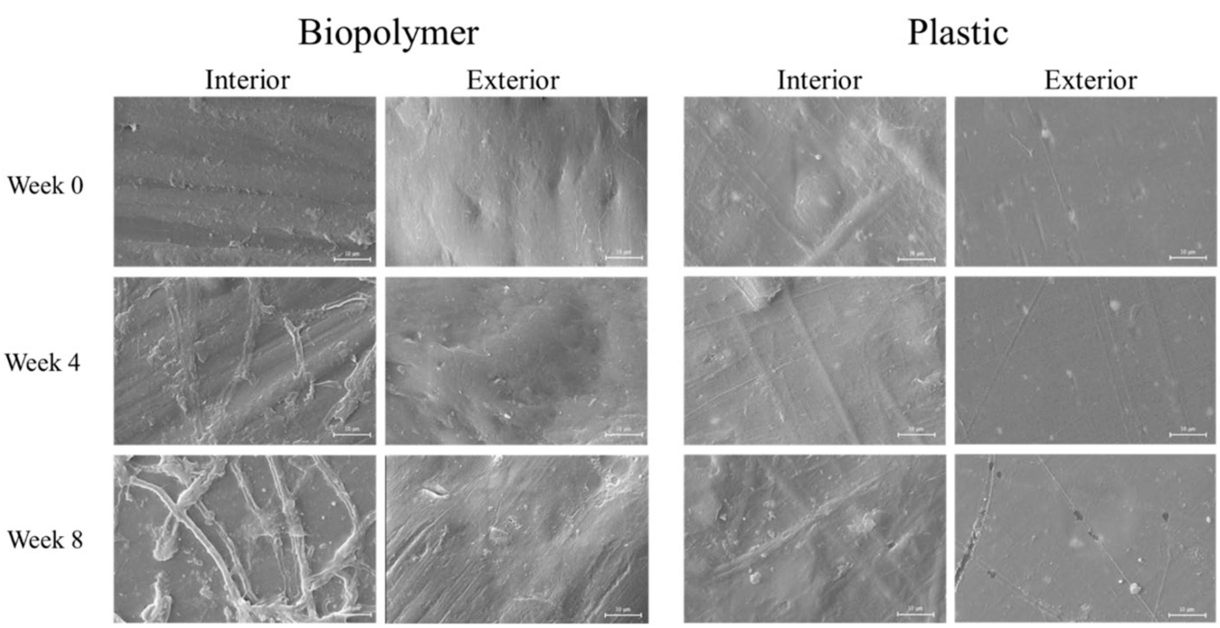

Fig. 8. Scanning electron microscope images of interior and exterior surfaces of biopolymer and plastic containers at 6000× magnification captured at weeks 0, 4, and 8 of the production cycle.

