IMPROVING THE QUALITY AND SHELF LIFE OF BEDDING AND POTTED PLANTS WHILE REDUCING WATER USAGE

A Dissertation

by

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ABSTRACT

Retail environments are rarely optimal for ornamental plants, and wilting caused by water stress is a major cause of postproduction shrinkage. The objective of this study was to determine the effect of reducing substrate moisture content (SMC) from 40% to 20% during bedding and potted plants greenhouse production on growth and development, plant production and postproduction quality, and economic value.

Five experiments were conducted to evaluate the response of bedding plants species/cultivars and the response of poinsettias to reduced SMC. In experiment 1, two SMC levels were applied during greenhouse production to angelonia (*Angelonia angustifolia*) ‘Angelface Blue’ and heliotrope (*Heliotropium arborescens*) ‘Simply Scentsational’. Growth and physiological parameters were evaluated, as well as subsequent postproduction quality during simulated retail conditions. 20% SMC produced more compact angelonia with less inputs and higher postproduction quality. Heliotrope grown at 20% SMC produced the same size plant as 40% SMC, but had a higher visual quality compared with 40% SMC. In experiments 2 and 3, two SMC levels (20% or 40%) were applied with four timing of application combinations to poinsettia (*Euphorbia pulcherrima*) ‘Freedom Red’ in 2016 and ‘Christmas Eve Red’ in 2017. Total production (TP) time was 14 (2016) or 12 (2017) weeks, during which vegetative production (VP) occurred from week 33 (2016) or 35 (2017) to week 39 and reproductive production (RP) continued from week 40 to 47. The four timing of application treatments were: 40/40 = TP at 40% SMC; 20/40 = VP at 20% + RP at 40%;

40/20 = VP at 40% + RP at 20%; 20/20 = TP at 20% SMC. After simulated shipping in the dark, plants were evaluated in a simulated retail environment with two packaging treatments: no sleeve covering or plastic perforated plant sleeves covering container and plant. Reducing SMC to 20% during TP or during RP reduced water usage during production and produced more compact plants with increased postproduction quality. In experiments 4 and 5, two SMC levels (20% or 40%) were applied during production of six bedding plant species/cultivars *Solenostemon scutellarioides* 'French Quarter' (coleus), *Petunia* × *hybrida* 'Colorworks Pink Radiance' (petunia), *Lantana camara* 'Lucky Flame' (lantana), *Impatiens* × *hybrida* 'Sunpatiens Compact Hot Coral' (SCC) and ‘Sunpatiens Spreading Lavender’ (SSL) (impatiens), and *Salvia splendens* ‘Red Hot Sally II’ (salvia) greenhouse production. Considering production and/or postproduction quality, using 20% SMC during greenhouse production is beneficial as an alternative irrigation method for these cultivars of angelonia, heliotrope, coleus, petunia, impatiens SSL, salvia and poinsettia, but not for impatiens SCC or lantana.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Researchers determined that, in 2014, the green industry generates about $136.44 billion in direct output annually, of which $16.77 billion was contributed by greenhouse and nursery growers (Hodges et al., 2015). In 2015, the wholesale value of floriculture crops in the United States was $4.37 billion, of which annual bedding plants generated $1.29 billion and potted flowering plants generated $810 million (USDA, 2016). Total crop values ranged from $4.00 billion in 2009 to a peak of $4.37 billion in 2015 (USDA, 2016). Within 10 years, the number of producers in the top 15 production states declined from 7,178 in 2005 to 5,913 in 2015, a reduction of 17.6% (USDA, 2007; USDA, 2016). This consolidation of the greenhouse production sector reflects the fact that the floriculture industry is in the mature stage of the industry life cycle. Growers have changed from being price setters to being price takers, accepting the prevailing market price for the plants (Fisher et al., 2014).

Considering the present market climate, the economic value of potted and bedding plants, and the environmental need to save water, many reduced-irrigation methods have been proposed: limited irrigation volume, evapotranspiration replacing, weight-based dry-down cycle, etc. Research has found that moderated water deficit during greenhouse production leads to more compact plants with higher water-use efficiency in American alumroot (*Heuchera americana*), gaura (*Gaura lindheimeri*), impatiens (*Impatiens walleriana*), salvia (*Salvia splendens*), vinca (*Catharanthus roseus*), and poinsettias (*Euphorbia purcherrima*) (Alem et al., 2015a; Burnett and van Iersel, 2008; Jacobson et al., 2015; van Iersel and Nemali, 2004). Earlier research also showed that moderated water deficit could improve the visual quality of petunias by increasing their flower number (Alem et al., 2015). In geranium crops, reducing irrigation water volume by 25% during the vegetative growth stage resulted in earlier flowering time without affecting the number of open flowers. This lower irrigation input produced geraniums with a smaller leaf area and an acclimating response to applied water deficit, potentially reducing water loss (Álvarez et al., 2013). Under moderated water deficient conditions, geraniums (*Pelargonium* × *hortorum*) increased root growth without affecting shoot morphology and flowering (Chyliński et al., 2007). Consumer preference research has also indicated that customers are more likely to purchase if products are produced with less water and higher sustainability (Behe et al., 2013; Yue et al., 2011).

Even though several studies have been conducted to study the effects of water deficit on plants' responses, there is a lack of information regarding these effects on postharvest quality (Islam and Joyce, 2015). The need for postproduction water research is relevant, especially given reductions in water availability and poor water quality, both of which negatively affect plant production and postproduction (Cregg, 2002; Zhu, 2002). A recent study showed that growers could lose up to one-third of their products during postproduction (Hall et al., 2011). Knowing how reduced irrigation during greenhouse production affects postproduction physiology and quality of potted and bedding plants will provide useful information that growers in the floriculture industry can apply to produce higher-quality crops with fewer inputs.

1.2 Plants Postproduction Quality

Growers can also increase their profits by reducing the shrink associated with postproduction. Shrink is the portion of crops grown but considered unsalable. During greenhouse production, shrinkage has a major impact on financial outcomes. The later shrinkage occurs in the value chain, the larger the impact on profitability because more inputs such as overhead, labor, water, fertilizer, and pesticides have been used prior to disposed. A recent survey of larger growers reported that production level shrink ranged from 2-10%, with a median of 5% whereas retail-level shrink ranged from 8-33%, with a median of 19% (Hall et al., 2011). Postproduction is the phase of the distribution chain that potted plants and bedding plants go through after they leave the greenhouse. Postproduction research on potted and bedding plants is related to environmental factors and cultural practices during production, shipping conditions, and interior conditions (this does not apply to bedding plants) (Nell, 1993). Factors influencing the postproduction of crops include greenhouse temperature, fertilization, irrigation, lighting, and the shipping and retail environment (Jones, 2002).

Compared to the optimized greenhouse environment, the postproduction environment is rarely ideal. Hardening off or toning plants at the end of the production cycle by reducing the temperature, fertilization levels, irrigation frequency and light intensity can increase plant longevity during postproduction (Beach et al., 2009; Jones, 2002; Starman et al., 2007). Different crops respond differently to the toning and hardening off. One study indicated that reducing end-of-production fertilization rate two weeks before marketing increased postproduction quality of bracteantha (*Bracteantha bracteata*), nemesia (*Nemesia ×hybrida*), sutera (*Sutera hybrida*), argyranthemum (*Argyranthemum frutescens*), angelonia (*Angelonia angustifolia*), calibrachoa (*Calibrachoa hybrid*), and petunia (*Petunia ×hybrida*), whereas the postproduction quality of diascia (*Diascia ×hybrida*) and lantana (*Lantana camara*) was not affected (Beach et al., 2009).

Different methods have been used to identify whether the production condition or the shipping environment is the main influences on postproduction quality. A systematic theme-based modeling study reported that the quality of ornamental plants was influenced more by the mismanagement in the shipping environment rather than the greenhouse production conditions (Ottosen, 2007). This indicated that the shipping environment should be the main focus of the research. However, a postproduction study based on 21 cultivars from nine species of vegetative annuals indicated that length of shipping has an effect on flower abscission. Only when shipping is longer than two days would it cause a significant reduction in flower numbers, but not in a shorter shipping time. Only a few flowers abscised immediately after shipping and more decline happened as postproduction time continued (Starman et al., 2007). Another postproduction study indicated that applying water deficit during the greenhouse production of angelonia (*Angelonia angustifolia*) could acclimate the plant to reduce/prevent wilting caused by water deficit during the postproduction period (Jacobson et al., 2015). A study of Persian violet (*Exacum affine*) showed that higher light intensity during production reduced production time and increased flower development during postproduction in an interior environment (Serek and Trolle, 2000). Other researchers reported that reducing the light intensity and temperature 6 to 10 days before shipping allowed moon orchid (*Phalaenopsis amabilis*) to acclimate to the dark shipping environment and resulted in higher postproduction quality and faster recovery once the shipping period ended (Hou et al., 2011; Hou et al., 2010). Contrary to the systematic theme-based model Ottosen proposed in 2007, these experiments showed that plants acclimate during greenhouse production; both greenhouse production conditions and the shipping time could have a significant effect on postproduction quality of plants. Because most shipping in the U.S. is shorter than two days, the shipping environments may not be as important as Ottosen (2007) suggested.

1.3 Water Deficit Review: Past Research and Methods Used

Water deficit (water content of tissues or cells that is below the highest water content exhibited at the most hydrated state) is a major challenge during postproduction of bedding and potted plants, as water deficit is often present in agriculture habitats. In the literature, drought stress and water stress are interchangeable terms. Technically, drought is defined as a meteorological term for a period of insufficient rain or water supplies that causing plants to have water deficit (Taiz et al., 2015). Because all greenhouse studies reviewed in the dissertation are on a seasonal rather than a meteorological scale, we use the term water stress to describe all the plant physiological and morphological responses to water deficit. Plants response to water deficit has varied by plant species. Some species had an obvious morphology change that affects their aesthetic value; others were less affected by water deficit application. Two categories of methods have been used to apply water deficit during greenhouse production: constant substrate moisture content (SMC) or the dry-down cycle.

Another term used frequently in this dissertation is plant acclimation, which is defined as the morphological and physiological adjustment by individual plants to compensate for the decline/change in the environment without new genetic modification, also called phenotypic plasticity (Debat and David, 2001). Most commonly known as stress resistance or stress tolerance, it describes a plant's ability to survive and prosper under a suboptimum environment (Taiz et al., 2015). Past studies reported that water deficit could limit leaf size, stem length, internode length and leaf number due to the growth rate reduction. Plants respond to water deficit by changing cell wall and membrane biosynthesis, cell division, and protein synthesis to reduce the canopy area, limiting water loss, which limits the total photosynthetic production (Burssens et al., 2000; Taiz et al., 2015).

1.3.1 Constant substrate moisture content

1.3.1.1 Using sensor technology

One method of applying water deficit is using soil moisture sensor–controlled irrigation systems to hold SMC constant throughout production (Nemali and van Iersel, 2006). In this system, sensor location in the container is crucial in order to reduce the variation in quantifying spatial and temporal substrate water content. The soil moisture sensor should be placed where the greatest amount of plant water uptake occurs according to plant root distribution within the container (van Iersel et al., 2009)

Using eight levels (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 $m^3 \cdot m^{-3}$) of constant SMC, hibiscus (*Hibiscus acetosella* 'Panama Red') had decreased plant height as SMC level decreased. A combination of reduced SMC level and lower fertilizer rate produced salable plants with less environmental impact, even though fertilizer rate had greater effect on plant shoot growth than SMC (Bayer et al., 2015b).

Four SMC levels (0.20, 0.30, 0.40, or 0.50 $m^3 \cdot m^{-3}$) were applied to gardenia (*Gardenia jasminoides*), low SMC (0.2 and 0.3 $m^3 \cdot m^{-3}$) had reduced plant height, width, shoot dry weight (DW), and leaf size. 0.5 SMC led to over irrigation without increased shoot growth compared to 0.4 SMC, but increased the substrate leachate amount and reduced flower and bud number (Bayer et al., 2015a). Hibiscus (*Hibiscus acetosella*) was tested at eight SMC levels (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 $m^3 \cdot m^{-3}$), and plant height increased as SMC level increased. The water-use efficiency (WUE, grams of shoot DW produced per liters of water used) decreased for SMC above 0.35 $m^3 \cdot m^{-3}$. This experiment suggested that water deficit can be adjusted to control plant growth (Bayer et al., 2013). Further research validated this suggestion; another study used 20% SMC treatment as a plant height-control method at different periods of time during poinsettia greenhouse production, allowing poinsettias to reach different target heights at 35.6 cm, 39.4 cm, or 43.2 cm (Alem et al., 2015c). Another study reported agave (*Agave weberi*) grown under four SMC levels (0.05, 0.12, 0.19, or 0.26 $m^3 \cdot m^{-3}$) not only plant DW decreased as SMC level decreased, chlorophyll content and nutrient uptake decreased as well (Bergsten and Stewart, 2013). Water deficit at 0.10 or 0.20 $m^3 \cdot m^{-3}$

produced compact guara (*Gaura lindheimeri*) with a decreased number and length of branches (compactness = leaf area/height) (Burnett and van Iersel, 2008).

Water deficit produced compact scarlet sage (*Salvia splendens*) (Blanusa et al., 2009), but not marigold (*Tagetes erecta*) (van Iersel and Nemali, 2004). The height, net photosynthesis (P_n), transpiration (E), and stomatal conductance (g_s) of rosemary (*Rosmarinus officinalis*) reduced as SMC decreased, whereas the DW, instant WUE, and P_n, E, g_s of Canadian columbine (*Aquilegia canadensis*) and cheddar pink (*Dianthus gratianopolitanus*) were not affected by the change in SMC (Zhen et al., 2014). Mild water deficit (SMC at 0.20 and 0.30 $m^3 \cdot m^{-3}$) on two English lavender (*Lavandula angustifolia*) cultivars 'Munstead' and 'Hidcote' decreased P_n, E and g_s; plants responded to decreasing SMC level differently at the end of the study, and plant height, width, inflorescence number, total leaf number, total leaf area and DW were reduced as the SMC level decreased (Zhen and Burnett, 2015). Petunia (*Petunia × hybrida*) grown under four SMC level (0.10, 0.20, 0.30, or 0.40 $m^3 \cdot m^{-3}$) showed decreased g_s and P_n and leaf abscisic acid (ABA) concentration increased as midday leaf water potential decreased. At 0.10 $m^3 \cdot m^{-3}$, ABA catabolism decreased (Kim et al., 2011). Similar results were reported for two garden rose species (*Rosa ×hybrida*) where a 10% constant SMC reduced midday leaf water potential, P_n, g_s, and E and root DW compared to 30% and 40% constant SMC (Cai et al., 2014).

1.3.1.2 Limited irrigation volume

Drought levels of 70%, 50%, or 35% of control irrigation, determined by irrigating at the wilting point until it has 15% leachate (by volume), were applied to plants to measure plant acclimation. When water deficit was applied during greenhouse production, carnation (*Dianthus caryophyllus)* and crimson bottlebrush (*Callistemon citrinus*) increased WUE and root/shoot ratio, reduced gs, and had more compact growth without affecting flowering or visual quality (Álvarez et al., 2009; Álvarez et al., 2011; Álvarez and Sánchez-Blanco, 2013).

Reducing irrigation water volume by 25% during the geranium (*Pelargonium* × *hortorum*) vegetative growth stage resulted in earlier flowering time with the same flower number, and this lower irrigation input produced geraniums with smaller leaf area, which reduced the g_s and thus the water consumption (Álvarez et al., 2013).

Another study reported that severe water deficit (irrigation maintained at 20% and 40% container capacity) not only reduced the growth index and leaf area, but also the visual quality of saliva (*Salvia dolomitica*) and trailing dusty miller (*Helichrysum petiolare*). Re-watering would recover effectively only plants from moderate water stress (irrigation maintain at 60% or 80% container capacity) (Caser et al., 2012).

1.3.1.3 Replacing 24-hour evapotranspiration

Another method determines water stress by measuring and replacing water lost by evapotranspiration in the previous 24 hours (ETp) based on gravimetrically mean weight loss in six plants over a 24 hours period after been irrigated to container capacity. In this study, 100%, 75%, 50%, or 25% ETp were used as regulated deficit irrigation treatments. Daily evapotranspiration was determined based on the change in pot weight. Only plants grown in 100% ETp were allowed to be watered back to container capacity daily. Plants grown in 25% ETp irrigation treatments (low SMC level in this experiment) only received 25% of the water of that the 100% treatment received. Under a low SMC level (25% ETp), petunia (*Petunia × hybrid*) had increased flower production efficiency (more flowers per unit biomass), but flower number, plant height, and flower size were reduced 50, 33 and 13%, respectively. In addition, impatiens (*Impatiens walleriana*) grown under low SMC (25% ETp) had a 75% reduction in flower number (Blanusa et al., 2009). Woody ornamental plants responded to water deficit by reduction in plant growth improving plant quality with shorter internodes and final shoot length. The best time to apply 50% ETp was summer, which resulted in quality plants that retained their shape throughout the growing season until the following spring (Cameron et al., 2006).

1.3.2 Dry-down cycle

1.3.2.1 Container weight change method

Plant species have varied physiological and morphological responses when water deficit is applied in a dry-down cycle during greenhouse production. One method of measuring water deficit is based on changes in the weight of the growing container. In this method, monitored pots are allowed to reach the wilting or mild wilting point, at which time the pot weight is measured gravimetrically. This was the target weight for the water deficit treatment in the experiment, and water loss was re-supplied at this target point. The target weight was predetermined by allowing the majority of replications of a tested species to exhibit signs of mild wilting. Once the pot reached the target weight, pots were re-watered to container capacity for subsequent dry-down cycles, which were repeated throughout the experiment (Andersson, 2000; Cai et al., 2014; Cai et al., 2012; Chyliński et al., 2007; Eiasu et al., 2012; Niu et al., 2008; Niu et al., 2007; Niu et al., 2006; Starman and Lombardini, 2006). Using the container weight change method of water deficit, plant DW was reduced for several bedding plant species including dusty miller (*Jacobaea maritima*), petunia (*Petunia* × *atkinsiana*), and plumbago (*Plumbago auriculata*). This was not the case for agastache (*Agastache foeniculum*), ornamental pepper (*Capsicum annuum*), or vinca (*Vinca minor*) (Niu et al., 2006). Plumbago leaf area was reduced by water deficit and plant height was reduced in plumbago and vinca. The photosynthetic rate of all species declined as leaf temperature or water deficit increased, and P_n, g_s, and E of petunia and vinca decreased at a greater rate than other species tested (Niu et al., 2006).

Big Bend bluebonnet (*Lupinus havardii*) grown at 12% to 15% SMC had a reduced number of racemes per plant, canopy size, leaf greenness (SPAD reading), and shoot DW compared to 20% to 33% SMC, but there was no difference between 25% and 33% SMC (Niu et al., 2007). During water deficit, oleander (*Nerium oleander*) had reduced shoot DW, P_n, g_s, and E, and increasing root to shoot DW ratio, which increased the plant survival rate under subsequent drought conditions in the landscape. The more drought-hardy cultivars also had an increased number of new shoots (Niu et al., 2008). Four garden rose cultivars responded to water deficit with reduced shoot DW, P_n, g_s, and E, but only two cultivars tested had a reduction in root DW (Cai et al., 2012).

Geranium (*Pelargonium zonale*) had reduced plant height, number of leaves, leaf area and DW as SMC level was reduced (pot weight decreased at 20, 50, 90, or 120 g compared to initial pot weight), but the WUE was not affected (Andersson, 2000). In this study, the SMC level was not calculated or reported, and is hard to compare to other studies because the initial pot weight or volume were not provided in the report.

Root growth was reduced under severe water deficit (30% SMC, weight-based) compared to a well-watered treatment (80% SMC) for impatiens (*Impatiens walleriana*) and geranium (*Pelargonium hortorum*), and leaf chlorophyll concentration decreased when impatiens were under water stress (Chyliński et al., 2007).

1.3.2.2 Relative water content of leaves

Another method to measure water deficit has been to use varying irrigation frequencies (daily, every 2nd, 3rd, 4th, or 5th day) and the level of plant stress was determined based on relative water content (RWC) of leaves as RWC (%) = (Fresh Weight – DW)/(Turgid Weight – DW) × 100% (Eiasu et al., 2012). Lower irrigation frequency (irrigate every 3rd, 4th, or 5th day) during greenhouse production caused physiomorphological adaptation of geranium to water deficit, including reduced g_s and E without a significant effect on plant water potential and RWC of leaves (Eiasu et al., 2012).

1.3.2.3. Soil water potential (tensiometer)

The last method to measure water deficit has been based on soil water potential measured with a tensiometer. Water deficit was applied as a soil water potential of -50 kPa, compared to a control with a soil water potential of -5kPa. Applied water deficit during the vegetative growth stage of poinsettia (*Euphorbia pulcherrima* 'Lilo'), reduced leaf E and g_s. However, at the flowering and bract coloring development stage, leaf g_s and E were not affected by water deficit (Nowak, 2002).

1.4 Plant Physiological Response and the Mechanism

Studies have documented varying species' responses to water deficit differently. Poinsettia (*Euphorbia pulcherrima*), crimson (*Callistemon citrinus*), hibiscus (*Hibiscus acetosella*), gardenia (*Gardenia jasminoides*), English lavender (*Lavandula angustifolia*), fan flower (*scaevola aemula*), geraniums (*Pelargonium zonale*), impatiens (*Impatiens walleriana*), oleander (*Nerium oleander* L.), Big Bend bluebonnet (*Lupinus havardii*), dusty miller (*Cineraria maritima*), petunia (*Petunia ×hybrida*), and plumbago (*Plumbago auriculata*) were reported to have morphology change [lower growth index (GI), lower DW] when irrigation volume is reduced (Andersson, 2000; Álvarez et al., 2011; Alem et al., 2013; Alem et al., 2015; Bayer et al., 2013; Bayer et al., 2015; Chyliński et al., 2007; Niu et al., 2006; Niu et al., 2007; Niu et al., 2008; Starman and Lombardini, 2006). However, the morphology of lantana (*Lantana camara*), cardinal flower (*Lobelia cardinalis*), geranium, agastache (*Agastache urticifolia*), ornamental pepper (*Capsicum annuum*), and vinca (*Catharanthus roseus*) was not affected by reducing irrigation volume (Chyliński et al., 2007; Niu et al., 2006; Starman and Lombardini, 2006).

Three aspects affected plant response to controlled water deficit: duration of treatment, severity of the water deficit, and anatomy and morphology of the plant itself. 30% SMC had no effect on geranium over a 10-day period (Chyliński et al., 2007) whereas when sever water deficit was applied throughout the production period, geranium growth was inhibited (Andersson, 2000). Another study reported that two months of moderated water deficit won't affect geranium growth, while two months of severe water deficit would reduce the plant growth (Sánchez-Blanco et al., 2009). Other studies reported similar findings related to the duration and the intensity of water deficit influencing the plant response toward the stress. In another study conducted on roses (*Rosa hybrida*), 30% SMC had no affect on plant growth when the 20% SMC and 10% SMC reduced the plant growth (Cai et al., 2014). Under the same controlled water deficit, various results may be caused by species-specific leaf morphology including leaf size, cuticle thickness, leaf surface texture, or number and structure of trichomes which all affect transportation rate The waxy cuticle and leaf hair covering the leaf surface could effectively increase the boundary layer resistance on the water movement, thus reducing water loss for plants under a water-deficient environment (Taiz et al., 2015).

Also, species with shoot morphology change often reported a reduction in P_n, E, and g_s (Álvarez et al., 2011; Bayer et al., 2013; Niu et al., 2006; Niu et al., 2007; Niu et al., 2008; Starman and Lombardini, 2006). Lower photosynthetic rate was caused by the lower CO_2 abortion when stomatal closure reduced the available C source for the Calvin-Benson cycle. This caused lower total plant growth, reflected by the lower plant DW. The stomata closure/regulation and gene expression under a water-deficient situation is a well-known characteristic of ABA. Under the water-deficient condition, ABA could be synthesized in both root and leaves, but is better known to be synthesized in roots, and translocate into shoots through both phloem and xylem (mainly through the phloem) (Seo and Koshiba, 2002; W J Davies and Zhang, 1991). The exact location of ABA synthesis in the root is under debate; some research has reported that ABA concentration increases at the root tip or three cm away from the root tip (Zhang and Davies, 1987;

Zhang and Tardieu, 1996). In more recent years, the concern of measuring ABA content rather than activity was raised by other researchers calling for the exact location of ABA synthesis to be re-examined (Schachtman and Goodger, 2008). Some research reported that ABA regulating guard cells could be produced in the leaf (Fambrini et al., 1995). A key enemy for ABA synthesis, NCED (9'-cis-Neoxanthin), is a water stress-induced enzyme. Increased *NCED* mRNA expression, NCED protein concentration and ABA concentration were observed in both under water-deficient leaf and root of common bean (*Phaseolus vulgaris*) (Qin and Zeevaart, 1999). In the meantime, multiple studies reported increasing pH (from 6.2 to 7.2) in xylem sap during water deficit (Gollan et al., 1992; Hartung et al., 1998; Wilkinson and Davies, 1997). The alkalinization of xylem sap is considered a stress signal itself. It favored the dissociated form of ABAH to ABA^-, which is more unlikely to pass through membranes and is metabolized by mesophyll cells, thus increasing the apoplast accumulation of ABA around the guard cell (Schachtman and Goodger, 2008; Taiz et al., 2015; Wilkinson, 1999). In the calcium-dependent ABA induced stomata closure, the ABA binding receptor leads to a formation of reactive oxygen species (ROS) and then activates Ca^{2+} channels to influx Ca^{2+} into the guard cell cytosol. This leads to a further release of Ca^{2+} and $malate^{2-}$ (anion) from the guard cell vacuole and an inhibited K^+ influx into the guard cell cytosol. Stomata closure, also known as flaccid guard cell, is a net effect of an efflux of K^+ and Cl^- or anion from the guard cell caused by increased intercellular pH, combined with an ABA-induced cytosolic Ca^{2+} rise (depolarization of plasma membrane). Meanwhile, in a Ca^{2+} independent pathway, ABA caused alkalinity in cytosol leading to a K^+ efflux could also cause stomata closure without Ca^{2+} concentration change (Schachtman and Goodger, 2008; Taiz et al., 2015).

Reduced shoot growth has been associated with the inhibition of cell expansion during water deficit (Taiz et al., 2015). When water was deficient, shoot osmotic adjustment occurred slowly, cell wall loosening ability didn't change, and the meristem was hydraulically isolated from the vascular system. When high evaporative demand exposed leaves to further water potential reduction, leaves became more sensitive and less favored to growth under water deficit (Hsiao and Xu, 2000). Some species are more tolerant to mild water deficit during production and rehydrated at night, allowing leaf growth to occur (Taiz et al., 2015). Plants have avoidance mechanisms that allow them to reduce water loss by regulating stomata and maintaining water uptake through their extensive root system by increasing aspects such as biomass, length, density and depth (Kavar et al., 2008). For the plant species with leaf hairs, they respond to water deficit by increasing their hair density (Roy et al., 1999). Glaucousness or waxy bloom on leaves assisted plants to maintain high-tissue water potential and increased WUE during water deficit (Richards et al., 1986). Plants also could maintain physiological activity during extended periods of water deficit by adjusting osmotic pressure and changing cell wall elasticity (Kramer and Boyer, 1995, Morgan, 1990, Subbarao et al., 2000).

When plants were under severe water deficit during greenhouse production, reduction of flower number and/or flowering time was observed in petunia (*Petunia* x*hybrida*), carnation (*Dianthus caryophyllus*), crimson bottlebrush (*Callistemon citrinus*), geranium, impatiens (*Impatiens walleriana*) and Big Bend bluebonnet

(*Lupinus havardii*) (Alem et al., 2015b; Álvarez et al., 2013; Álvarez et al., 2009; Álvarez and Sánchez-Blanco, 2013; Blanusa et al., 2009; Chyliński et al., 2007; Niu et al., 2007; Sánchez-Blanco et al., 2009). This reduction could be caused by the plants defense mechanism known as escape. In this case, plants shortened their life cycle or growing season, for some species possibly leading to early flowering (Araus et al., 2002). However, moderate water deficit could stimulate plants to increase ABA, resulting in higher anthocyanin concentration at the cellular level (González-Villagra et al., 2017). Anthocyanin is the pigment stored in plant vacuoles that is responsible for displaying colors in leaves and that could increase the plant's tolerance of water deficit, prevent photoinhibition, maintain cell turgor pressure, function as an ultraviolet (UV) screen, and serve as an antioxidant to protect plants from free-radicals (Chalker-Scott, 2002; González-Villagra et al., 2017; Gould, 2004; Zhao and Tao, 2015). Pea (*Pisum sativum*), rennet (*Withania somnifera*), and chickpea (*Cicer artietinum*) were reported to increase leaf anthocyanin concentration under a water deficit situation (Alexieva et al., 2001; Kalefetoğlu Macar and Ekmekçi, 2009; Singh et al., 2015). In ornamental plants such as poinsettia, this plant defense mechanism could have a potential to increase crop quality or reduce production time.

Other than lower root DW under water deficit in certain species (Cai et al., 2012; Chyliński et al., 2007), there were insufficient studies regarding plant root response to water deficit. But root growth compared to shoot growth was less affected by water deficit. The difference between root and shoot response is caused by different cellular-level responses when water potential was suddenly reduced. Compared to leaf cells, when water potential was reduced, root cell osmotic adjustment happened rapidly to recover turgor pressure and water potential, cell wall loosening ability increased, and the isolation from the mature vascular system allowed roots to keep growing (Hsiao and Xu, 2000). Woody plants modified their root system architecture by producing new lateral meristems above the fine root tip, which never recovered from the water stress (*Pinus nigra* L. saplings) (Chiatante et al., 1999). Other studies reported that increased endogenous ABA induced by water deficit could increase root to shoot ratio and support primary root growth by suppressing ethylene production (Saab et al., 1990; Taiz et al., 2015). Root distribution and response to water deficit are worth further investigation.

1.5 Poinsettia Wet and Dry Growth

Potted poinsettias are one of the most important greenhouse ornamental crops in the U.S. with a wholesale value of $140 million in the top 15 states. The potted poinsettia was ranked number two among potted plants for its economic value and was ranked number one for total amount of potted plants sold (32 million pots) (USDA, 2016).

The greenhouse production process of poinsettias could have an influence on their economic value. As a major crop in fall greenhouse production, research has been conducted in order to increase grower profits. One aspect of increasing profits is to reduce production input, such as irrigation water input, fertilizer, plant growth regulators (PGRs), overhead, and labor. Applying liquid fertilizer with each irrigation is a common practice for poinsettia production (Ecke et al., 2004). Thus, irrigation plays a major role in greenhouse production of poinsettia and multiple studies have focused on this area.

Traditionally, water deficit was considered a concern during greenhouse poinsettia production because wilting between watering was not allowed, as it decreases plant quality by causing lower leaf drop. Additionally, using water deficit for plant height control was reported ineffective (Dole and Wilkins, 1999; Schuch et al., 1996). However more recent studies reported that constant low SMC (20%) could be used as replacement for PGRs (daminozide, or B-Nine), which has been a common PGR used in poinsettia production during greenhouse production to produce more compact plants (Joiner and Harrison, 1967). Plant growth regulators have had a long-lasting effect on plants in some species even years after treatment, and also may influence flower production and could lead to advanced or delayed flowering in different species (Meijón et al., 2009). Considering the limited availablity of local markets when using PGRs, using water deficit as a replacement for PGRs could not only save on water and fertilizer, but also could solve the market availability issue (Clifford et al., 2004). During greenhouse production, the poinsettia has two growth and development stages: vegetative growth and reproductive growth. The timing for applying water deficit affected poinsettias (*Euphorbia pulcherrima*) stem elongation (Alem et al., 2015a; Alem et al., 2015c). A study reported that 40% SMC is considered well-irrigated for poinsettias, and 20% SMC is considered as the water deficit treatment. Periods of 20% SMC application could be used as a height control method for poinsettia stem elongation when the plant height is taller than the height tracking curve. This method could control plant height less than 2 cm different from the target heights of 39.4 and 43.2 cm by applying 20% SMC at two different times and durations (Alem et al., 2015c). Applied water stress during the vegetative growth stage of poinsettias reduced the leaf E and g_s, but leaf g_s and E were not affected by water stress during the flowering and bract coloring development stage (Nowak, 2002).

1.6 Bedding Plants

Bedding and garden plants represent the largest crop segment in the floral industry, having generated $1.86 billion in 2015 and representing 44% of the total wholesale value of the floriculture crops in the U.S. Within the bedding and garden plants segment, annual bedding plants generated $1.3 billion, representing 69% of the total bedding and garden plant segment. Although the wholesale value of bedding and garden plants was down 1% from the previous year, those sold in hanging baskets and those in five inches or larger containers increased while those sold in smaller containers or flats reduced compared to the previous year (USDA, 2016).

Under or over watering is the most common cause for greenhouse production shrinkage (Nelson et al., 2012). Irrigation decisions were especially challenging for bedding plants due to the different water-use requirements among different species. The species we studied in this dissertation are as follows:

Angelonia (*Angelonia angustifolia*) is from the Scrophulariaceae family and ismostly used as a summer annual in the south. Native to Mexico and islands in the West Indies, angelonia is very heat-tolerant (Arnold and Arnold, 2008).

Heliotrope (*Heliotropium arbrescens*) is from the Boraginaceae family and has dense short hairs on the both sides of the leaves and stems (Arnold and Arnold, 2008; Cormier et al., 2011; Sakazaki, 2011). Heliotrope's ornamental value is the fragrant purple-blue flower clusters. Native to the Peruvian Andes, heliotropes have limited tolerance to heat or cold and are used as a transition annual or summer annual in the southern part of the U.S. (Arnold and Arnold, 2008).

Coleus (*Solenostemon scutellarioides*) is from the Lamiaceae family. Leaves have a thick, fleshy texture with a variegation pattern. The ornamental value is from its foliage's characteristic colorful pattern. Native to Malaysia and Southeast Asia, coleus thrives in shaded areas and is used as a summer annual in the southern region of the U.S. (Arnold and Arnold, 2008). Coleus greenhouse production requires proper irrigation management to maintain moisture and well-drained substrate with a pH of 5.35 to 6.0 and weekly 150 to 250 ppm of fertilizer irrigation (Bills, 2012). The Coleus recommended production temperature is between 23.9 °C to 29.4 °C. Plant growth regulators are used for plant size control. Some common production problems includes diseases due to over irrigation, low light and nutrient deficit; small plants caused by high night temperature, and pests damage (Croxton and Kessler, 2007).

Petunia (*Petunia* x *hybrida*), from the Solanaceae family, is used as a cool season annual in the southern U.S. Petunia is grown in full sun or part shade and requires higher nitrogen fertilization to maintain flowering. Its variety of flower color choice and its dependability make it a favored annual. Petunia is a cross between *P. axillaris* and *P. violacea*, both native to Argentina. Petunia height control is a greenhouse production challenge usually managed with several PGRs to produce compact plants with shorter internodes (Dole and Wilkins, 1999). Earlier research showed that water deficit could inhibit petunia shoot growth, which implying that lower SMC could be used as an effective control method for petunia greenhouse production (Blanusa et al., 2009; Niu et al., 2006).

Lantana (*Lantana camara*), from the Verbenaceae family, is very adaptable to the environment and is tolerant to drought and salt stress. Native to Florida and South America, lantana thrives in full sun and is common in Texas gardens. Lantana is used as woody shrub in the southern U.S. and as a summer annual in the northern U.S. (Arnold and Arnold, 2008). Studies reported that lantana shoots do not exhibit morphological change under a dry-down cycle water deficit (Starman and Lombardini, 2006). Another study reported that under constant SMC, lantana DW decreased as SMC level decreased from 50% to 8% (Kim and van Iersel, 2009). Controlling plant size is a challenge for lantana greenhouse production after the plant is established (Currey et al., 2015). Growers often use PGR during production of lantana to control plant height, but this may cause flower delay (Trellinger, 2012).

Impatiens × *hybrida* is a hybrid between *Impatiens wallerana* and *Impatiens hawkeri* that is native to New Guinea and is also known as New Guinea impatiens. (Dole and Wilkins, 1999; Sato and Minemura, 2014; Sato and Minemura, 2016; Siskin, 2011; Wegley, 2007). Impatiens were bred to have strong roots, thrive under high heat, and humidity, full sun, and are unaffected by downy mildew (SunPatiens, 2018). The plant also has a high water requirement during greenhouse production (Sun et al., 2015).

Salvia (*Salvia splendens*), from the Lamiaceae family, is native to northern temperate regions throughout the world and is used as a cool season annual in the northern U.S. and as a transitional annual in the southern U.S. *Salvia splendens* is not very heat or drought tolerant compered to other *salvia spp*, requires regular irrigation, and is susceptible to salt damage (Arnold and Arnold, 2008).

1.7 Project Objectives

Based on the gaps identified in the current literature, the following objectives were established for this project:

1. Ascertain the effects on plant quality of lowering SMC to conserve water during production.
2. Determine if plants produced with less water will acclimate to infrequent irrigation during shelf life.
3. Analyze the economic dimensions of traditional vs. water-conserving irrigation practices considering production inputs and reduction in shrinkage through the market channels.
4. Quantify plant quality effects on shelf life in a simulated retail environment.

CHAPTER II

REDUCING SUBSTRATE MOISTURE CONTENT (SMC) DURING GREENHOUSE PRODUCTION AND POSTPRODUCTION OF AGELONIA AND HELIOTROPE IMPROVES CROP QUALITY AND ECONOMIC VALUE[1]

2.1 Abstract

The objective of this study was to determine the effect of two levels of substrate moisture content (SMC) applied during greenhouse production on angelonia (*Angelonia angustifolia*) 'Angelface Blue' and heliotrope (*Heliotropium arborescens*) 'Simply Scentsational' growth and physiological parameters and subsequent postproduction quality during simulated retail conditions. At the end of production, angelonia total plant shoot dry weight (DW) was reduced with 20% SMC compared with 40% SMC, and plants grown with 20% SMC had higher shoot coloring percentage, reduced internode length, and required less irrigation labor related costs compared with 40% SMC. Heliotrope grown at 20% SMC produced the same size plant as 40% SMC, but had a higher shoot coloring percentage at the end of production and postproduction, indicating lower SMC resulted in higher visual quality compared with 40% SMC. For both species, 20% SMC increased plant visual quality compared with 40% SMC and reduced irrigation water input throughout production, resulting in reduced production costs and increased floral crop economical value.

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2.2 Introduction

In 2013, the U.S. green industry generated $136.44 billion in direct output, of which $16.77 billion were contributed by greenhouse and nursery growers (Hodges et al., 2015). In order to produce high-quality, uniform and consistent products, commercial floriculture greenhouses and nurseries apply irrigation and fertilization at a high frequency, thus potentially leading to the contamination of ground and surface water (Richards and Reed, 2004). Reducing volume or frequency of irrigation would not only save water, but could also reduce the greenhouse production time and costs by reducing water-related energy, labor, fertilizer, pesticides, growth regulators, and overhead costs, thus increasing sustainability (Lichtenberg et al., 2013). Also, studies show that plants with more sustainable attributes positively impact consumer preferences (Behe et al., 2013; Hall et al., 2010).

The portion of crops grown but considered unsalable is termed shrinkage. The later shrinkage occurs in the value chain, the larger impact it has on profitability, because more inputs such as overhead, labor, water, fertilizer, and pesticides have been used prior to plants being thrown away. A recent survey of larger growers reported that production level shrink ranged from 2-10%, with a median of 5% whereas retail-level shrink ranged from 8-33%, with a median of 19% (Hall et al., 2011). Leaf and flower senescence and flower abscission induced by ethylene or water deficit during shipping and shelf life causes the plant to lose its aesthetic value, another cause of postharvest shrinkage for bedding and potted plants (Starman et al., 2007). Inadequate irrigation is a major challenge during postproduction (shelf life) since irrigation systems are almost never ideal in retail environments due to untrained personnel or under staffing.