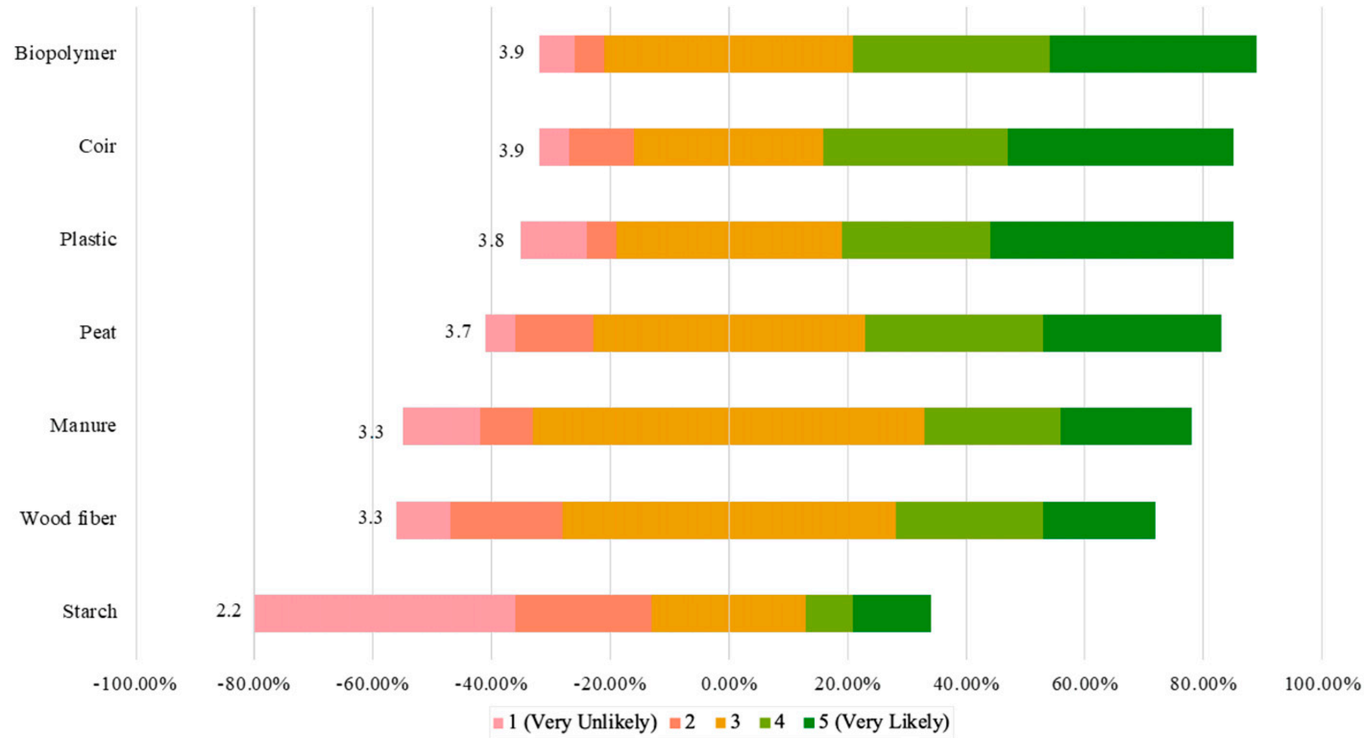

Fig. 9. Participant responses to the prompt of "based on appearance, how likely would you be to purchase a plant in these containers" from an online survey of 64 faculty members, staff, and students at Auburn University. The stacked bars represent the distribution of responses across a 5-point Likert scale, with 1 indicating very unlikely and 5 indicating very likely. A response of 3 was considered neutral, contributing equally to both positive (0% to 100%) and negative (−100% to 0%) sentiments. The average response score is displayed to the left of each stacked bar. Survey responses were collected from Apr 2023 to Jun 2023.

of plants grown in biodegradable containers, the durability of these containers under typical production settings, and their marketability at the end of long production cycles will result in lower profits. These concerns remain key barriers to widespread adoption by both producers and retailers.

This study addressed each of these points. The results showed that, apart from the tapioca starch containers, plants grown in biodegradable containers reached marketable size and quality by the end of the 8-week trial. In terms of durability, biopolymer containers maintained the greatest tensile strength throughout the study and are most likely to withstand the physical demands of commercial production systems. These containers also showed strength comparable to that of plastic in terms of MOE and maximum force at failure. Additionally, consumer survey results indicated that biopolymer containers were preferred over plastic containers, particularly after participants learned they were not petroleum-based.

While biopolymer containers showed promise, other biodegradable containers, such as starch and wood fiber, were ranked lowest in consumer preference after the 8-week trial and exhibited significant structural degradation over time. These findings suggest that although biodegradable options can produce commercially acceptable plants, not all materials are equally suited to withstand the rigors of production or meet consumer expectations at the point of sale.

Because of the growing consumer enthusiasm for sustainable alternatives, considerable research and product development will be necessary to improve the industry's trust in biodegradable and biobased containers. Continued improvements in mechanical performance, aesthetics, and postproduction handling characteristics will be essential. This study contributes evidence that biodegradable containers, particularly those made from biopolymer materials, can meet many of the practical and market expectations of the industry, thus offering a potential pathway toward more sustainable container use in horticultural production.

References Cited

American Society for Testing and Materials. 2012. ASTM D6400 standard specification for labeling of plastics designed to be aerobically composted in municipal or industrial facilities. Engineering360. ASTM Standards. 3. https://doi.org/10.1520/D6400-23.

American Society for Testing and Materials. 2023. D883-22 standard terminology relating to plastics. https://doi.org/10.1520/D0883-22.2.

Baidurah S. 2022. Methods of analyses for biodegradable polymers: A review. Polymers (Basel). 14(22):4928–4948. https://doi.org/10.3390/polym14224928.

Bher A, Cho Y, Auras R. 2023. Boosting degradation of biodegradable polymers. Macromol Rapid Commun. 44(5):e2200769. https://doi.org/10.1002/marc.202200769.

Borelbach P, Kopitzky R, Dahringer J, Gutmann P. 2023. Degradation behavior of biodegradable man-made fibers in natural soil and in compost. Polymers (Basel). 15(13):2959. https://doi.org/10.3390/polym15132959.