Nemali and van Iersel developed a sensor based automatic irrigation system to reduce irrigation water usage by maintaining distinct and constant substrate moisture content (SMC) levels throughout the production period (2006). By controlling the timing and length of lower SMC level, a controlled water deficit was applied to potted floral plants. Utilizing controlled water deficit irrigation during greenhouse production could not only reduce water input and increase plant water use efficiency, but also increase plant quality by producing a more compact plant without applying a plant growth regulator. Applying water at a consistent 20% SMC during greenhouse production of angelonia (*Angelonia angustifolia*) 'Angelface Blue' produced a more compact crop due to shorter internodes, and reduced or prevented wilting during the water deficit postproduction period, thus increasing plant postproduction quality. This consistent water deficit throughout angelonia production also increased the water use efficiency (WUE) (Jacobson et al., 2015). Similar results were reported for poinsettia (*Euphorbia pulcherrima*). A constant 20% SMC was also an effective alternative shoot height control method compared to plant growth retardant (PGR; daminozide, B-Nine) application during poinsettia greenhouse production (Alem et al., 2015).

The objective of this study was to determine the effect of water deficit using two levels of SMC applied by the dry down method during greenhouse production on angelonia and heliotrope growth and physiological parameters. The dry down method used in this study was conducted by irrigating to container capacity (CC) when the target

SMC level was indicated by the sensor reading. The root substrate was dried back down to the target SMC and re-watered to CC repeatedly as needed throughout the experiment. We also studied the effects on postproduction performance during simulated retail conditions. Lastly, we examined the effects on associated economic costs. Our hypothesis was that lower SMC during greenhouse production would lower irrigation costs, better acclimate plants for the retail environment, and allow plants to maintain higher quality during postproduction.

2.3 Materials and Methods

2.3.1 Plant material and growing conditions

Rooted cuttings of angelonia and heliotrope (*Heliotropium arborescens*) 'Simply Scentsational' were obtained from a commercial propagator (EuroAmerican Propagators, Bonsall, CA) during production week 4 (26 Jan., 2016) and graded for uniformity upon arrival. One rooted cutting was planted in each of forty 3.79 L nursery containers (Nursery Supplies Inc., Kissimmee, FL) with commercial peat-based soilless root substrate (85% Canadian sphagnum peatmoss and 15% perlite; BM 6, Berger, Saint-Modeste, Canada) with 17 g of 15N-3.9P-9.9K slow release fertilizer per container (Osmocote, Peters Professional, Scotts-Sierra, Marysville, OH) incorporated evenly throughout before planting. Plants were grown in a glass wall and polycarbonate roof greenhouse in College Station, TX for the greenhouse production stage [from 11 Feb. (production week 6) to 17 April (production week 16), 2016.]. Plants were treated with an etridiazole and thiophanate-methyl (Banrot, Everris NA Inc. Dublin, OH) root substrate drench to prevent root rot. Plants were then allowed 14 days for root establishment before initiation of irrigation treatments. During this time, they were watered once in addition to the Banrot drench.

The average temperature in the greenhouse during the experiment was 24.7 ºC day/19.7 ºC night. Average daily light integral (DLI) was 23.43 $mol\cdot m^{-2}\cdot d^{-1}$ and relative humidity was 56.2% during the greenhouse production stage of experiment. Environmental data was measured by WatchDog 450 data loggers and LightScout quantum light sensors (Spectrum Technologies Inc., Aurora, IL).

At week 13 (1 April, 2016), plants were deemed to be marketable based on industry standards. At this time, plants went through a simulated shipping process. Simulated shipping consisted of hand-watering to CC before moving plants by cart into a dark lab for 48h at 20 ± 2 °C and 42.1% relative humidity. After shipping, plants were returned to the greenhouse by cart and held under 50% shade cloth for two weeks (week 14 and 15) for simulated shelf life, during which plants were only watered when wilting began to occur. During the postproduction, the average temperature in the greenhouse during the experiment was 22.4 °C day/19.8 °C night. Average daily light integral (DLI) was 11.1 $mol\cdot m^{-2}\cdot d^{-1}$ and relative humidity was 65.1%.

2.3.2 Substrate moisture content (SMC) treatments.

Two irrigation treatments (20% and 40% SMC) were applied in two experiments (one species per experiment) starting at production week 8 and ending at production week 13 (the greenhouse production stage). SMC was defined as V_w/V_T (V_w is the volume of water; V_T is the total volume of substrate particles, water, and air space). The 40% SMC treatment (well-watered, traditional irrigation method) consisted of allowing the substrate to dry down to 40% SMC before hand-watering to CC (59.6% SMC,) which was until the initiation of drainage. The 20% SMC treatment (alternative irrigation method) consisted of allowing substrate to dry down to 20% SMC before hand-watering to CC. Substrate moisture contents were monitored by a watchdog 1000 series Micro Station, and SM 100 WaterScout soil moisture sensors (Spectrum Technologies, Inc. Aurora, IL). There was one sensor per treatment per species inserted in the root substrate of a container that was closer to the center of the greenhouse bench to reflect the average SMC of the treatment and avoid the drying effect of the bench edges. Sensors recorded SMC every 30 minutes and each irrigation event was determined based on the sensor readings (observed daily) and the calibration of the sensor (Fig. 2.1). All irrigations used reverse osmosis (RO) water.

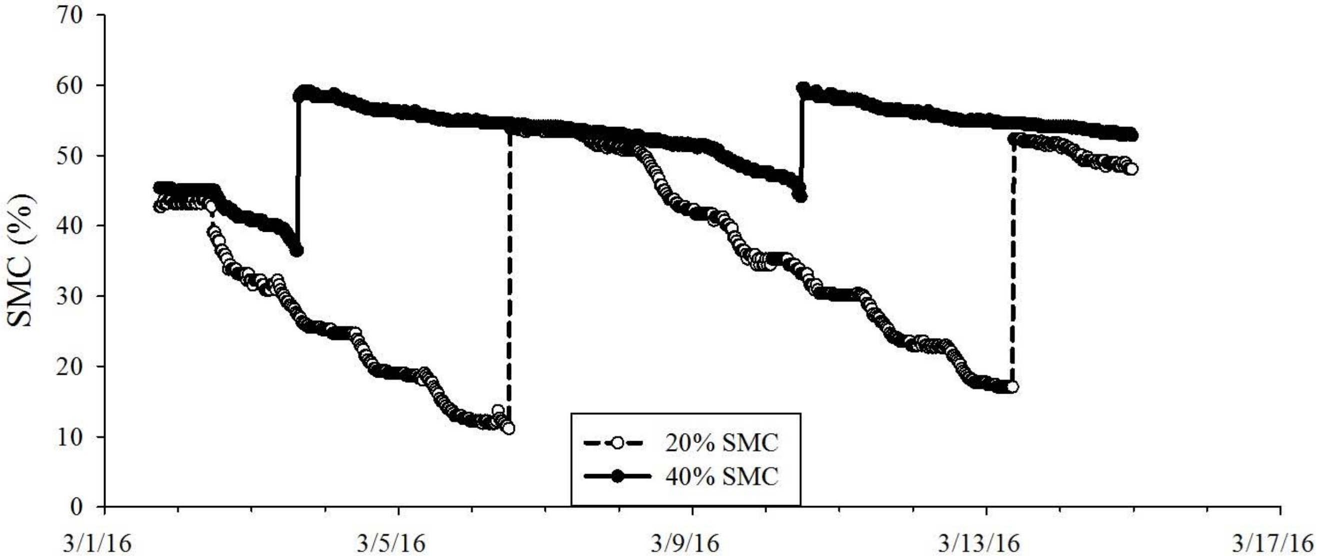

Figure 2.1. Fourteen days (1 to 14 Mar., 2016) of 20% and 40% substrate moisture content (SMC) treatment sensor readings during greenhouse production. The 20% and 40% SMC substrates were irrigated to container capacity (CC) when the target SMC levels were indicated on the sensors. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000 (Guo et al., 2018a).

2.3.3 Sensor calibration

Soil moisture sensors were calibrated by filling five 1-L plastic beakers with 1-L volume of oven dried root substrate. Substrate density was standardized by tapping dry substrate filled plastic beakers five times from a uniform height approximately 3 to 6 cm above a sturdy table (Fonteno et al., 1995). Each beaker was emptied into one of five polyethylene plastic bags (Ziploc, S.C. Johnson & Son, Inc. Racine, WI), and 100, 200, 300, 400, or 500 ml of water was poured into one of the five bags. Root substrate was mixed with the water thoroughly and allowed to incubate for 24 h. All dry weight (DW), wet weight (WW) and the net weight of the beakers were measured and recorded. Root substrate was repacked into the same plastic beaker as previously. Three sensor readings were taken at three different locations in the beaker, avoiding taking readings too close to the edge of the beaker according to the WaterScout SM 100 Soil Moisture Sensor Product Manual. Substrate moisture content was calculated as SMC = (WW - DW) x 100% /1000 (Cai et al., 2012).

2.3.4 Data collection

For the economic analysis of water usage, containers were weighted before each irrigation event during the production and postproduction stage of the experiments. After irrigation, containers were allowed to drain for 1 h and then reweighed. The weight difference was calculated and recorded to determine total irrigation volume. Each irrigation event was documented and summed to determine total number of irrigation events during production and/or postproduction.

Starting production week 6, substrate leachate electrical conductivity (EC) and pH were monitored weekly for 40% SMC, and measured after each irrigation event for 20% SMC using the pour-thru method (LeBude and Bilderback, 2009; Wright, 1986), with a LAQUA twin EC22 Meter and a LAQUA twin pH22 Meter (Spectrum Technologies Inc., Aurora, IL). The pH for both angelonia and heliotrope was 6.0 at the beginning of the experiment and 5.5 at the end of the experiment. For both angelonia and heliotrope, EC decreased as the experiment proceeded and was not affected by the SMC treatment (Fig. 2.2).

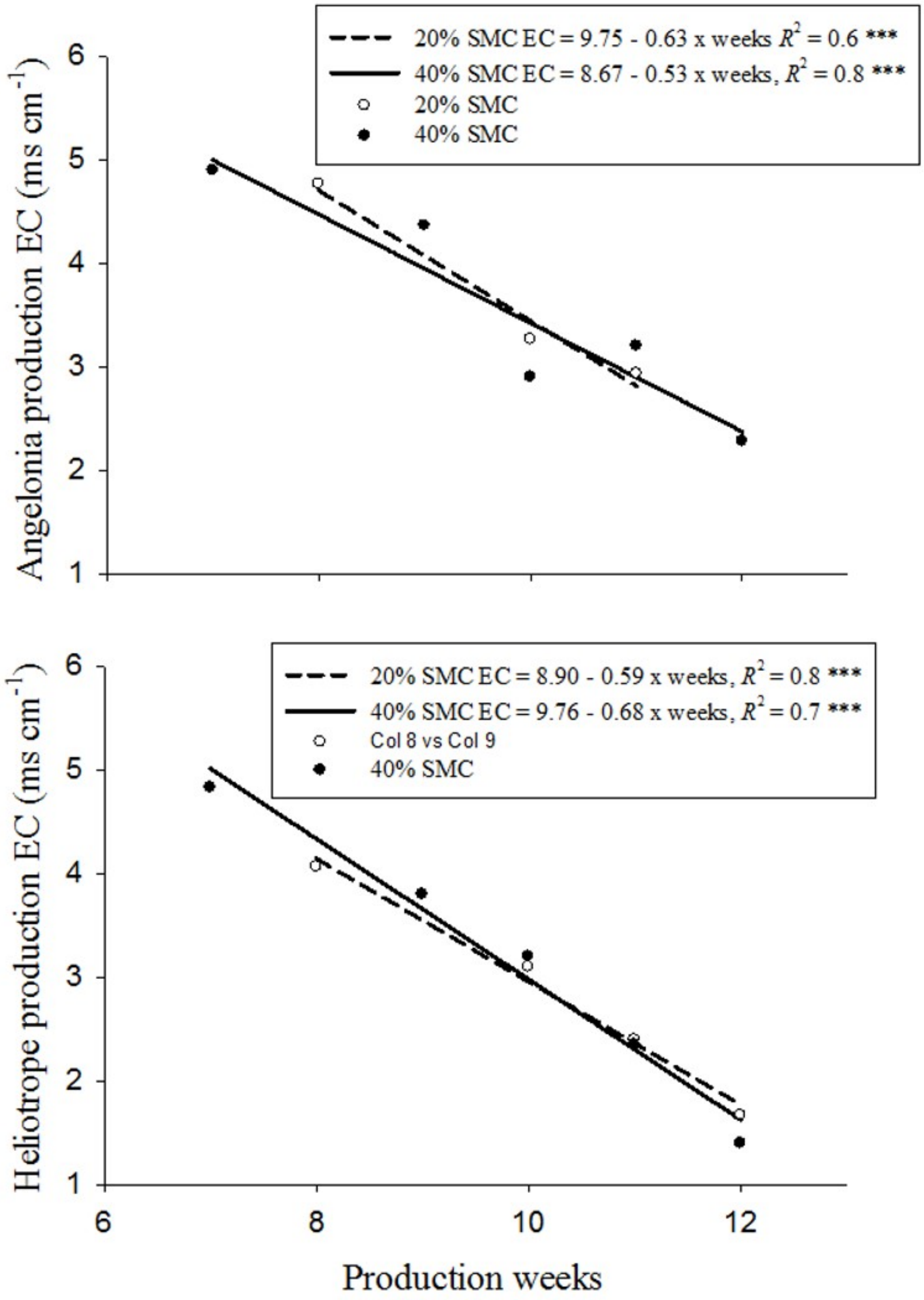

Figure 2.2. Electrical conductivity (EC) of *Angelonia angustifolia* ‘Angelface Blue’ and *Heliotropium arborescens* ‘Simply Scentsational throughout the greenhouse production stage of the experiment (production weeks 6 to 13). *** significance of the linear regression at $P \leq 0.001$(Guo et al., 2018a).

Plant height and width were recorded weekly. Plant height was measured from the root substrate surface to the plant growing point. Two plant widths were measured across the greatest plant width and the perpendicular width. Growth index (GI) was calculated as: GI = plant height/2 + (plant width1+plant width2)/4 (Niu et al., 2007).

At the end of postproduction, all 10 replications for both species were destructively harvested. Data taken on angelonia at the end of postproduction included flower and bud number/stem on three major stems on each plant, total plant shoot DW, and total raceme number. Angelonia stems were divided into three sections: vegetative, flower, and bud. Length and node number of the three sections of the stem were measured and internode length was calculated as length divided by node number. Flowers were those with the reproductive organs visible and buds were those not fully revealing the reproductive organs. Data taken on heliotrope at the end of postproduction included total flower number, cyme number, and total plant shoot DW. Total plant shoot DW was determined after being oven-dried at 80 °C for 48 h to constant weights.

In order to quantify the quality of plants, photos of shoots for both species were taken from above at the end of production and postproduction to determine the shoot coloring percentage (the percentage of the shoot covered by flowers). To determine how SMC affected root orientation in the container, root ball photos were taken at the end of postproduction from the bottom of the root ball and both sides of the root ball. Root ball covering percentage was the percentage of the substrate surface covered by roots after removal from the container. The shoot coloring percentage and root ball coverage percentage were analyzed with Photoshop CS6 (Adobe Systems Inc. San Jose, CA).

Photoshop quantified the colored area (flowers) and green area (leaves), and the total shoot area was calculated as colored area + green area. The shoot coloring percentage was then calculated as colored area divided by total shoot area. To determine root ball coverage percentage Photoshop quantified the total root ball area as root area + substrate area. The root ball coverage percentage was calculated as root coverage area divided by total area.

The relative greenness of leaves was measured by a chlorophyll meter (Special Products Analysis Division, SPAD-502 Minolta Camera Co., Osaka, Japan) starting in week 10. SPAD readings of three fully expanded green leaves per plant were taken from three plants of each treatment. SPAD readings ranged from 0 to 100 by measuring the light transmission at wavelengths of 650 and 940nm (Markwell et al., 1995).

2.3.5 Experimental design and data analysis

The experiment was a randomized complete design (RCD) with 10 replications and two treatments (20% and 40% SMC). Each species was analyzed separately. The data were analyzed by SAS (version 9.4; SAS Institute, Cary, NC). Mean separation was conducted using student t-tests, if significant at the 5% level. The EC and GI were plotted against production weeks and linear or cubic regression was conducted and the significance was analyzed using JMP (SAS Institute, Cary, NC).

2.3.6 Economic analysis

Partial budgeting modeling procedures were used to measure the costs and potential benefits of short-run changes in cultural practices in the production systems analyzed. For both tested plants, estimated container number per bench was calculated based on industry standard bench size (19.5’ x 5.5’) and the finished plant width. Space saved was calculated based on final spacing difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC. Labor saved was calculated based on the difference in the number of irrigation events between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC. Total water input was documented during each irrigation event. Irrigation amount saved was calculated based on the difference between total irrigation applied during the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.

2.4 Results and Discussion

2.4.1 Plant morphology

At the end of postproduction (production week 15), there was no difference between SMC treatments for angelonia flower or bud stem lengths, vegetative or flower stem node numbers, flower or bud number per stem, total flower or bud numbers, or bud stem internode length (data not shown). Substrate moisture content at 40% increased total plant shoot dry weight (DW), total raceme number, total stem length, bud stem node number, and vegetative and flower stem internode lengths (Table 2.1). Angelonia growth index (GI) was greater with 40% SMC one week after SMC treatment began (week 9) and continued to be greater throughout production and post-production (Fig. 2.3).

For heliotrope, there was no difference between SMC treatments for cyme number, shoot DW or GI; only flower number differed between SMC treatments (data not shown). At the end of production, all heliotrope had 22 cymes (SD = 1.9). Total flower number was greater with 20% SMC (567 flowers, SD = 38.6) compared with 40% SMC (389 flowers, SD = 40.9), which indicated an average cyme was larger with 20% SMC than 40% SMC, improving visual quality of 20% SMC plants. Heliotrope GI was not different between SMC treatments at the end of greenhouse production (39.3 cm, SD = 1.5 cm, week 13) or postproduction (44.2 cm, SD = 1.3 cm, week 15). At the end of postproduction (week 15), shoot DW was not affected by SMC treatments (31.3 g, SD = 0.9g).

The reduction in final GI (Fig. 2.3) and DW for angelonia was due to reduced internode length in the vegetative and flower stem sections. Reduced internode length has been associated with the inhibition of cell expansion during water deficit (Taiz et al., 2015). When water was deficient, shoot osmotic adjustment occurred slowly, cell wall loosening ability didn't change, and the meristem was hydraulically isolated from the vascular system. When high evaporative demand exposed leaves to further water potential reduction, plant shoots became more sensitive and less favored to growth under water stress (Hsiao and Xu, 2000).

Other studies have documented varying species response to reduced irrigation volume. Poinsettia (*Euphorbia pulcherrima*), crimson bottlebrush (*Callistemon citrinus*), hibiscus (*Hibiscus acetosella*), gardenia (*Gardenia jasminoides*), english lavender (*Lavandula angustifolia*), fan flower (*Scaevola aemula*), geranium (*Pelargonium zonale*), impatiens (*Impatiens walleriana*), oleander (*Nerium oleander* L.), big bend bluebonnet (*Lupinus havardii*), dusty miller (*Cineraria maritima*), petunia (*Petunia ×hybrida*), and plumbago (*Plumbago auriculata*) were reported to have lower GI and DW when irrigation volume was reduced (Andersson, 2000; Álvarez et al., 2011; Alem et al., 2013; Alem et al., 2015; Bayer et al., 2013; Bayer et al., 2015; Chyliński et al., 2007; Niu et al., 2006; Niu et al., 2007; Niu et al., 2008; Starman and Lombardini, 2006). However, the morphology of lantana (*Lantana camara*), cardinal flower (*Lobelia cardinalis*), geranium (*Pelargonium hortorum*), agastache (*Agastache urticifolia*), ornamental pepper (*Capsicum annuum*), and vinca (*Catharanthus roseus*) were not affected by reducing irrigation volume (Chyliński et al., 2007; Niu et al., 2006; Starman and Lombardini, 2006).

Different responses of plants to controlled water deficit in studies reported in the literature could be due to different experimental methods, or the anatomical and morphological variation among different plant species. Studies indicated that prolonged exposure to severe water deficit reduced plant growth whereas short periods of moderate water deficit did not affect plant growth (Jacobson et al., 2015; Niu et al., 2006). When geraniums were held at 30% SMC for 10 days there was no significant effect on plant growth (Chyliński et al., 2007). In another study, reduced irrigation during geranium's entire production cycle showed significant growth inhibition (Andersson, 2000). Various results of water deficit effects may be due to species specific leaf morphology including leave size, cuticle thickness, leaf surface texture, or number and structure of trichomes which all affect transportation rate (Taiz et al., 2015). The different response to water deficit between species in this study may be due to the dense short hairs on both sides of heliotrope leaf surfaces (Cormier et al., 2011; Sakazaki, 2011) forming a thicker boundary layer, thus reducing transpiration under water deficit situations. Leaf hairs, formed by trichome cells, reduce transpiration water loss by covering the stomata crypts and increasing moisture in the boundary layer of the leaf surface (Begg, 1980; Monneveux and Belhassen, 1996).

Table 2.1. The effect of substrate moisture content (SMC) on total plant shoot dry weight (DW), total raceme number, total stem length, bud stem node number, vegetative stem internode length, and flower stem internode length at the end of the postproduction (week 15) of *Angelonia angustifolia* 'Angelface Blue'. Substrate moisture content (SMC) was calculated as SMC = (substrate wet weight – substrate DW) x 100% /1000.

SMC	Total plant shoot DW (g)	Total raceme number	Total stem length (cm)	Bud stem node number	Vegetative stem internode length (cm)	Flower stem internode length (cm)
20%	15.62 b [z]	11.0 b	57.3 b	5.1 b	11.8 b	1.9 b
40%	19.06 a	12.7 a	60.4 a	6.0 a	13.2 a	2.0 a

[z] Means separation by student t-test at $P \leq 0.05$.

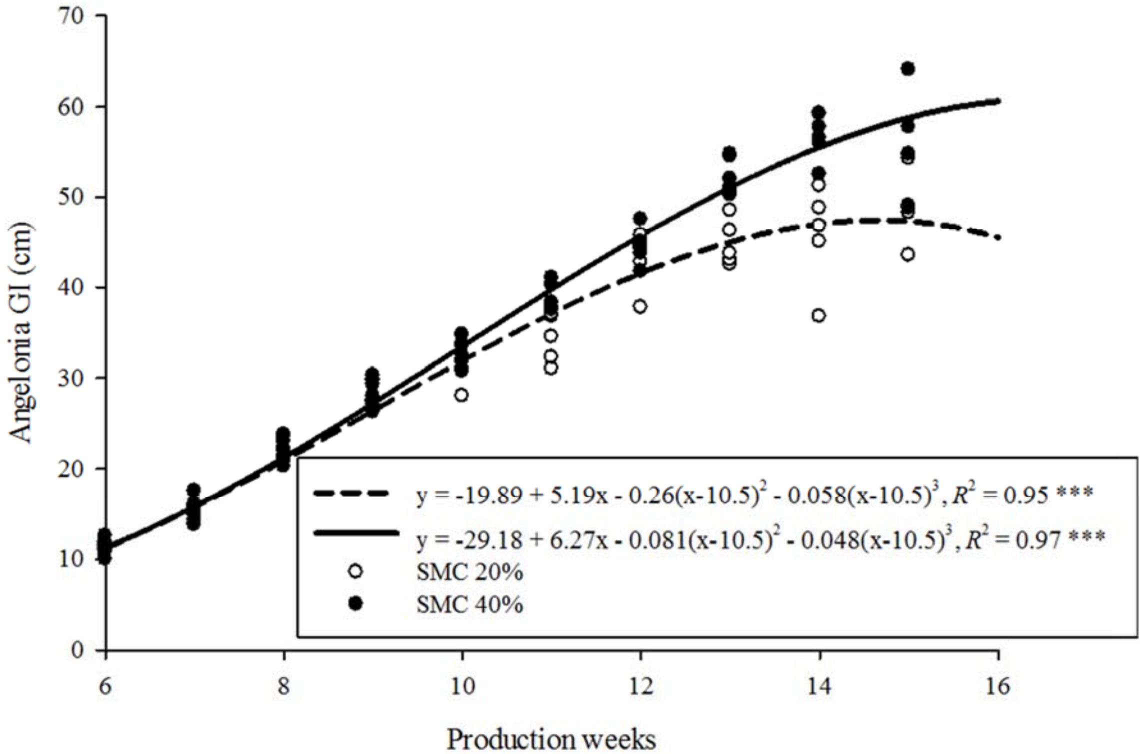

Figure 2.3. Effect of 20% and 40% substrate moisture content (SMC) on weekly growth index (GI = plant height/2 + (plant width 1 + plant width 2)/4.) from production week 6 to 13, and post-production from week 14 to 15 of *Angelonia angustifolia* 'Angelface Blue'. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000. *** significance of the cubic regression at $P \leq 0.001$ (Guo et al., 2018a).

2.4.2 Water usage and economics

In this study, we considered the 40% SMC treatment as the traditional well-irrigated method that is currently used by floral industry growers. Compared with angelonia grown under 40% SMC, plants grown under 20% SMC have a smaller canopy, thus they required less bench space, which may translate to lower overhead costs associated with bench space. Compared with 40% SMC, angelonia grown under 20% SMC saved 9.0% and 20.6% space during production or postproduction (Table 2.2), respectively. 20% SMC required less irrigation during production, thus angelonia saved 25.0% in irrigation labor-related costs during production, however, the postproduction irrigation event was not affected by SMC treatment. Compared with 40% SMC, 20% SMC saved 16.3% and 8.8% irrigation amount during production or postproduction (Table 2.2), respectively.

Heliotrope canopy size was not affected by SMC treatment during production, thus the overhead-related savings was only 2.8% during production and even a negative 12% during postproduction. 20% SMC saved 25% in labor during production but was not affected by SMC treatment during postproduction. Compared with 40% SMC, 20% SMC saved 5.3% and 3.5% irrigation amount during heliotrope production and postproduction (Table 2.3), respectively.

These results show that costs of production were reduced by using an alternative watering method (20% SMC) compared with the traditional irrigation method (40% SMC). The reduction in costs are a result of reduced bench space required (which reduced the residency cost or overhead costs), reduction of total irrigation water applied, and the irrigation labor-related costs (e.g. checking emitters, etc.).

Table 2.2. The cost of *Angelonia angustifolia* 'Angelface Blue' grown at two substrate moisture contents (SMC) (20% and 40%) in greenhouse production and postproduction (Guo et al., 2018a).

Production								
SMC %	Estimated container number/bench	Space saved (%)	Total no. of irrigation events		Labor saved (%)	Irrigation amount (L/pot)		Irrigation amount saved (%)
20.0	77.0[z]	9.0[y]	6.0[x]	b[w]	25.0[v]	6.5[u]	b	16.3[t]
40.0	70.0	0.0	8.0	a	0.0	7.8	a	0.0
Postproduction								
SMC %	Estimated container number/bench	Space saved (%)	Total no. of irrigation events		Labor saved (%)	Irrigation amount (L/pot)		Irrigation amount saved (%)
20.0	45.0	20.6	2.0	a	0.0	2.3	b	8.8
40.0	36.0	0.0	2.0	a	0.0	2.5	a	0.0

[z] Estimated container number/bench was calculated as standard bench size (19.5' x 5.5')/average canopy size of the plant.
[y] Space saved was calculated based on final spacing difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[x] Total no. of irrigation events during eight weeks of greenhouse production.
[w] Means separation by student-t test multiple comparisons at $P \leq 0.05$. Means with same letter are not different.
[v] Labor saved was calculated based on irrigation events number difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[u] Total irrigation amount per container was the sum of each irrigation water input during eight weeks of greenhouse production.
[t] Irrigation amount saved was calculated based on total irrigation amount difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.

Table 2.3. The cost of *Heliotropium arborescens* 'Simply Scentsational' grown at two substrate moisture contents (SMC) (20% and 40%) in greenhouse production and postproduction (Guo et al., 2018a).

SMC %	Estimated container number/bench	Space saved (%)	Total no. of irrigation event		Labor saved (%)	Irrigation amount (L/pot)		Irrigation amount saved (%)
Production								
20.0	56.0[z]	2.8[y]	6.0[x]	b[w]	25.0[v]	7.5[u]	b	5.3[t]
40.0	54.0	0.0	8.0	a	0.0	8.0	a	0.0
Postproduction								
20.0	31.0	-12.0	2.0	a	0.0	1.19	a	3.5
40.0	35.0	0.0	2.0	a	0.0	1.23	a	0.0

[z] Estimated container number/bench was calculated as standard bench size (19.5' x 5.5')/average canopy size of the plant.
[y] Space saved is calculated based on final spacing difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[x] Total no. of irrigation events during eight weeks of greenhouse production.
[w] Means separation by student-t test multiple comparisons at $P \leq 0.05$. Means with same letter are not different.
[v] Labor saved is calculated based on irrigation events number difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[u] Total irrigation amount per container was the sum of each irrigation water input during seven weeks of greenhouse production.
[t] Irrigation amount saved is calculated based on total irrigation amount difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.

2.4.3 Visual quality

Shoot coloring percentage was greater for both species with 20% SMC at the end of production and post-production (Fig. 2.4). For angelonia, shoot coloring percentage was 36.0% or 26.1% during production and 25.7% or 20.7% during postproduction, for 20% or 40% SMC respectively. For heliotrope, shoot coloring percentage were 11.8% or 8.2% during production and 11.9% or 8.0% during postproduction, for 20% or 40% SMC, respectively. For heliotrope the 20% SMC produced plants with higher shoot color percentage by increasing the number of flowers in a cyme resulting in increased cyme size. Shoot color percentage declined during postproduction for angelonia, but not for heliotrope. Root ball covering percentage also varied with species. Angelonia had less roots at the side of the container but not the bottom of the container with 20% SMC compared with 40% SMC. Heliotrope had more roots at the bottom of the container but not the sides of the container with 20% SMC compared with 40% SMC (Fig. 2.5 and Fig. 2.6).

For angelonia and heliotrope, in the first two weeks of treatment (week 10-11), 40% SMC had higher SPAD, however, three weeks after starting SMC treatment, 20% SMC had higher leaf chlorophyll index throughout the production stage. During postproduction, SPAD readings were not different for angelonia but for heliotrope the 20% SMC still had higher SPAD readings compared with 40% SMC (Fig. 2.7). The higher SPAD reading for 20% SMC in angelonia and heliotrope could have been due to increased leaf thickness, lower leaf water content, or increased leaf chlorophyll content

(Martínez and Guiamet, 2004). SPAD readings provided a quick, nondestructive and objective estimation of visual quality of plant foliage (Wang et al., 2005).

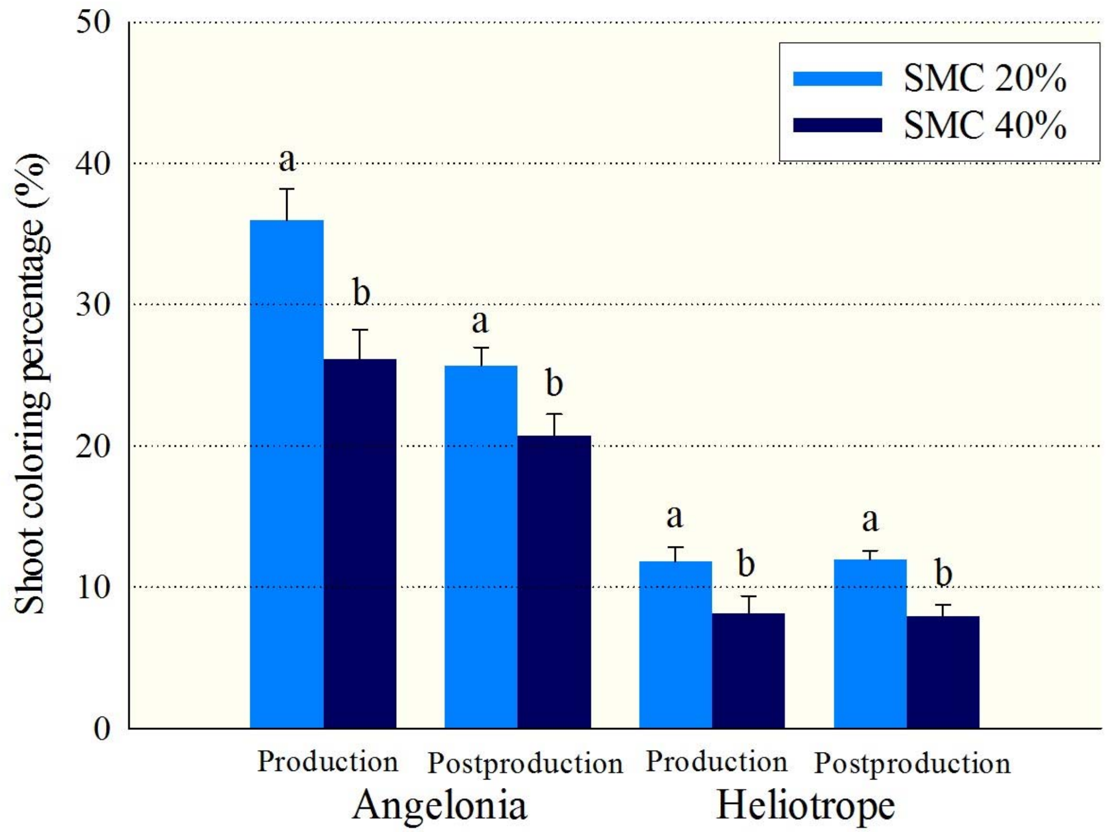

Figure 2.4. The shoot coloring percentage of *Angelonia angustifolia* ‘Angelface Blue’ and *Heliotropium arborescens* ‘Simply Scentsational’ at the end of production (week 13), and the end of post-production (week 15). Values obtained through Photoshop image process. Mean separation for both production times by student t-test at $P \leq 0.05$. Means with same letter are not different. Substrate moisture content (SMC) was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000 (Guo et al., 2018a).

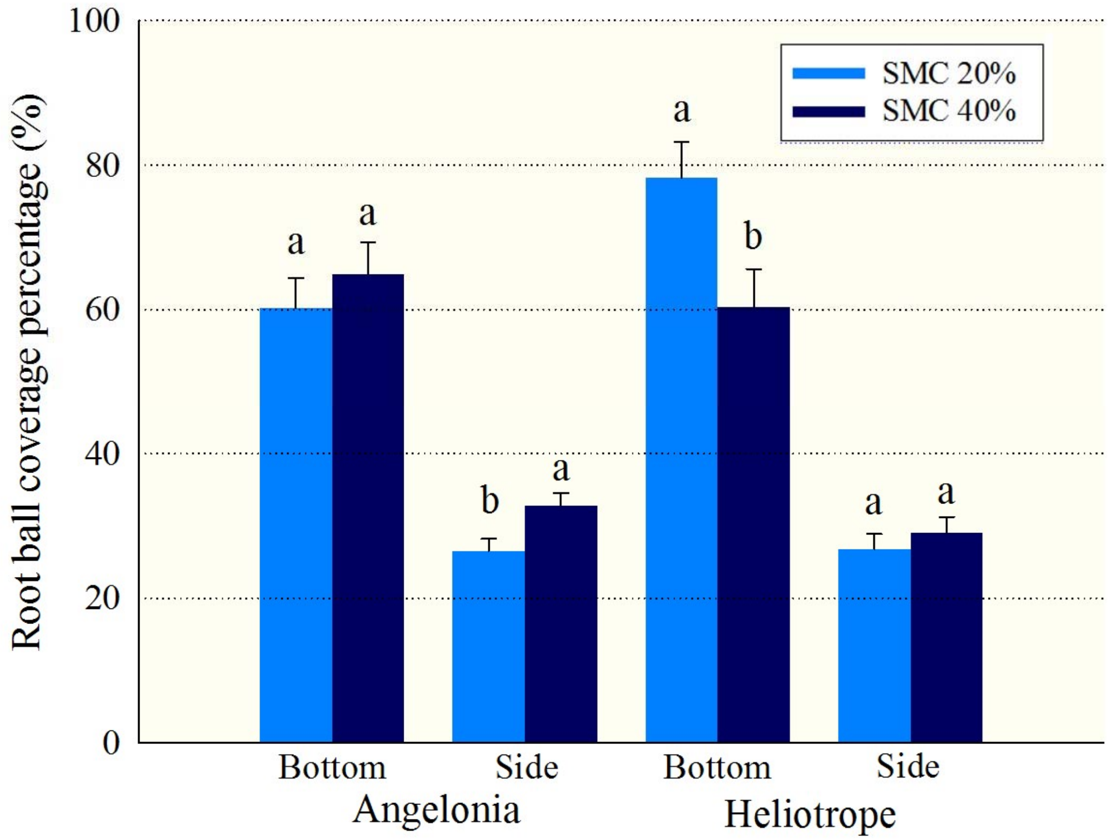

Figure 2.5. The effect of 20% and 40% substrate moisture content (SMC) on root ball covering percentage, on the bottom and the average of two sides of the root balls after removal from the container for *Angelonia angustifolia* 'Angelface Blue' and *Heliotropium arborescens* 'Simply Scentsational'. Values obtained through Photoshop image process. Mean separation within the group by student t-test at $P \leq 0.05$. Means with same letter are not different. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000 (Guo et al., 2018a).

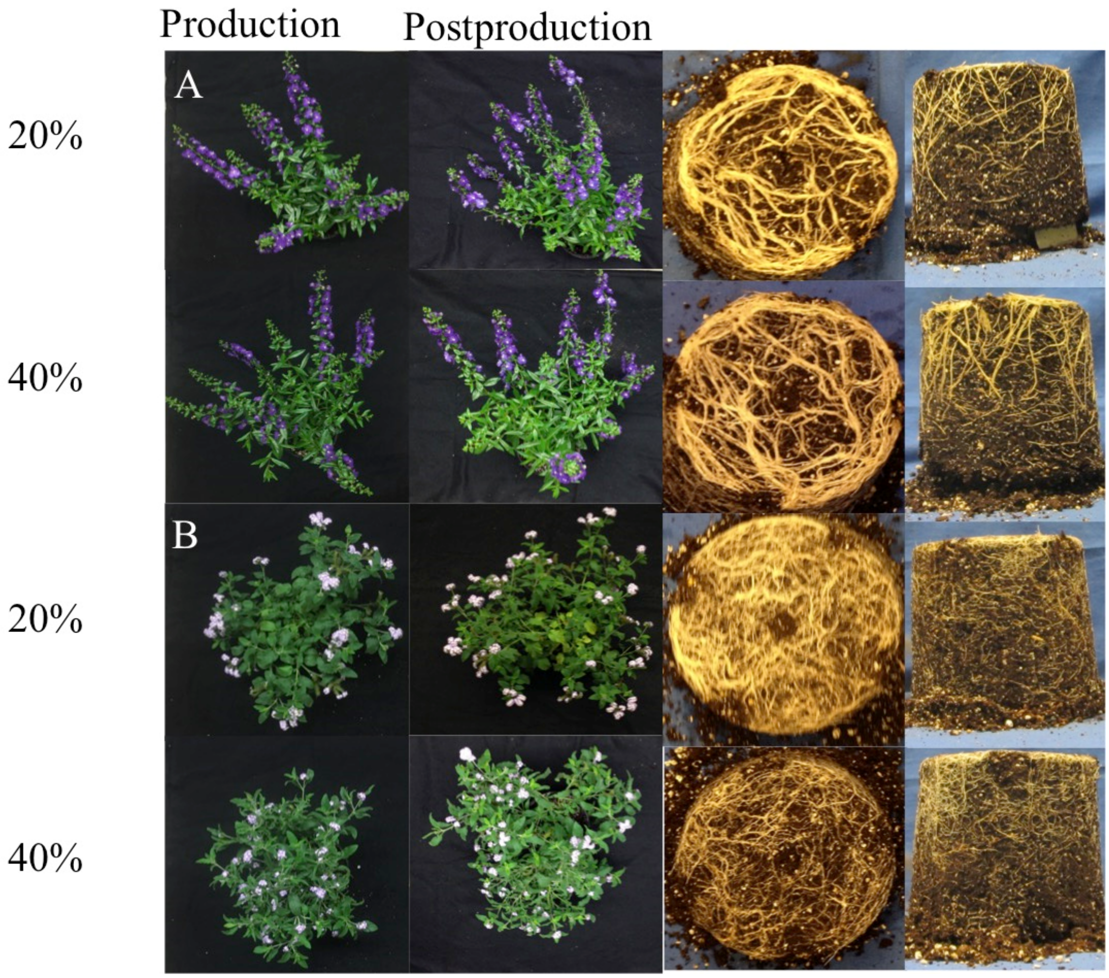

Figure 2.6. Illustration of shoot coloring percentage and root ball coverage percentage for (a) *Angelonia angustifolia* ‘Angelface Blue’, and (b) *Heliotropium arborescens* ‘Simply Scentsational’ at the end of postproduction. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000 (Guo et al., 2018a).