Brumfield RG, Devincentis AJ, Wang X, Thomas Fernandez R, Nambuthiri S, Geneve RL, Koeser AK, Bi G, Li T, Sun Y, Niu G, Cochran D, Fulcher A, Ryan Stewart J. 2015. Economics of utilizing alternative containers in ornamental crop production systems. HortTechnology. 25(1):17–25. https://doi.org/10.21273/HORTTECH.25.1.17.

Bulgari R, Petrini A, Cocetta G, Nicoletto C, Ertani A, Sambo P, Ferrante A, Nicola S. 2021. The impact of COVID-19 on horticulture: Critical issues and opportunities derived from an unexpected occurrence. Horticulturae. 7(6):124. https://doi.org/10.3390/horticulturae7060124.

California State Senate. 2021. SB-343: Environmental advertising: Recycling symbol: Recyclability: Products and packaging. 2021–2022 Legislative session. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB343. [accessed 13 Nov 2024].

California State Senate. 2022. SB-54: Solid waste: Reporting, packaging, and plastic food service ware. 2021–2022 Legislative session. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB54. [accessed 13 Nov 2024].

Chappell M, Knox GW. 2012. Alternatives to petroleum-based containers for the nursery industry. http://extension.uga.edu/publications/files/pdf/B%201407_1.PDF. [accessed 13 Aug 2025].

Colorado State Senate. 2022. HB22-1355: Producer responsibility program for recycling. 2022 Regular Session. https://leg.colorado.gov/bills/hb22-1355. [accessed 13 Nov 2024].

Conneway R, Verlinden S, Koeser AK, Evans M, Schnelle R, Anderson V, Ryan Stewart J. 2015. Use of alternative containers for long- and short-term greenhouse crop production.