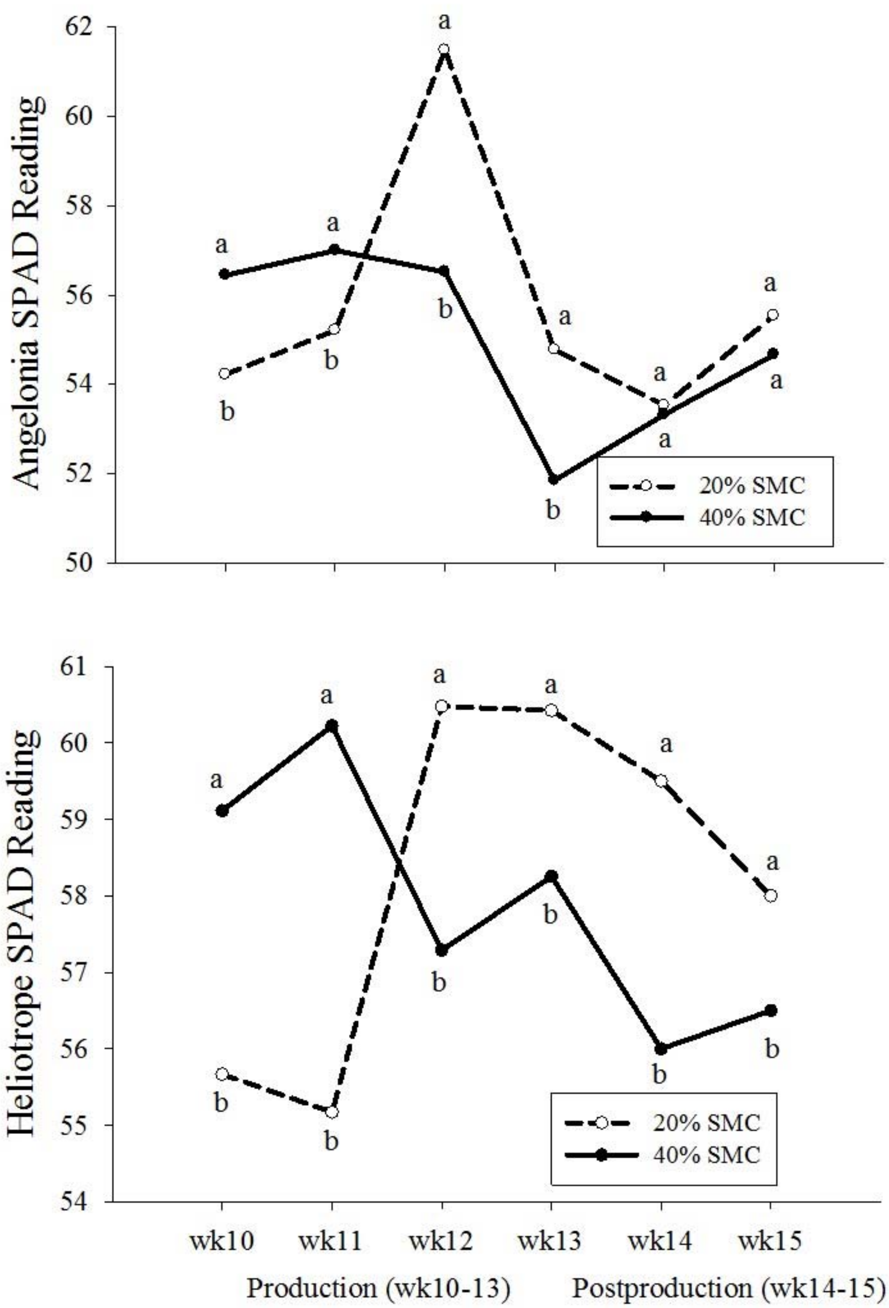

Figure 2.7. Leaf chlorophyll index [Special Products Analysis Division (SPAD) values] for two soil moisture content (SMC) treatments for *Angelonia angustifolia* 'Angelface Blue' and *Heliotropium arborescens* 'Simply Scentsational' during greenhouse production from week 10 to week 15, and post-production from week 14 to 15. Means separation by student t-test at $P \leq 0.05$. Means with same letter are not different. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000 (Guo et al., 2018a).

2.5 Conclusions

Angelonia shoot and root growth were reduced with 20% SMC compared with 40% SMC manifested as reduced total shoot DW and lower root ball coverage percentage on the sides of the pot. The visual quality of 20% SMC was higher at the end of production and postproduction, as shown in higher shoot coloring percentage, and shorter internode length, compared with 40% SMC. In short, 20% SMC produced more compact angelonia plants with increased visual quality.

Heliotrope morphological and physiological responses to SMC treatments were in contrast to angelonia. Shoot growth was not affected by SMC treatment and there was greater root ball coverage percentage on the bottom of the container with 20% SMC. Heliotrope grown at 20% SMC had higher shoot coloring percentage at the end of production and postproduction compared with 40% SMC indicating lower SMC resulted in higher visual quality. Therefore, 20% SMC produced the same size heliotrope with more potential for a higher survival rate, and a better visual quality compared with 40% SMC.

The 20% SMC reduced total irrigation event number and associated costs for both angelonia and heliotrope during production. Angelonia responded to 20% SMC with reduced plant canopy size compared with 40% SMC, thus reducing bench space needed, thereby reducing overhead costs incurred during greenhouse production. Based on partial budgeting modeling procedures we used in this experiment, 20% SMC proved to be a more cost-efficient production method for angelonia and heliotrope greenhouse growers. Further studies should be conducted to explore how other plant species respond to reduced SMC and their impact on economic value.

CHAPTER III

REDUCING SUBSTRATE MOISTURE CONTENT DURING GREENHOUSE PRODUCTION OF POINSETTIA IMPROVES POSTPRODUCTION QUALITY AND ECONOMIC VALUE[2]

3.1 Abstract

The objective was to determine the effect of substrate moisture content (SMC) during poinsettia (*Euphorbia pulcherrima*) greenhouse production on plant quality, postproduction longevity and economic value. Two experiments were conducted one in 2016 with 'Freedom Red' and the other in 2017 with 'Christmas Eve Red'. Treatments included two SMC levels (20% or 40%) applied in four timing of application combinations. Total production (TP) time was 14 (2016) or 12 (2017) weeks in which vegetative production (VP) occurred from week 33 (2016) or 35 (2017) to week 39 and reproductive production (RP) continued from week 40 to 47. The four timing of application treatments were: 40/40 = TP at 40% SMC; 20/40 = VP at 20% + RP at 40%; 40/20 = VP at 40% + RP at 20%; 20/20 = TP at 20% SMC. After simulated shipping in the dark, plants were evaluated in a simulated retail environment with two packaging treatments: no sleeve covering or plastic perforated plant sleeves covering container and plant. At the end of greenhouse production, plants grown in 20% SMC during RP (20/20 and 40/20) had shorter bract internode length, stem length and smaller growth index

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[2] Reprinted with permission from "Reducing substrate moisture content during greenhouse production of poinsettia improves postharvest quality and economic value" by Guo, Y., T. Starman, and C. Hall. 2018. HortScience. 53(11): 1-11. Copyright 2018 by HortScience.

(GI), decreased shoot and root dry weight (DW), and bract and leaf surface area compared with those in 40% SMC during RP (40/40 and 20/40). Photosynthetic rate was higher when plants were watered at 40% SMC regardless of production stage compared with those in 20% SMC. Leaf thickness, petiole thickness, total bract and leaf number were not affected by SMC treatments. Plants in 20% SMC during RP (20/20 or 40/20) had earlier bract coloring despite days to anthesis being the same for all SMC treatments. Compared with 40/40, 40/20 and 20/20 could save 44.2% or 43.6%, respectively, irrigation and fertilizer usage, and 39.1% and 47.8%, respectively, labor time. During postharvest, ethylene concentration was not affected by packaging method. Sleeved plants, regardless of SMC treatment, received lower light intensity in the middle of the plant canopy causing plants to have lower total leaf number due to abscission and SPAD reading at the end of postproduction. The 40/40 treatment abscised more bracts during five weeks (in 2016) of postproduction and with no sleeve had higher number of bracts with bract edge burn (BEB). In summary, reducing SMC to 20% during TP or during RP reduced water usage during production and produced more compact plants with increased postproduction quality.

3.2 Introduction

Potted poinsettias are one of the most important greenhouse ornamental crops in the U.S. with wholesale value of $140 million in the top 15 states. The potted poinsettia was ranked number two among potted plants for its economic value and ranked number one for total amount of potted plants sold (32 million pots) (USDA, 2016).

The greenhouse production process of poinsettias could have an influence on its economic value, especially when the poinsettia production margin was low due to competitive pricing (Barnes et al., 2014). One aspect of increasing profits is to reduce production inputs, such as irrigation water, fertilizer, plant growth regulators (PGR), overhead i.e. bench space, and labor. Applying liquid fertilizer with each irrigation is a common practice for poinsettia production (Ecke et al., 2004). Traditionally, water deficit was considered detrimental during greenhouse poinsettia production because wilting between watering decreased plant quality by causing lower leaf drop. Additionally, using water deficit as plant height control was reported not effective (Dole and Wilkins, 1999; Schuch et al., 1996). However more recent studies reported that a constant 20% substrate moisture content (SMC) could be used as a replacement for PGR (daminozide) applications to produce more compact plants (Alem et al., 2015a). Plant growth regulator application may reduce bract size in poinsettia, which is detrimental to plant quality (Meijón et al., 2009).

Poinsettia is an obligate short day/long night photoperiodic plant and therefore has distinct vegetative growth and reproductive development stages during greenhouse production. The timing of application of water deficit affected poinsettia (*Euphorbia pulcherrima* 'Classic Red') stem elongation depending on growth and development stage (Alem et al., 2015a; Alem et al., 2015b). Periods of 20% SMC application were used for height control when plant height exceeded the target height using graphical tracking. Applied water deficit during the vegetative growth stage of poinsettia reduced transpiration rate (E) and net photosynthetic rate (P_n), but not during the flowering and bract coloring development stage (Nowak, 2002).

Grower profits are increased when overhead and labor costs and postharvest shrinkage are reduced. Poinsettia postproduction disorders include stem breakage, bract fading, leaf yellowing, bract edge burn (BEB, also known as bract necrosis) and bract bruising (Ranch, 2012). Frequent irrigation with fertilization throughout the production cycle increased botrytis infection, weak lateral stems and late stretch, resulting in postproduction stem breakage and BEB (Barrett et al., 1995; Ecke et al., 2004; Islam and Joyce, 2015; Nell and Barrett, 1986). Postproduction environment temperature, humidity and irregular irrigation were believed to cause leaf yellowing and leaf drop (Islam and Joyce, 2015). Meanwhile, despite the nearly four decades of research, the effect of production water usage on poinsettia postproduction longevity was still unclear (Islam and Joyce, 2015; Nell et al., 1995).

The objectives of the current study were to: a) ascertain the effects of lowering SMC to conserve water during production on plant quality; b) determine if plants produced at lower SMC will acclimate to suboptimum irrigation conditions during shelf life; c) analyze the economic dimensions of traditional well-irrigated vs. water-conserving alternative irrigation methods considering production inputs and reduction in shrinkage through the market channels; and, d) quantify plant quality during shelf life in a simulated retail environment.

3.3 Materials and Methods

3.3.1 Plant materials and growing conditions

In 2016, 240 poinsettia (*Euphorbia pulcherrima* ‘Freedom Red’) well-rooted cuttings with an initial growth index (GI = plant height/2 + (plant width1+plant width2)/4) of 39.5 cm were obtained from a local nursery, graded for uniformity and transplanted on week 33 (17 Aug.) into 1.67 L azalea containers (The HC Companies, Inc., Middlefield, OH) with commercial peat based soilless root substrate (85% Canadian sphagnum peatmoss and 15% perlite; BM 6, Berger, Saint-Modeste, Canada). On 1 Sept. 2017, (week 35) 192 poinsettia 'Christmas Eve Red' well-rooted cuttings with an initial GI of 13.1 cm were received through Dümmen Orange (Columbus, OH), graded for uniformity and transplanted to 1.25 L azalea containers (The HC Companies, Inc., Middlefield, OH) with the same substrate. All plants were pinched two weeks after transplanting, leaving seven nodes, according to protocols for commercial poinsettia production (Ecke et al., 2004).

During greenhouse production, plants were grown in a glass wall and polycarbonate roof greenhouse in College Station, TX. Plants had 14 days for root establishment before initiation of SMC treatments. During the greenhouse production period, a water-soluble fertilizer (20N-4.4P-16.6K Peters 20-10-20; Scotts Miracle-Gro Company, Marysville, OH), was applied with each irrigation, with a nitrogen concentration of 200 $mg{\cdot}L^{-1}$ and reverse osmosis water (RO). Plants were treated with an etridiazole and thiophanate-methyl (Banrot, Everris NA Inc. Dublin, OH) root substrate drench monthly to prevent root rot. Imidacloprid (Marathon, OHP, Inc. Bluffton, SC) was applied early in production to target whiteflies. No plant growth regulators were used.

The average temperature in the greenhouse during the production stage of 'Freedom Red' (2016) was 25.8°C day/ 23.3°C night. Average DLI was 13.8 mol·m^{-2}·d^{-1} and relative humidity was 70.3%. During 2017, 'Christmas Eve Red' production stage the average temperature, DLI and relative humidity were 25.4°C day/ 22.7°C night, 16.2 mol·m^{-2}·d^{-1} and 63.8%, respectively. Environmental data were measured by WatchDogs 450 and LightScout quantum light sensors (Spectrum Technologies Inc., Aurora, IL). Root substrate EC and pH were measured weekly after irrigation event using the Pour-Through method (Cavine et al., 2000), and were not different between SMC treatments within cultivars. The EC and pH were 2.1 ms·m^{-1} and 5.7 for 'Freedom Red' and 2.6 ms·m^{-1} and 6.2 for 'Christmas Eve Red'.

3.3.2 Substrate moisture content (SMC) treatments

The experiments consisted of two SMC levels, 20 and 40% SMC applied in four timing applications. Total production (TP) Week 33-47 (2016) or 35-47 (2017) consisted of vegetative production (VP) Week 33-39 (2016) and Week 35-39 (2017) and reproductive production (RP) Week 40-47 (2016 and 2017). Four timing of application treatments included: (1) 40/40 = TP at 40% SMC; (2) 20/40 = VP at 20% + RP at 40%; (3) 40/20 = VP at 40% + RP at 20%; (4) 20/20 = TP at 20% SMC. Natural short days began at week 40 and that was when SMC treatments were interchanged for treatment two and three. SMC was defined as V_W/V_T (V_W is the volume of water; V_T is the total volume of substrate, water and air space). The 40/40 was considered to be a traditional well-irrigated method, which allows the substrate to dry down to 40% SMC before hand-watered to container capacity (CC, 65.5 % SMC); whereas the other three SMC treatments, 20/40, 40/20 and 20/20 were alternative water-conserving irrigation methods, which during VP and/or RP production allows substrate to dry down to 20% SMC before hand-watered to CC. Each irrigation event was determined based on the average of readings of SMC level within the same SMC treatment. Substrate moisture contents were monitored by WatchDog 1000 series Micro Stations and SM 100 WaterScout soil moisture sensors (Spectrum Technologies, Inc. Aurora, IL). There was one sensor per block per irrigation treatment. The greenhouse production stage used the same irrigation sensor system described in a previous study (Guo et al., 2018a).

3.3.3 Sensor calibration.

Soil moisture sensors were calibrated before the experiment by filling five 1-L plastic beakers with 1-L volume of oven dried root substrate. Substrate density was unified by tapping dry substrate filled plastic beakers five times from a uniform height approximately 3 to 6 cm above a sturdy table (Fonteno et al., 1995). This was followed by emptying each beaker into one of five polyethylene plastic bags (Ziploc; S.C. Johnson & Son, Inc. Racine, WI), and 100, 200, 300, 400, or 500 ml of water were poured into one of the five bags. Next, root substrates were mixed with the water thoroughly and allowed to incubate for 24 h. Each substrate's dry weight (DW) and wet weight (WW) was measured and recorded before repacking into the same plastic beaker as previously. Three sensor readings were taken at three different locations in the beaker, avoiding taking readings too close to the edge according to WaterScout SM 100 Soil Moisture Sensor Product Manuals. SMC calculation was SMC = (WW - DW) x 100% /1000 (Cai et al., 2014; Cai et al., 2012).

3.3.4 Postproduction treatments

During simulated shipping and shelf life in both experiments, plants were treated with one of two packaging methods (PM): either no sleeve (NS) or sleeved (PS) with plant sleeves that were half non-woven cloth-like polypropylene fiber and half micropunched clear polypropylene (Super Breather™, A-ROO Company of Texas LLC, Seguin, Texas). In week 47 (27 Nov. 2016), 'Freedom Red' poinsettias were deemed marketable with one open cyathia and red bracts covering 88% of the shoot canopy prior to simulated shipping. Simulated shipping consisted of hand-watering plants with reverse osmosis (RO) water to container capacity (CC) before applying sleeve treatments and moving by cart into a dark lab for 48h at 19.3°C and 55.5% relative humidity. After shipping, plants were held in the lab environment with 24/7 interior incandescent + fluorescent lighting for five weeks (week 47-52) for simulated shelf life, during which plants were watered with RO water only when wilting began to occur. During postproduction, the average temperature, daily light integral (DLI) and relative humidity were 20.2°C, 1.3 $mol \cdot m^{-2} \cdot d^{-1}$ and 39.2%, respectively.

In 2017, with 'Christmas Eve Red', an additional factor of harvest time was added during postharvest to determine if harvesting before or after cyathium shed pollen would affect shelf life. Therefore, the three factors during postproduction were: (1) SMC; (2) PM; and, (3) harvest time (HT). HT consisted of either early harvest shipped week 46, and postproduction week 47 to 48, or late harvest shipped week 47, and postproduction week 48 to 49. For early harvest, plants had red bracts covering 80% of the plant canopy and no open cyathia or pollen shed; whereas for late harvest, plants had red bracts covering 90% of the plant canopy and one open cyathia with pollen shed prior to simulated shipping. The simulated shipping process was the same as in 2016 with the exceptions of a reduced dark period of 12 h at 21.8°C and 42.4% relative humidity and a simulated shelf life of two weeks with average temperature, DLI and relative humidity of 21.7°C, 1.6 $mol \cdot m^{-2} \cdot d^{-1}$ and 42.5%, respectively. During postproduction in 2017, plants were irrigated with 300 ml plain RO water when they showed signs of wilting.

3.3.5 Physiological parameters

Instantaneous leaf gas exchange parameters [net carbon assimilation rate (P_n), stomatal conductance (g_s), and transpiration rate (E)] were measured weekly during production on the third fully unfolded young leaf between 1000 and 1200HR, using a portable photosynthesis system (LI-6400XT, LI-COR Inc., Lincoln, NE) with the cuvette conditions set at 25 ºC, 1200 $\mu mol \cdot m^{-1} \cdot s^{-1}$, and 400 µmol CO_2. Weekly measurements from week 38 to 45 included relative greenness of leaves (SPAD) measured with a chlorophyll meter (SPAD-502 Minolta Camera Co., Osaka, Japan), and predawn and mid-day leaf water potential with a pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, CA). SPAD reading ranged from 0 to 100 by measuring the light transmission at wavelengths of 650 and 940nm (Markwell et al., 1995).

3.3.6 Production plant quality parameters

Plant growth index (GI) was recorded weekly. At the end of greenhouse production, for both 'Freedom Red' and 'Christmas Eve Red', half of the plants per treatment per block were destructively harvested to collect total bract and leaf number, bract and leaf surface area, stem length, node number, internode length, and shoot dry weight. In 2017, leaf thickness between two major leaf veins and petiole diameter were measured on a young fully expanded leaf with a digital caliper during early HT, and open and closed cyathia number per lateral branch were counted during late HT. The other half of the plants were used for the postharvest stage of the study.

To quantify the bract coloring percentage (the percentage of the plant canopy that was covered by red bracts) during production week 44 to 46, photos of poinsettia shoots were taken from above. Photoshop CS 6 (Adobe Systems Inc. San Jose, CA) was used to quantify the red area (bracts) and green area (leaves), and the coloring percentage was calculated as [red area / (red area + green area)] x 100%. At the end of greenhouse production root ball pictures were taken from the bottom of the root ball and both sides of the root ball. Root ball coverage percentage was quantified by Photoshop and was calculated as root area x 100% / root area + substrate area (Guo et al., 2018a). The bract and leaf surface area were estimated by removing all the bracts and leaves and laying them on a flat surface before photographing them from above. Using Photoshop CS 6 the bract surface area was then calculated as red area / total bract number and leaf surface area was calculated as green area / total leaf number.

3.3.7 Production plant quality parameters

After postproduction (week 1 of 2017 for the 2016 experiment, and week 49 or week 50 in 2017), the remaining half of the plants were harvested and total leaf and bract number, number of bracts with bract edge burn (BEB), number of stems with BEB bracts, yellow leaf number, and SPAD were collected. Open and closed cyathia number per lateral branch were collected on the four main lateral branches, whereas open cyathia was defined as cyathia with pollen shed. Plant visual quality was rated at the end of production and postproduction from 0 (senescent plant) to 5 (healthy plant) (Starman et al., 2007) based on symptoms of open and closed cyathia abscission, red bract color fading, leaf abscission, leaf chlorotic and BEB. In 2017 only, ethylene and photosynthetic active radiation (PAR) were measured to determine differences between PM treatments. Five replications of gas samples were taken using syringes within the plant sleeve or between plant canopies with no sleeve. Approximately 1 ml of the gas sample was injected into a digital gas chromatograph fitted with a photoionization detector (10S plus photovac, digital gas chromatograph, SRI Instruments, CA). Photosynthetic active radiation (PAR) was measured at the top and under the plant canopy, and above the substrate surface with a quantum meter (AccuPAR PAR/Lai Ceptometer, Model LP-80, Decagon Devices, Inc. Pullman WA.).

3.3.8 Experimental design and statistical analysis

During greenhouse production in 2016, the experimental design was a randomized complete block design (RCBD) with four blocks on four greenhouse benches with15 replications for a total of 240 plants. In 2017, the experimental design was RCBD with six blocks on six greenhouse benches with eight replications in each treatment for a total of 192 plants. When the interaction between two factors was significant means were separated into each treatment combination by Student-Newman-Keuls multiple comparison at $P = 0.05$. When the interaction was not significant, data were pooled by the significant factor across SMC or PM. Student-t-test were used to separate means at *P* = 0.05 when the factor contained only two levels. At postproduction in 2016, a two-factorial experimental design (four SMC x two PM) was analyzed by a two-way analysis of variance procedure. In 2017, a three-factorial experimental design (four SMC x two PM x two HT) was analyzed by a split-split plot with PM as main plot, HT as sub plot and SMC as sub-sub plot. When the interaction between factors was significant means were separated into each treatment combination by Tukey HSD at *P* = 0.05. When the interaction was not significant, data were pooled by the significant factor across SMC or PM. Student-t-test were used to separate means at *P* = 0.05 when the factor contained only two levels. All statistical analyses were performed using SAS (Version 12; SAS Institute, Cary, NC).

3.3.9 Economic analysis

For the economic analysis of water usage, containers were weighed before each irrigation event during the production stage of the experiment. After irrigation, containers were allowed to drain for 1 h and then reweighed. The weight difference was calculated and recorded to determine total irrigation volume. Each irrigation event was documented and summed to determine total number of irrigation events during production and/or postproduction. For both tested cultivars, estimated container number per bench was calculated based on the industry standard bench size (19.5’ x 5.5’) and the finished plant width. Space saved was based on poinsettia final width, labor saved was based on irrigation event number, irrigation amount saved was based on total irrigation amount, and fertilizer saved was calculated based on the fertilizer usage. All were calculated as the difference between the alternative irrigation method (20/40, 40/20, 20/20) and the traditional irrigation method (40/40). Fertilizer usage was calculated based on total irrigation amount x 200 mg·L^{-1} 20-10-20 (20N-4.4P-16.6K Peters 20-10-20; Scotts Miracle-Gro Company, Marysville, OH).

3.4 Results and Discussion

3.4.1 Plant morphology.

'Freedom Red' growth index (GI) differed among the four SMC beginning two weeks after their initiation until the end of production. At week 39, plants grown in VP at 40% SMC (40/40 and 40/20) had greater GI compared with VP at 20% SMC (20/40 and 20/20) (Fig. 3.1a). Starting at week 44 to the end of greenhouse production (week 47), plants grown in RP at 40% SMC (40/40 and 20/40) had greater GI than those grown in RP at 20% SMC (40/20 and 20/20). The final GI, at week 47 for plants grown in RP at 20% SMC (54.5 cm), was 14.3% lower than those grown in RP at 40% SMC (63.6 cm). Similar trends occurred with 'Christmas Eve Red'. At the end of greenhouse production, plants grown in RP at 20% SMC had 15% reduced GI (34.9 cm) than those grown in RP at 40% SMC (41.1 cm) (Figure 3.1b).

'Freedom Red' plants grown in RP at 40% had greater stem length, internode length, total leaf surface area, single leaf and bract surface area, leaf thickness, and petiole thickness and shoot DW (Table 3.1) compared with those grown in RP at 20% SMC. At both HT (week 46 and 47) in 2017, ‘Christmas Eve Red’ plants grown in RP at 40% had increased stem length, bract internode length, and single bract surface area (Table 3.1). Increased stem length was due to increased bract internode length and not leaf internode length. The 40/20 SMC plants did not differ from the RP at 40% plants for leaf surface area (Table 3.1). There were no differences among SMC treatments for total leaf and bract numbers for both cultivars and no difference in open or closed cyathia per lateral branch on ‘Christmas Eve Red’ plants harvested week 47. At both HT, ‘Christmas Eve Red’ plants grown in RP at 40% had increased shoot dry weight (Table 3.1).

'Freedom Red' root ball coverage percentage at the bottom of the container was the least with 20/20 SMC, while the other three SMC were not different (Fig. 3.2). At the side of the root ball, 20% SMC during RP had lower root ball coverage percentage compared with 40% SMC during RP (Fig. 3.2). Compared with 40/40, 40/20 root ball coverage was reduced on the side of the container, not at the bottom of the container, whereas the 20/20 had less root ball coverage both on the bottom and the side of the pot. This indicated water deficit reduced the root growth at the side of the container first before it was reduced at the bottom of the container. The root growth inhibition was also found with ‘Christmas Eve Red’ at late HT as quantified by root DW (Fig. 3.3).

Late stretch is a challenge for growers caused by elongation of internodes between bracts prior to shipping, which decreases quality and causes stem breakage during shipping. Water stressed plants have lower turgor potential, which drives the cell expansion during stem elongation, therefore, moderate water deficit (20% SMC) would reduce stem elongation and produce more compact plants with shorter internodes (Nemali and van Iersel, 2006). Other research also reported that 20% SMC reduced poinsettia leaf and bract surface area (Alem et al., 2015b). Leaf surface area reduction occurred in other species with applied water deficit, such as geraniums (*Pelargonium zonale*), mealy sage (*Salvia farinacea*), helichrysum (*Helichrysum petiolare*), English lavender (*Lavandula angustifolia*), geranium (*Pelargonium* × *hortorum*), and Lindheimer's beeblossom (*Gaura lindheimeri*) (Andersson, 2000; Burnett and van Iersel, 2008; Caser et al., 2012; Sánchez-Blanco et al., 2009; Starman and Lombardini, 2006). Bract surface area reduction was reported as a possible result of prolonged exposure to water deficit in poinsettia 'Classical Red'. The longer the water deficit, the smaller the bract size (Alem et al., 2015b). But this was not reported as a consistent event since the bracts surface area was not affected by 20% SMC in another experiment conducted by the same researchers with the same cultivar (Alem et al., 2015a). Another study showed that under suddenly reduced water potential, leaf cell osmotic adjustment occurred slowly, and cell wall loosening ability stayed the same, which led to significant growth inhibition. The meristem of leaves had prolonged water stress due to isolation from the xylem system combined with high evaporative demand (Hsiao and Xu, 2000).

Past research reported that compared with shoot growth, the root growth was less affected by water deficit due to different cellular level responses. Compared with leaf cells, when water potential was suddenly reduced, root cell osmotic adjustment happened rapidly to recover turgor pressure and water potential, cell wall loosening ability increased, and the isolation from mature vascular system allowed root meristem to keep growing (Hsiao and Xu, 2000). Pine tree saplings (*Pinus nigra* L.) modified their root system architecture by producing new lateral meristems above the fine root tip, which never recovered from the water stress (Chiatante et al., 1999). Increased endogenous abscisic acid (ABA) induced by water deficit could increase root to shoot ratio and support primary root growth by suppressing ethylene production (Saab et al., 1990; Taiz et al., 2015). Reduction of root DW under water deficit environments were reported in other species such as rose (*Rosa* x*hybrid*), impatiens (*Impatiens walleriana*); and geranium (*Pelargonium hortorum*) (Cai et al., 2012; Chyliński et al., 2007).

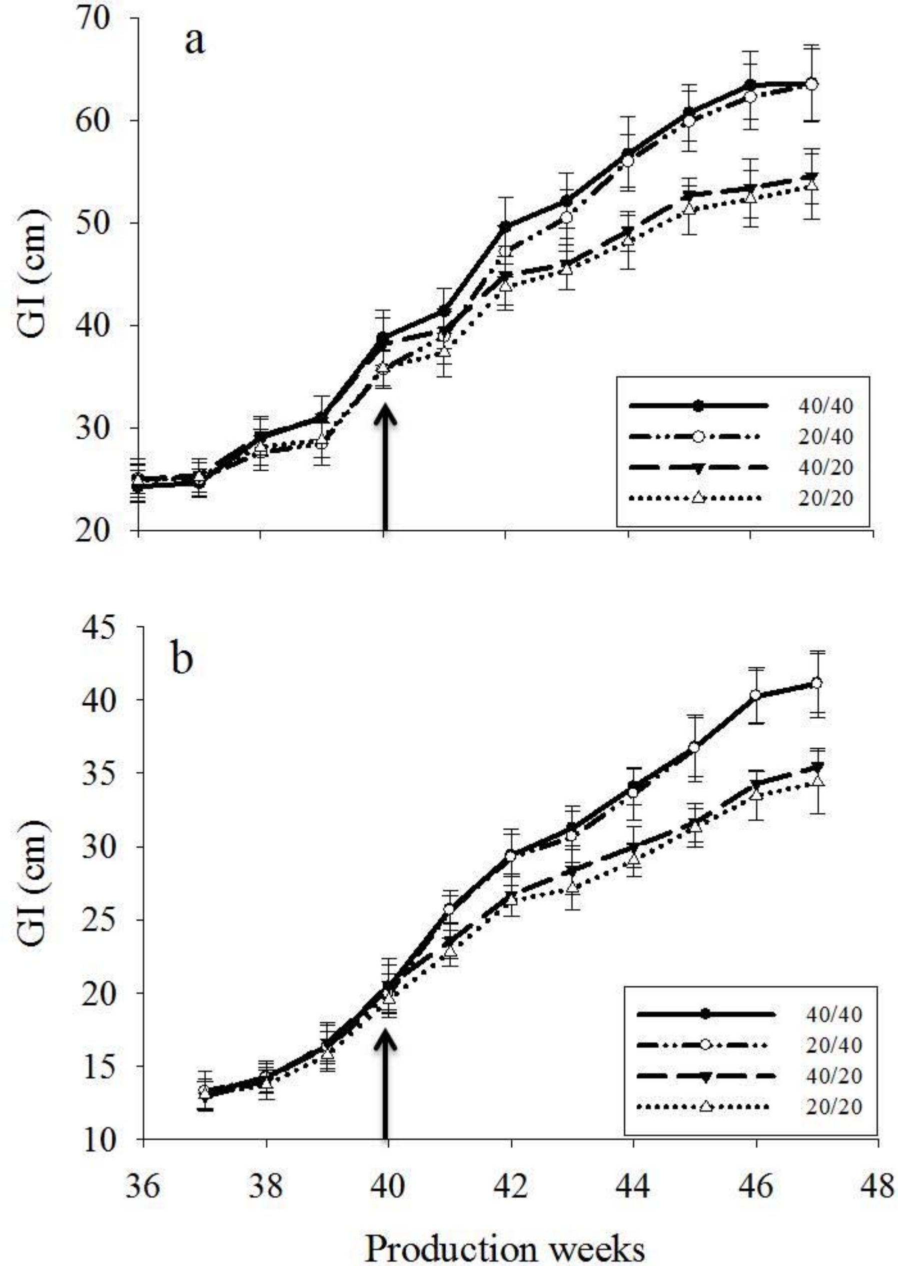

Figure 3.1. Effects of four SMC treatments (40/40, 40/20, 20/40, 20/20% SMC) on weekly growth index (GI = plant height/2 + (plant width 1 + plant width 2)/4.) from production week 36 to production week 47 of ‘Freedom Red’ in 2016 experiment (a), and from production week 37 to production week 47 of ‘Christmas Eve Red’ in 2017 experiment (b). The arrow denotes week 40 as the start of short day photoperiod and when SMC treatments were interchanged (Guo et al., 2018b).

Table 3.1. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on stem length, internode lengths, total leaf and bract surface area, single leaf and bract surface area, total leaf and bract number (no.), leaf thickness, petiole thickness and shoot dry weight (DW) in week 47 for ‘Freedom Red’ in 2016; and in week 46, 47 for ‘Christmas Eve Red’ in 2017 (Guo et al., 2018b).

2016 'Freedom Red' wk 47 harvest

	Stem length (cm)		Internode length (cm)		Single leaf surface area (cm^2)		Single bract surface area (cm^2)		Total leaf no.	Total bract no.	Leaf thickness (µm)		Petiole thickness (µm)		Shoot DW (g)	
40/40	39.3	a^z	2.6	a^z	76.7	a	78.2	a	67.6	41.9	11.3	a	104.3	a	57.2	a^z
20/40	38.1	a	2.6	a	73.1	a	81.9	a	64.6	39.1	10.8	ab	104.8	a	54.7	a
40/20	32.9	b	2.1	b	65.0	b	62.8	b	65.1	44.3	9.8	ab	94.3	b	40.4	b
20/20	33.2	b	2.1	b	66.7	b	66.1	b	67.0	48.0	9.3	b	92.0	b	42.8	b
SMC	***^{y}		***		**		***		ns	ns	*		***		***^{y}	

2017 'Christmas Eve Red' wk 46 early harvest

	Stem length (cm)		Bract internode length (cm)		Leaf internode length (cm)	Single leaf surface area (cm^2)		Single bract surface area (cm^2)		Total leaf no.	Total bract no.	Leaf thickness (µm)	Petiole thickness (µm)	Shoot DW (g)	
40/40	22.3	a	1.1	a	1.7	55.7	a	59.1	a	38.0	35.6	0.2	2.1	26.9	a
20/40	22.7	a	1.1	a	1.5	57.1	a	64.4	a	34.9	30.6	0.3	1.9	27.9	a
40/20	19.9	b	0.9	b	1.6	53.4	a	45.8	b	40.0	34.6	0.7	2.0	22.7	b
20/20	18.3	b	0.9	b	1.7	46.2	b	47.1	b	42.6	33.1	0.2	2.2	20.9	b
SMC	***		***		ns	*		***		ns	ns	ns	ns	***	

2017 'Christmas Eve Red' wk 47 late harvest

	Stem length (cm)		Bract internode length (cm)		Leaf internode length (cm)	Single leaf surface area (cm^2)		Single bract surface area (cm^2)		Total leaf no.	Total bract no.	Leaf thickness (µm)	Petiole thickness (µm)	Shoot DW (g)	
40/40	22.4	a	0.8	a	1.5	54.9	a	74.4	a	36.8	47.2	--	--	31.8	a
20/40	21.4	a	0.9	a	1.5	52.1	a	75.3	a	37.3	44.4	--	--	28.8	a
40/20	19.2	b	0.7	b	1.5	51.0	a	62.4	b	34.7	43.4	--	--	22.1	b
20/20	18.0	b	0.7	b	1.4	46.9	b	63.7	b	30.2	40.4	--	--	19.9	b
SMC	***		***		ns	*		**		ns	ns	--	--	***	

^{z} Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

^{y} Significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

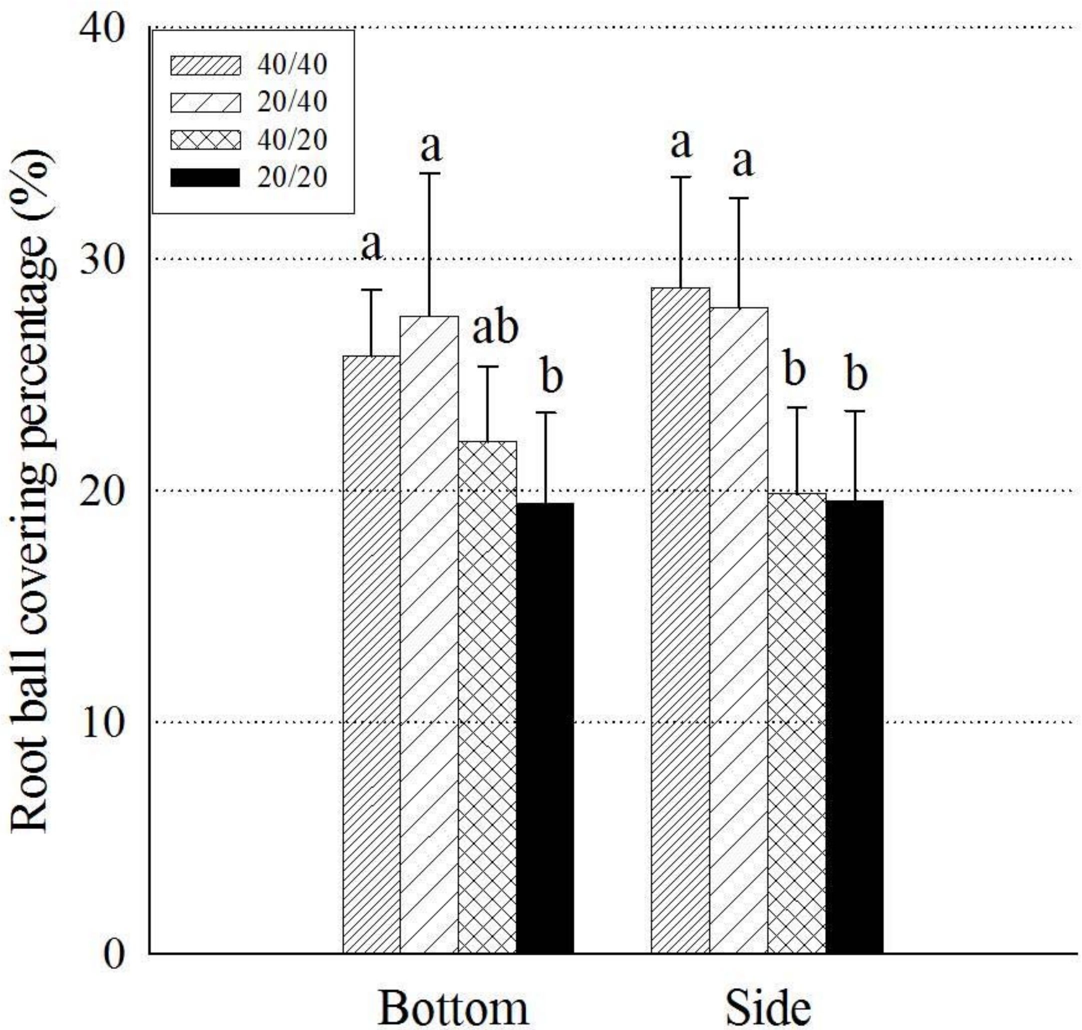

Figure 3.2. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on root ball coverage percentage at the bottom and side of 'Freedom Red' in 2016 experiment. Means separation within the group by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different (Guo et al., 2018b).