HortTechnology. 25(1):26–34. https://doi.org/10.21273/HORTTECH.25.1.26.
Conneway RL. 2013. Evaluating biodegradable containers as alternatives to plastic pots. The Research Repository at WVU. https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=1544&context=etd. [accessed 22 Mar 2023].
Eckel F, Van Opdenbosch D, Schandl KS, et al. 2024. Dependency of tensile properties and biodegradation on molecular mass during hydrolysis of poly(butylene succinate). npj Mater Degrad. 8:97. https://doi.org/10.1038/s41529-024-00512-3.
Emmert A. 2021. The rise of the eco-friendly consumer. Strategy+business. https://www.strategy-business.com/article/The-rise-of-the-eco-friendly-consumer. [accessed 22 May 2023].
Environmental Protection Agency. 2023a. Plastics: Material-specific data. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data. [accessed 13 Nov 2024].
Environmental Protection Agency. 2023b. Sustainable management of food: Approaches to composting. https://www.epa.gov/sustainable-management-food/approaches-composting. [accessed 4 Aug 2024].
European Standards (EN). 2005. EN 13432 Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:24478,6242&cs=1478300CA54FDC2D03F8CCE3EA70693FF. [accessed 13 Aug 2025].
Evans MR, Karcher D. 2004. Properties of plastic, peat, and processed poultry feather fiber growing containers. HortScience. 39(5):1008–1011. https://doi.org/10.21273/HORTSCI.39.5.1008.
Evans MR, Taylor M, Kuehny J. 2010. Physical properties of biocontainers for greenhouse crops production. HortTechnology. 20(3):549–555. https://doi.org/10.21273/HORTTECH.20.3.549.
Fuentes RA, Berthe JA, Barbosa SE, Castillo LA. 2021. Development of biodegradable pots from different agroindustrial wastes and byproducts. Sustainable Mater Technol. 30. https://doi.org/10.1016/J.SUSMAT.2021.E00338. [accessed 15 Mar 2023].
Fulcher A, Cochran DR, Koeser AK. 2015. An introduction to the impact of utilizing alternative containers in ornamental crop production systems. HortTechnology. 25(1):6–7. https://doi.org/10.21273/HORTTECH.25.1.6.
Geyer R, Jambeck JR, Law KL. 2017. Production, use, and fate of all plastics ever made. Sci Adv. 3(7):e1700782. https://doi.org/10.1126/sciadv.1700782.
González A, Gastelú G, Barrera GN, Ribotta PD, Álvarez Igarzabal CI. 2019. Preparation and characterization of soy protein films reinforced with cellulose nanofibers obtained from soybean by-products. Food Hydrocoll. 89:758–764. https://doi.org/10.1016/j.foodhyd.2018.11.051.
Hall CR, Campbell BL, Behe BK, Yue C, Lopez RG, Dennis JH. 2010. The appeal of biodegradable packaging to floral consumers. HortScience. 45(4):583–591. https://doi.org/10.21273/HORTSCI.45.4.583.
Harris BA, Pennisi SV, Florkowski WJ. 2020. Horticulture industry adoption of biodegradable containers. HortTechnology. 30(3):372–384. https://doi.org/10.21273/HORTTECH04563-19.
Khachatryan H, Campbell B, Hall C, Behe B, Yue C, Dennis J. 2014. The effects of individual environmental concerns on willingness to pay for sustainable plant attributes. HortScience. 49(1):69–75. https://doi.org/10.21273/HORTSCI.49.1.69.
Koeser A, Lovell ST, Evans M, Stewart JR. 2013. Biocontainer water use in short-term greenhouse crop production. HortTechnology. 23(2):215–219. https://doi.org/10.21273/HORTTECH.23.2.215.
Kratsch HA, Schrader J, McCabe K, Srinivasan G, Grewell D, Graves W. 2015. Performance and biodegradation in soil of novel horticulture containers made from bioplastics and biocomposites. HortTechnology. 25(1):119–131. https://doi.org/10.21273/HORTTECH.25.1.119.
Kuehny JS, Taylor M, Evans MR. 2011. Greenhouse and landscape performance of bedding plants in biocontainers. HortTechnology. 21(2):155–161. https://doi.org/10.21273/HORTTECH.21.2.155.
Lopez RG, Camberato D. 2011. Growth and development of 'Eckespoint Classic Red' poinsettia in biodegradable and compostable containers. HortTechnology. 21:419–423. https://doi.org/10.21273/HORTTECH.21.4.419.
Maine State Senate. 2021. MRSA 2146: Stewardship Program for Packaging. 2021 Special Session. https://www.maine.gov/dep/waste/recycle/epr.html. [accessed 13 Nov 2024].
Mattson N. n.d. Testing container media. Cornell University, Ithaca, NY, USA. https://www.css.cornell.edu/courses/260/Media%20testing.pdf. [accessed 13 Nov 2024].
Mohamed NH, Kooi M, Diepens NJ, Koelmans AA. 2021. Lifetime accumulation of microplastic in children and adults. Environ Sci Technol. 55(8):5084–5096. https://doi.org/10.1021/acs.est.0c07384.
Nambuthiri S, Fulcher A, Koeser AK, Geneve R, Niu G. 2015. Moving toward sustainability with alternative containers for greenhouse and nursery crop production: A review and research update. HortTechnology. 25(1):8–16. https://doi.org/10.21273/HORTTECH.25.1.8.
Nambuthiri S, Schnelle R, Fulcher A, Geneve R, Koeser AK, Verlinden S, Conneway RL. 2013. Alternative containers for a sustainable greenhouse and nursery crop production. Univ Kentucky Coop Ext Publ HO. 110:1–11.
New Jersey State Senate. 2022. S2525: Establishing postconsumer recycled content requirements for rigid plastic containers, glass containers, paper and plastic carryout bags, and plastic trash bags; prohibits sale of polystyrene loose fill packaging. 2020–2021 Regular Session. https://www.nj.gov/dep/dshw/recycled-content/. [accessed 13 Nov 2024].