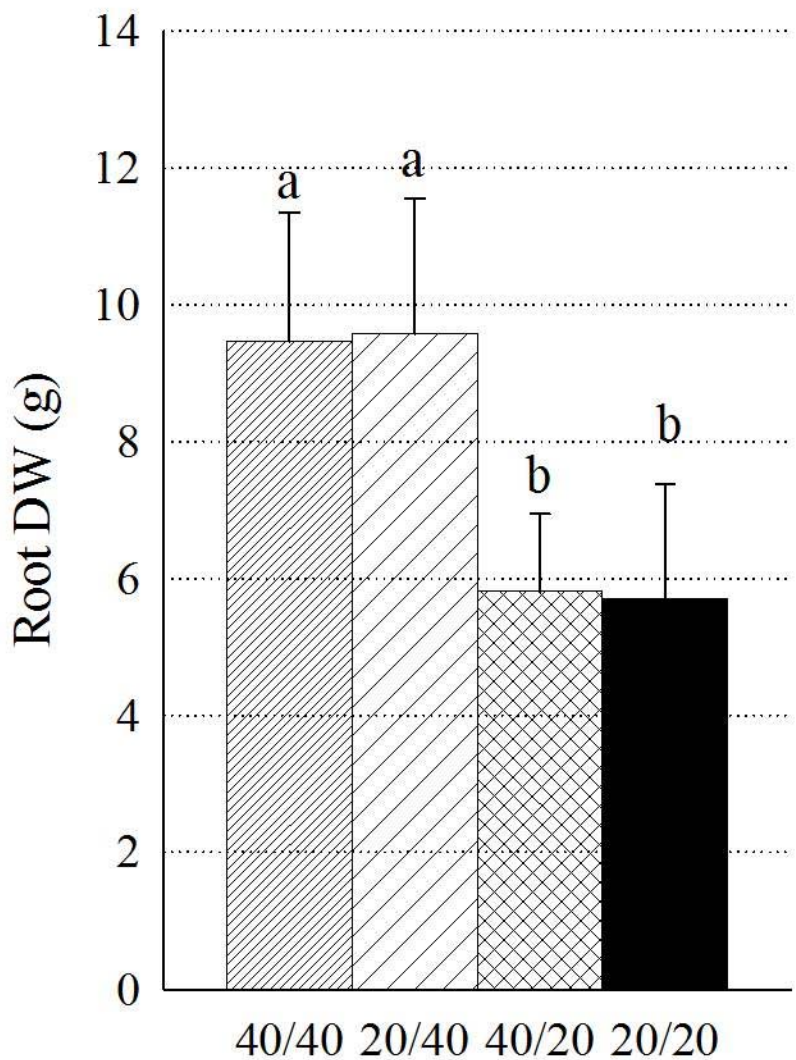

Figure 3.3. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on root dry weight (DW) of 'Christmas Eve Red' in 2017 experiment. Means separation within the group by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different (Guo et al., 2018b).

3.4.2 Photosynthesis, stomatal conductance, transpiration and water potential

In 'Christmas Eve Red', P_n and E were higher at 40% SMC during VP (Fig. 3.4). After treatment interchange at the start of short days (week 40), P_n, g_s and E on 20/40 compared with 40/20 was higher. From week 40 to week 44 (before the third bract transitioned to red), 40% SMC during RP had higher P_n, g_s, and E compared with those in 20% SMC during RP. After the third fully expanded bract transitioned to red in week 45, the P_n, g_s and E were taken on the first non-red leaf and were not different between SMC treatments.

Reductions on P_n, g_s and E under a water deficit environment were reported on poinsettia (*Euphorbia pulcherrima* Wild. ‘Lilo’), crimson bottlebrush (*Callistemon citrinus*), hibiscus (*Hibiscus acetosella*), dusty miller (*Cineraria maritima*), ornamental pepper (*Capsicum annuum*), vinca (*Catharanthus roseus*), Big Bend bluebonnet (*Lupinus havardii*) and oleander (*Nerium oleander* L.) (Álvarez et al., 2011; Bayer et al., 2013; Niu et al., 2008; Niu et al., 2007; Niu et al., 2006; Nowak, 2002). In most studies, the reduction in photosynthesis rate was accompanied by inhibition of growth rate, manifested in reduced dry weight and final plant height.

Midday water potential was not affected by SMC treatments in 'Christmas Eve Red' with the exception of week 40 (start of short days and when SMC was interchanged), predawn water potential was not affected by the SMC treatments. Midday water potential was reduced in week 40 with 40/20 and was 61.3% lower than other SMC treatments (Fig 3.5). This indicated an acclimation of plants to the water deficit environment shortly after exposure to the stress. Such acclimation was defined as morphological and physiological change in plants in order to compensate for the water deficit and is termed phenotypic plasticity (Debat and David, 2001). A similar acclimation was reported in angelonia (*Angelonia angustifolia*) (Jacobson et al., 2015).

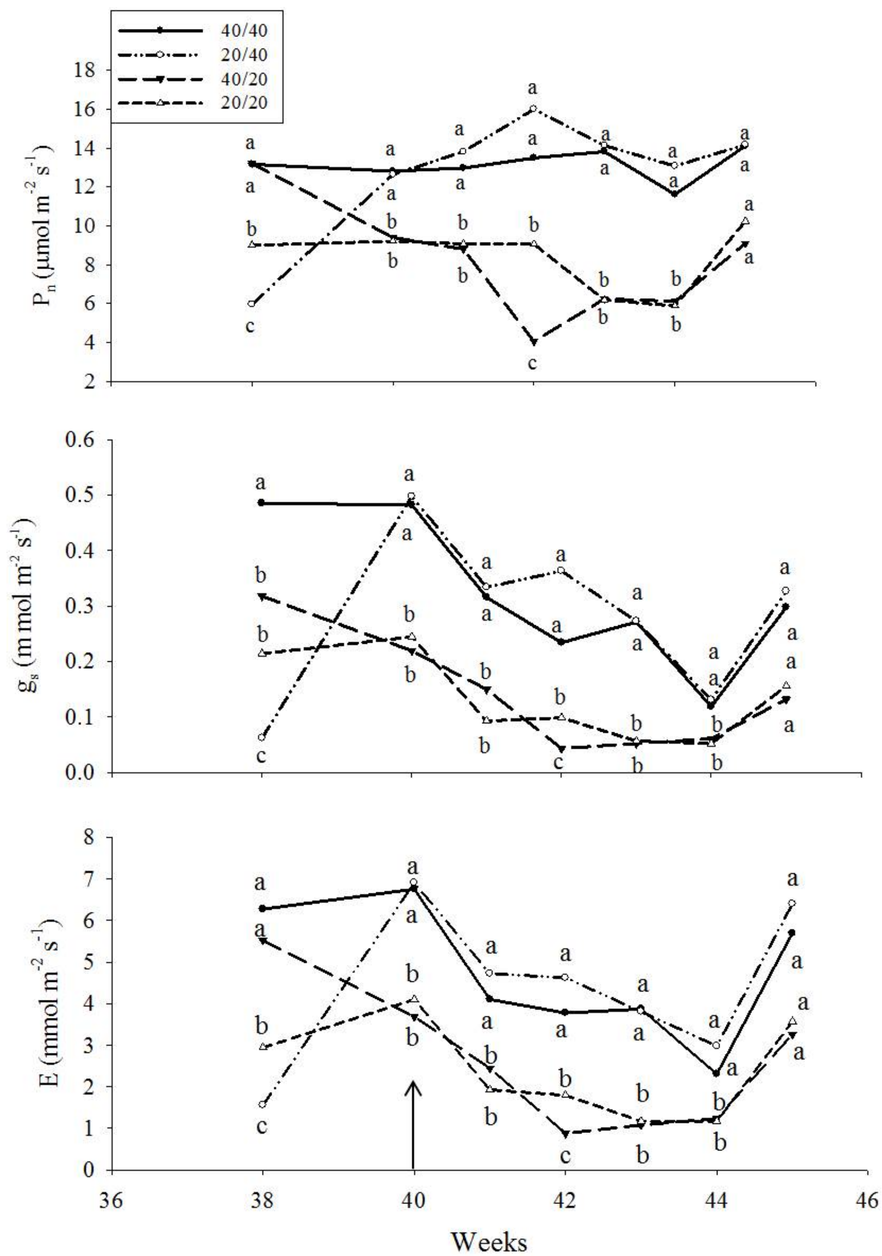

Figure 3.4. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on weekly leaf net photosynthesis (Pn), stomatal conductance (gs) and transpiration (E) of ‘Christmas Eve Red’ during greenhouse production week 38 to week 47 in 2017 experiment. Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different. The arrow denotes week 40 as the start of short day photoperiod and when SMC treatments were interchanged (Guo et al., 2018b).

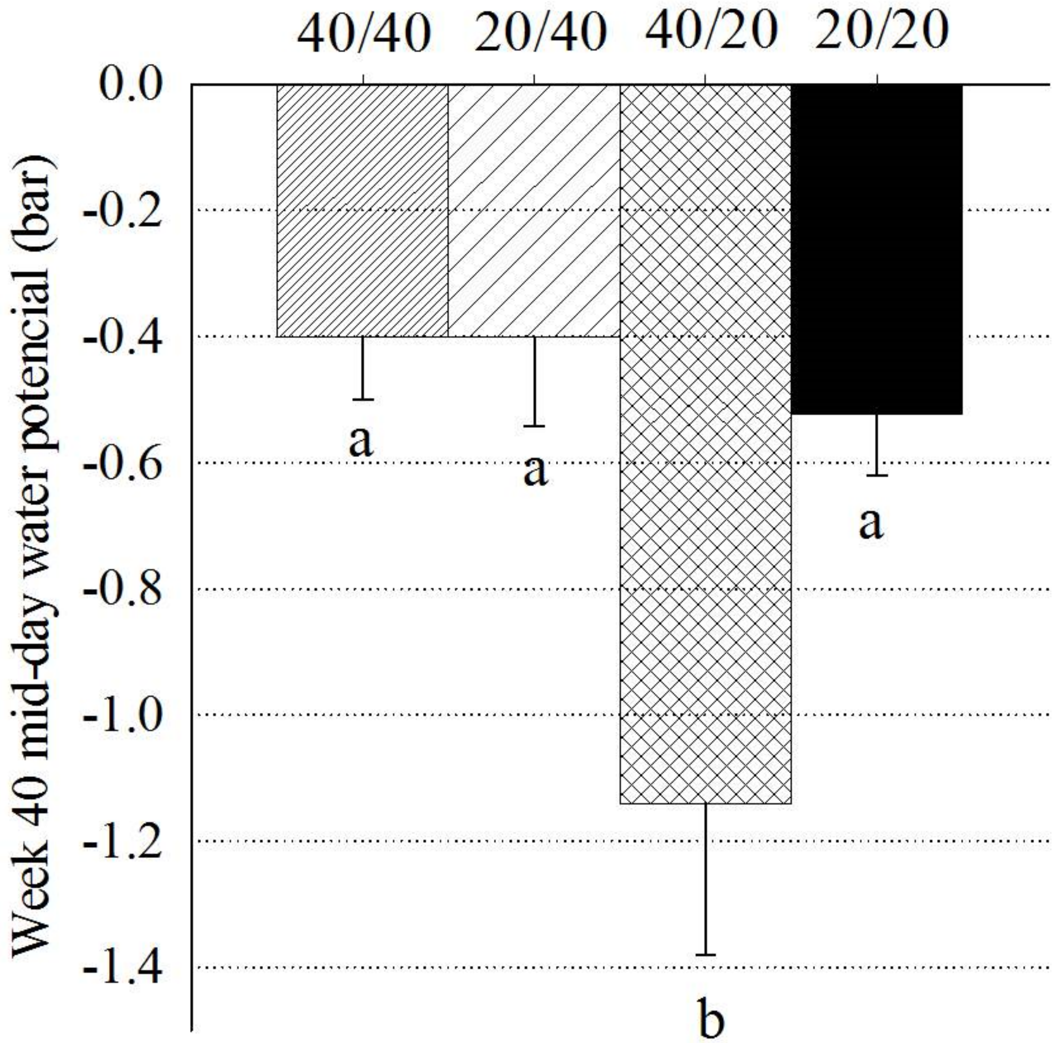

Figure 3.5. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on mid-day water potential of 'Christmas Eve Red' at production week 40 at the start of short-day photoperiod and when SMC treatment were interchanged in 2017 experiment. Means separation within the group by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different (Guo et al., 2018b).

3.4.3 Visual quality

During bract development of 'Freedom Red', the bract coloring percentage differed among SMC treatments during week 44 and 45 but by week 46 all SMC treatments had the same bract coloring percentage (Figs. 3.6a and 3.7). Week 44, ‘Freedom Red’ plants grown in RP with 20% SMC had 23.3% greater bract coloring percentage compared with those grown in RP with 40% SMC (Fig. 3.6a). Week 45, 40/20 had the highest bract coloring percentage of 69.5%, followed by 20/20 with 61.7%. By week 46, the bract coloring percentage was not different between SMC treatments with average of 86.5% (Fig. 6a). Similar early bract coloring was observed in 'Christmas Eve Red' (Fig. 3.6b). When bract coloring was first observed in week 42 and 43, the number of red bracts per lateral branch were 55.6% higher in 20% SMC during RP compared with 40% SMC during RP (Table 3.2).

Poinsettia bract color development is achieved by accumulation of anthocyanins in vacuoles of the epidermal cells predominating over chlorophylls (Eugster and Märki-Fischer, 1991; Pomar and Barceló, 2007). Cyanidin-3-glucoside is the predominant anthocyanin causing the red color in poinsettia bracts (Gould, 2004; Slatnar et al., 2013). Under water deficit, ABA would be sent from root to shoot as a drought-sensed signal (Wan et al., 2009; Xu et al., 2010). In leaves, increased ABA concentration level not only regulated stomata conductivity (Taiz et al., 2015; Wan et al., 2009), but it potentially played an important role for upregulated miRNA156. This produced a greater level of anthocyanin gene expression, thus increased the anthocyanin concentration in vacuoles (González-Villagra et al., 2017). Plants upregulated anthocyanin synthesis during water deficit is reported in other species as well, for anthocyanin has diverse protective roles in leaves, such as to protect leaves from photoinhibition (caused by high light intensity or stomata closure during water stress) and scavenging free radicals caused by water stress (singlet oxygen, superoxide, hydroxyl and hydrogen peroxide) (Gould, 2004; Xu et al., 2010).

In 'Freedom Red', SPAD readings were higher at 40% SMC treatment during VP until start of RP (Week 40). One week after SMC treatments were interchanged, SPAD readings on 20/40 increased (Fig. 3.8). By week 44, 20% SMC during RP had lower SPAD readings due to bract transitioning from green to red. Week 47, the SPAD readings were taken on the first non-red leaf and were not different between SMC treatments.

SPAD readings could be increased with nitrogen concentration, chlorophyll level, fresh leaf thickness or the water status of the leaf (Basyouni et al., 2015; Dole and Wilkins, 1999; Martínez and Guiamet, 2004). A study conducted by Niu et al. (2007) on Big Bend bluebonnet (*Lupinus havardii*) reported lower SPAD readings with water deficit plants. Poinsettias leaf SPAD readings were increased by a higher level of nitrogen application (Basyouni et al., 2015). Thus, the higher SPAD readings in 40% SMC found with ‘Freedom Red’ could be caused by the increased leaf nitrogen concentration, which would be due to the higher irrigation frequency in 40% SMC, combined with increased leaf thickness (Table 3.1).

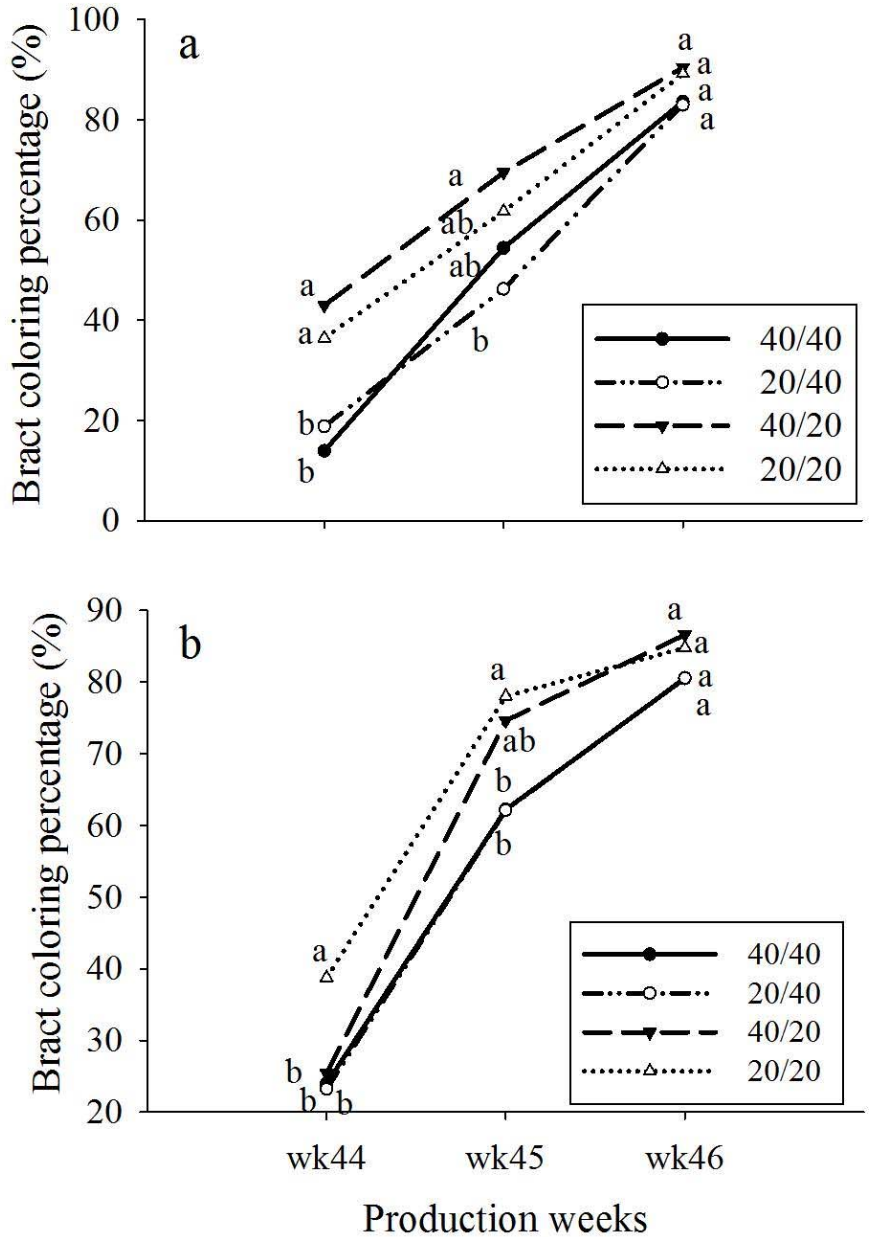

Figure 3.6. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on bracts coloring percentage measured over three production weeks for 'Freedom Red' in 2016 experiment (a) and 'Christmas Eve Red' in 2017 experiment (b). Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different. The lines of 40/40 and 20/40 are overlapping in the graph (Guo et al., 2018b).