Oregon State Senate. 2021. SB-582: Establishing producer responsibility program for packaging, printing and writing paper and food service ware. 2021 Regular Session. https://olis.oregonlegislature.gov/liz/2021R1/Measures/Overview/SB582. [accessed 13 Nov 2024].
Owen G, Cockson P, Henry J, Whipker BE, Curry CJ. 2018. Nutritional monitoring series: Basil. Fert, Dirt, and Squirt! http://www.fertdirtandsquirt.com/.
Pinto da Costa J, Rocha-Santos T, Duarte A. 2020. The environmental impacts of plastics and micro-plastics use, waste and pollution: EU and national measures. European Parliament Policy Department for Economic, Scientific and Quality of Life Policies, Brussels, Belgium.
Pires JRA, Souza VGL, Fuciños P, Pastrana L, Fernando AL. 2022. Methodologies to assess the biodegradability of bio-based polymers—Current knowledge and existing gaps. Polymers (Basel). 14(7):1359. https://doi.org/10.3390/polym14071359.
Pratibha SS, Hariprasad P. 2022. Paddy straw-based biodegradable horticultural pots: An integrated greener approach to reduce plastic waste, valorize paddy straw and improve plant health. J Cleaner Prod. 337:130588. https://doi.org/10.1016/j.jclepro.2022.130588.
San Fratello D, Campbell BL, Secor WG, Campbell JH. 2022. Impact of the COVID-19 pandemic on gardening in the United States: Postpandemic expectations. HortTechnology. 32(1):32–38. https://doi.org/10.21273/HORTTECH04911-21.
Schrader JA. 2013. Report on the annual consumption of plastics for specialty-crop containers in the United States. https://doi.org/10.13140/RG.2.2.29992.39689/1. [accessed 6 Oct 2025].
Schrader JA, McCabe K, Srinivasan G, Haubrich K, Grewell D, Madbouly S, Graves W. 2015. Development and evaluation of bioplastic containers for sustainable greenhouse and nursery production. Acta Hortic. 1104(1104):79–88. https://doi.org/10.17660/ActaHortic.2015.1104.13.
Silva RRA, Marques CS, Arruda TR, Teixeira SC, Oliveira TV. 2023. Biodegradation of polymers: Stages, measurement, standards and prospects. Macromol. 3(2):371–399. https://doi.org/10.3390/macromol3020023.
Sloan JJ, Cabrera RI, Ampim PAY, George SA, Mackay WA. 2010. Performance of ornamental plants in alternative organic growing media amended with increasing rates of expanded shale. HortTechnology. 20(3):594–602. https://doi.org/10.21273/HORTTECH.20.3.594.
Solano G, Rojas-Gätjens D, Rojas-Jimenez K, Chavarría M, Romero RM. 2022. Biodegradation of plastics at home composting conditions. Environ Challenges. 7:100500. https://doi.org/10.1016/j.envc.2022.100500.
Song JH, Murphy RJ, Narayan R, Davies GBH. 2009. Biodegradable and compostable alternatives to conventional plastics. Philos Trans R Soc Lond B Biol Sci. 364(1526):2127–2139. https://doi.org/10.1098/rstb.2008.0289.
Soulliere-Chieppo M. 2020. Plastic pots and the green industry—Production, use, disposal and environmental impacts. https://cdn.ymaws.com/www.mnla.com/resource/resmgr/docs/apldplastic-pots-white-pape.pdf. [accessed 22 Mar 2023].
United Nations Envrionmental Assembly. 2022. 5/14 End plastic pollution woards an international legally binding instrument. 5th Session. Nairobi, Kenya. https://digitallibrary.un.org/record/3999257?ln=en&v=pdf#files. [accessed 23 Aug 2025].
Wang X, Thomas Fernandez R, Cregg BM, Auras R, Fulcher A, Cochran DR, Niu G, Sun Y, Bi G, Nambuthiri S, Geneve RL. 2015. Multistate evaluation of plant growth and water use in plastic and alternative nursery containers. HortTechnology. 25(1):42–49. https://doi.org/10.21273/HORTTECH.25.1.42.
Wei X-F, Nilsson F, Yin H, Hedenqvist MS. 2021. Microplastics originating from polymer blends: An emerging threat? Environ Sci Technol. 55(8):4190–4193. https://doi.org/10.1021/acs.est.1c00588.
Wojnowska-Baryła I, Bernat K, Zaborowska M. 2022. Plastic waste degradation in landfill conditions: The problem with microplastics, and their direct and indirect environmental effects. Int J Environ Res Public Health. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9602440/.
Woodske D. 2015. Performance of biodegradable nursery containers. Acta Hortic. 1085:319–323. https://doi.org/10.17660/ActaHortic.2015.1085.58.
Wright RD, Grueber KL, Leda C. 1990. Medium nutrient extraction with the pour-through and saturated medium extraction procedures for poinsettia. HortScience. 25(6):658–660. https://doi.org/10.21273/HORTSCI.25.6.658.

Yu Y, Griffin-LaHue DE, Miles CA, Hayes DG, Flury M. 2021. Are micro- and nanoplastics from soil-biodegradable plastic mulches an environmental concern? J Hazardous Mater Adv. 4:100024. https://doi.org/10.1016/j.hazadv.2021.100024.

Yue C, Hall CR, Behe BK, Campbell BL, Lopez RG, Dennis JH. 2010. Investigating consumer preference for biodegradable containers. J Environ Hortic. 28(4):239–243. https://doi.org/10.24266/0738-2898-28.4.239.

Zeus Inc. 2005. Thermal degradation of plastics. Appalachian State University, Boone, NC, USA. http://www.appstate.edu/∼clementsjs/polymerproperties/zeus_thermal_degradation.pdf. [accessed 2 Oct 2024].