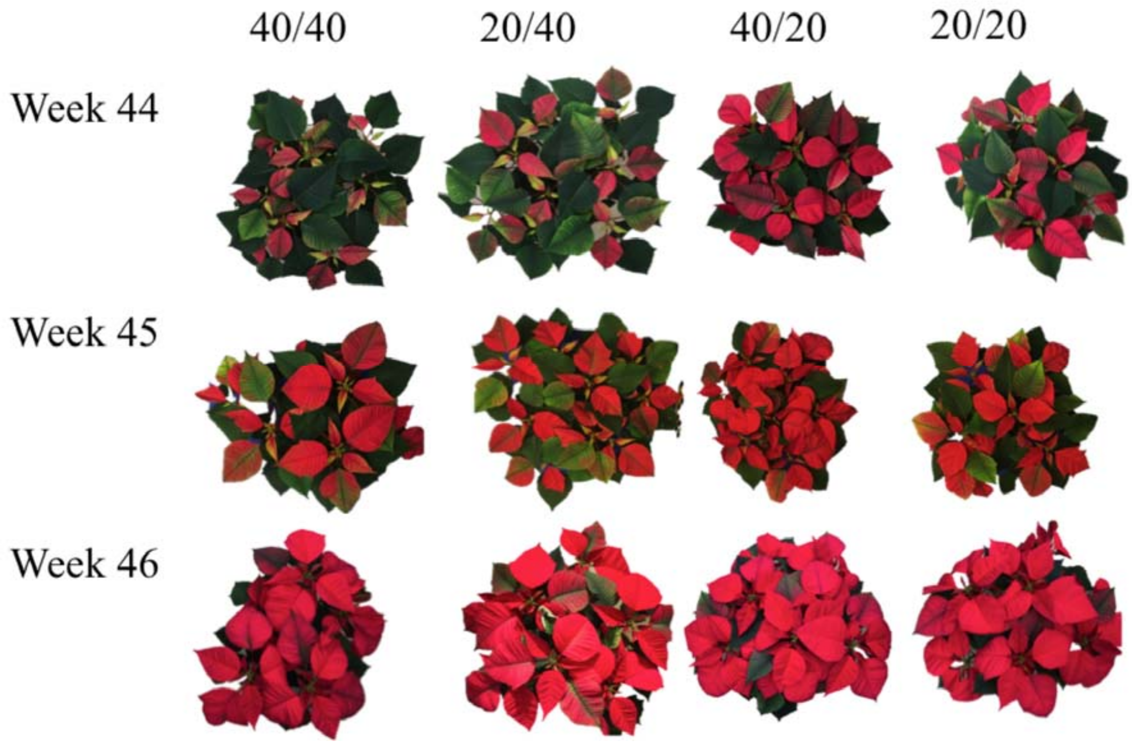

Figure 3.7. Visual bract coloring percentage for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC). Digital images taken over three production weeks for ‘Freedom Red’ in 2016 experiment (Guo et al., 2018b).

Table 3.2. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) on number (no.) of red bracts per lateral branch measured over two production weeks (42 and 43) for 'Christmas Eve Red' in 2017 (Guo et al., 2018b).

	No. of red bracts lateral branch	
	wk 42	wk 43
40/40	0.2 b[z]	0.7 b
20/40	0.3 b	0.7 b
20/20	0.7 a	1.4 a
40/20	0.6 a	1.3 a
SMC	***[y]	***

[z] Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

[y] Significant at $P \leq 0.001$ (***).

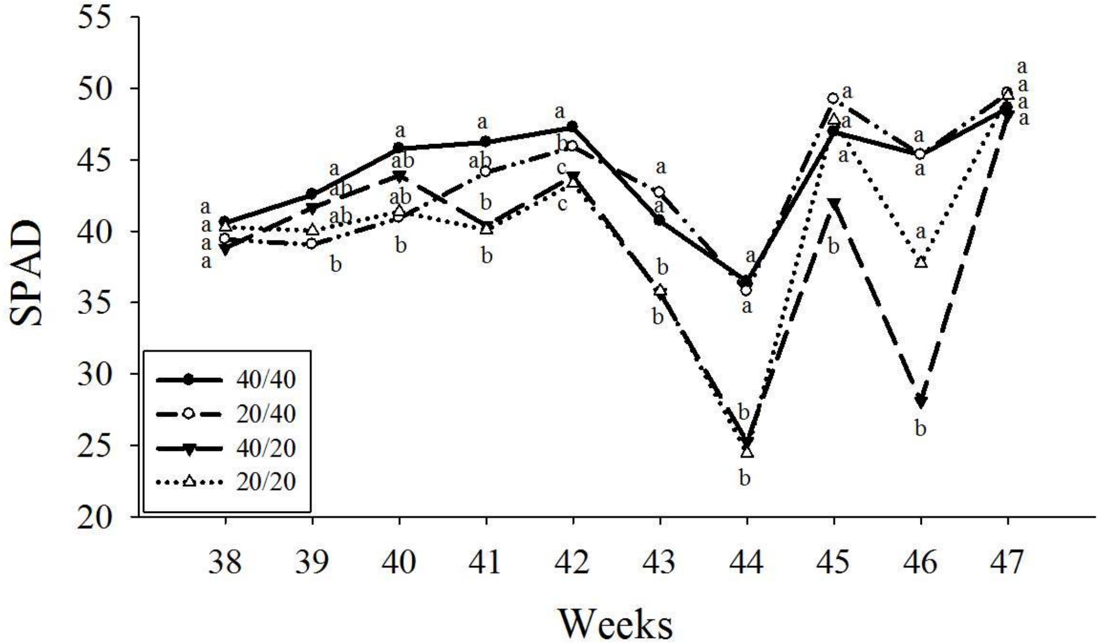

Figure 3.8. Leaf chlorophyll index [Special Products Analysis Division (SPAD) values] for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) of 'Freedom Red' during production week 38 to week 47 in 2016 experiment. Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. The arrow denotes week 40 at the start of short-day photoperiod and when SMC treatment were interchanged (Guo et al., 2018b).

3.4.4 Production irrigation and associated economic implications

Compared with the 40/40 treatment, plants grown with 20% SMC during production (20/40; 40/20 and 20/20) had a smaller canopy, thus they required less bench space (Table 3.3), which potentially translates to lower overhead cost associated with bench space.

Poinsettias require fertilization with each irrigation event, thus reducing irrigation frequency not only reduced the total amount of irrigation water applied (as well as the amount of irrigation-associated labor), and it also reduced the fertilizer usage. Compared with the 40/40 treatment, the other treatments saved irrigation-related labor, amount of irrigation water applied, and fertilizer usage (Table 3.3).

In the 2017 experiment, the greenhouse production stage exhibited higher savings in bench space used, irrigation-associated labor, and fertilizer usage because the 'Christmas Eve Red' crop began as smaller rooted cuttings combined with two weeks shorter production time, compared to 'Freedom Red' in 2016. In 2017, in early HT, at the end of 11 weeks of greenhouse production, the 20/40, 40/20 and 20/20 treatments saved 15.1%, 26.6% and 32% space, respectively; 10%, 40% and 50% savings in irrigation-related labor, respectively; and 20.8%, 44.7% and 48.1% savings in fertilizer usage, respectively, compared with the traditional irrigation 40/40 (Table 3.3). In the late harvest, at the end of 12 weeks of greenhouse production, the 20/40, 40/20 and 20/20 treatments had similar savings (Table 3.3).

Table 3.3. Irrigation and associated economic implications of 'Freedom Red' and 'Christmas Eve Red' to four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20% SMC) in 14 weeks of greenhouse production in 2016 or in 11 or 12 weeks in 2017 (Guo et al., 2018b).

				2016 production wk 47 harvest				
	Estimated pot number/bench	Space saved (%)	Total number of irrigation events	Labor saved (%)	Total irrigation amount (L/pot)	Irrigation amount saved (%)	Fertilizer usage (g/pot)	Fertilizer saved (%)
40/40	27.0[z]	0.0[y]	34.0[x] a[w]	0.0[v]	13.8[u] a	0.0[t]	197.2[s]	0.0[r]
20/40	29.0	5.0	32.0 b	5.9	12.9 b	6.5	184.3	6.5
40/20	37.0	25.4	23.0 c	32.4	10.5 c	24.1	149.7	24.1
20/20	43.0	35.8	21.0 d	38.2	10.2 c	26.1	145.7	26.1
				2017 production week 46 early harvest				
	Estimated pot number/bench	Space saved (%)	Total number of irrigation event	Labor saved (%)	Total irrigation amount (L/pot)	Irrigation amount saved (%)	Fertilizer usage (g/pot)	Fertilizer saved (%)
40/40	54.0	0.0	20.0 a	0.0	6.8 a	0.0	96.8	0.0
20/40	63.0	15.1	18.0 b	10.0	5.4 b	20.8	76.6	20.8
40/20	73.0	26.6	12.0 c	40.0	3.7 c	44.7	53.6	44.7
20/20	79.0	32.0	10.0 d	50.0	3.5 c	48.1	50.3	48.1
				2017 production wk 47 late harvest				
	Estimated pot number/bench	Space saved (%)	Total number of irrigation event	Labor saved (%)	Total irrigation amount (L/pot)	Irrigation amount saved (%)	Fertilizer usage (g/pot)	Fertilizer saved (%)
40/40	54.0	0.0	23.0 a	0.0	7.5 a	0.0	106.7	0.0
20/40	63.0	15.1	21.0 b	8.7	6.3 b	16.2	89.4	16.2
40/20	68.0	20.3	14.0 c	39.1	4.2 c	44.2	59.6	44.2
20/20	73.0	26.0	12.0 d	47.8	4.2 c	43.6	60.2	43.6

[z] Estimated pot number/bench was calculated as standard bench size (19.5' x 5.5')/average canopy size of the plant.
[y] Space saved is calculated based on final spacing difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).
[x] Total number of irrigation events during 14 weeks of production.
[w] Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different
[v] Labor saved is calculated based on irrigation event number difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).
[u] Total irrigation amount per pot was the sum of each irrigation water input during 14 weeks of greenhouse production.
[t] Irrigation amount saved is calculated based on total irrigation amount difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).
[s] Fertilizer usage is calculated based on total irrigation amount x 200 mg L^{-1} 20-10-20 (20N-4.4P-16.6K Peters 20-10-20; Scotts Miracle-Gro Company, Marysville, OH)
[r] Fertilizer saved is calculated based on the fertilizer usage difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).

3.4.5 Postproduction

At the end greenhouse production in 2016, all 'Freedom Red' plants had 66 total green leaves, 43 red bracts, a SPAD reading of 49, 10 cyathia per lateral branch, and a visual quality rating of 5.0 regardless of SMC treatments. At the end of 5 weeks of postproduction (week 1, 2017), there were no differences between SMC or PM for visual rating (2.3), number of bracts with BEB (6.1), or number of stems with BEB bracts (2.1). Total bract number at end of postproduction was affected by SMC with 40/40 abscising 15 bracts compared with the other SMC treatments, which abscised 7 bracts (Table 3.4). Total leaf number and SPAD were reduced by PM when plants were sleeved (Table 3.5). At the end of postproduction, PS packaged plants had abscised 29 total leaves, with a SPAD reading of 47.5 compared with NS packaged plants which abscised 20 leaves and had increased SPAD from that at the beginning of postharvest (Table 3.5).

At the early harvest in 2017, 'Christmas Eve Red' plants had 38.9 total green leaves, 33.5 red bracts, SPAD readings of 56.8, 10 closed cyathia and 0 open cyathia per lateral branch, and a visual quality rating of 5.0. At the late harvest, plants had 34.8 total green leaves, 43.9 red bracts, SPAD readings of 57.2, 9.0 closed cyathia and 0.5 open cyathia per lateral branch, and a visual quality rating of 5.0, regardless of SMC treatments. The differences between plants at the two HT were due to the poinsettia maturing process in which green leaves transition to red bracts and cyathia reach anthesis. In spite of these maturation processes, the overall quality of the plants was the same.

There were no SMC × PM × HT interactions for any measured variable at the end of two weeks of postproduction in 2017, and visual rating was not affected by treatments, decreasing from 5.0 to 2.8. There was an interaction between SMC and PM for open cyathia number per lateral branch and number of bracts with BEB (Table 3.6). The 20/20 with either PM had the same amount of open cyathia per lateral branch as 40/40 with NS packaging. Plants grown with 40/40 SMC and PS packaging during postharvest abscised more cyathia than other treatments. Plants grown in 40/40 with NS packaging had 77.0% higher number of bracts with BEB compared to other SMC/PM combinations (Table 3.7). Closed cyathia abscission was affected by SMC and 40% SMC during RP lost 4.4 closed cyathia per lateral branch compared to 20% SMC during RP which lost 5.9 closed cyathia per lateral branch (Table 3.7). Plants grown in 40/40 had a greater number of stems with BEB bracts compared to those grown in 20% SMC during RP (Table 3.7). The two experiment postproduction results indicated although 20% SMC during RP abscised more closed cyathia per lateral branch during postproduction, visual quality was the same as 40% SMC during RP with more bracts and a smaller number of bracts and stems with BEB.

The 40/40 with NS packaging had reduced postproduction quality due to the high number of bracts with BEB. Bract necrosis was related to high fertilizer level, calcium (Ca^{2+}) deficiency, and low Ca:K ratio (Harbaugh and Woltz, 1989; Nell and Barrett, 1986; Strømme et al., 1994) with Ca^{2+} deficiency considered to be the main cause of BEB in poinsettia (Dole and Wilkins, 1999; Woltz and Harbaugh, 1986). Low-light environment during postproduction contributed to poor Ca^{2+} uptake while stress or wounded tissues increased susceptibility to *Botrytis cinerea* infection which led to BEB development (Ranch, 2011). During postproduction, 40/40 with NS had the greatest irrigation demand indicating that compared to other treatments, 40/40 with NS was more frequently exposed to water deficit, and greater postproduction leaching from RO water irrigation. Also, without a protective sleeve, plants were more exposed to bract bruising during postproduction handling. Thus, the higher bracts with BEB in 40/40 with NS could have been due to higher frequency fertilization during production, more bracts bruising during postproduction handling, and more frequent postproduction water stress, all contributing to the severity of Ca^{2+} deficiency.

At the end of postharvest, open and closed cyathia number per lateral branch, SPAD, and total bract number were affected by HT (Table 3.8). Compared to the early harvest, late harvest plants had 1.9 and 0.7 more open and closed cyathia per lateral branch, respectively, higher SPAD reading, and 7 more bracts (Table 3.8).

Harvest timing influenced poinsettia end of postproduction quality due to the different maturity levels at the time of harvest. Other research indicated that flower maturity level affected potted plant postproduction longevity (Plummer et al., 1990). Poinsettia harvest after pollen shed increased open and closed cyathia retention, SPAD reading, bract and leaf + bract number after two weeks of postproduction. Even though the early harvest plants had some cyathia open during postproduction, overall, the late harvest plants had better cyathia retention, thus increased poinsettia postproduction quality.

SPAD and yellow leaf number were affected by PM (Table 3.9). Compared to NS packaging, PS packaging reduced SPAD and had four more yellow leaves (Table 3.9). PS packaging reduced light intensity by 90.6% at the middle of the plant canopy, compared with NS packaging (Fig. 3.9) even though light intensity was the same at the top of the canopy (13.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and at the substrate surface (1.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$). These perforated sleeves did not cause a build-up of ethylene. Measurements for ethylene were 302.0 ppb for sleeved and non-sleeved plants.

The light intensity and ethylene concentration measurements indicated that PS reduced SPAD and increased yellow leaf number due to the light deficiency in the middle of the canopy, not ethylene concentration. Irregular irrigation, low light intensity, warm temperature and low relative humidity caused poinsettia postproduction leaf drop from the abscission layer at the junction of petiole and the stem (Islam and Joyce, 2015). In our research, the dark-induced leaf senescence could be the major cause of lower total leaf number and SPAD reading and a higher yellow leaf number in plants with PS packaging during postproduction. Dark-induced senescence was considered to have two coexisted mechanisms: light-signaling pathway or carbon starvation. Under a prolonged darkness environment, without the Pfr phytochrome to inhibit the signaling pathway, the ethylene and ABA signaling start, which led to leaf yellowing and senescence. Also, lack of photosynthesis under prolonged darkness led to energy deprivation -- carbon starvation, which promoted catabolic process, could also contribute to dark-induced senescence (Dietrich et al., 2011; Liebsch and Keech, 2016). Leaf that is not exposed to the light catabolized and become an energy source to support cyathia retention.

Table 3.4. Effect of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two packaging methods (PM) [no sleeve (NS) or plastic sleeve (PS)] on total bract number (no.) at the end of postproduction (week 1, 2017) for 'Freedom Red' in 2016 (Guo et al., 2018b).

	Total bracts no.	
40/40	28.6	b[z]
20/40	34.6	a
40/20	35.4	a
20/20	38.1	a
SMC	*[y]	
PM	ns	
SMC x PM	ns	

[z] Means separation by Tukey HSD at $P \leq 0.05$. Means with same letter are not different.
[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*).

Table 3.5. Effect of four substrate moisture content (SMC) treatment (40/40, 20/40, 40/20, 20/20%) and two packaging methods (PM) [no sleeve (NS) or plastic sleeve (PS)] on total leaf number (no.) and SPAD at the end of postproduction (week 1, 2017) for ‘Freedom Red’ in 2016 (Guo et al., 2018b).

	Total leaf no.		SPAD	
NS	46.2	a[z]	51.8	a
PS	37.2	b	47.5	b
SMC	ns[y]		ns	
PM	*		***	
SMC x PM	ns		ns	

[z] Means separation by Student t-test at $P \leq 0.05$. Means with same letter are not different.
[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*) or 0.001 (***).

Table 3.6. Effect of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two packaging methods (PM) [no sleeve (NS) or plastic sleeve (PS)] on open cyathia number (no.) per lateral branch and no. of bracts with bract edge burn (BEB) measured at the end of postproduction for 'Christmas Eve Red' in 2017 (Guo et al., 2018b).

SMC	PM	Open cyathia no. per lateral branch		No. of bracts with BEB	
40/40	NS	1.9	a[z]	4.3	a
40/40	PS	0.8	b	1.3	b
20/40	NS	0.9	ab	0.6	b
20/40	PS	1.6	ab	1.3	b
40/20	NS	1.4	ab	0.9	b
40/20	PS	1.8	ab	1.2	b
20/20	NS	2.0	a	0.6	b
20/20	PS	1.9	a	0.8	b

[z] Means separation by Tukey HSD at $P \leq 0.05$. Means with same letter are not different.

Table 3.7. Effect of four substrate moisture contents (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on closed cyathia number (no.) per lateral branch, and no. of stem with BEB bracts measured at the end of postproduction for 'Christmas Eve Red' in 2017 (Guo et al., 2018b).

SMC	Closed cyathia no. per lateral branch	No. of stem with BEB bracts
40/40	5.3 a[z]	1.6 a
20/40	4.9 a	0.9 ab
40/20	3.6 b	0.6 b
20/20	3.6 b	0.5 b

[z] Means separation by Tukey HSD at $P \leq 0.05$. Means with same letter are not different.

Table 3.8. Effects of two harvest time (HT, early and late harvest) on open and closed cyathia number (no.) per lateral branch, SPAD, and total bract no. measured at the end of postproduction for 'Christmas Eve Red' in 2017 (Guo et al., 2018b).

HT	Open cyathia no. per lateral branch	Closed cyathia no. per lateral branch	SPAD	Total bract no.
Early	0.6 b[z]	4.0 b	51.2 b	31.2 b
Late	2.5 a	4.7 a	54.0 a	38.2 a

[z] Means separation by Student t-test at $P \leq 0.05$. Means with same letter are not different.

Table 3.9. Effect of two packaging methods (PM) [no sleeve (NS) or plastic sleeve (PS)] on SPAD and yellow leaf number (no.) at the end of postproduction for 'Christmas Eve Red' in 2017 (Guo et al., 2018b).

PM	SPAD		Yellow leaf no.	
NS	54.8	a[z]	3.8	b
PS	50.3	b	7.1	a

[z] Means separation by Student t-test at $P \leq 0.05$.

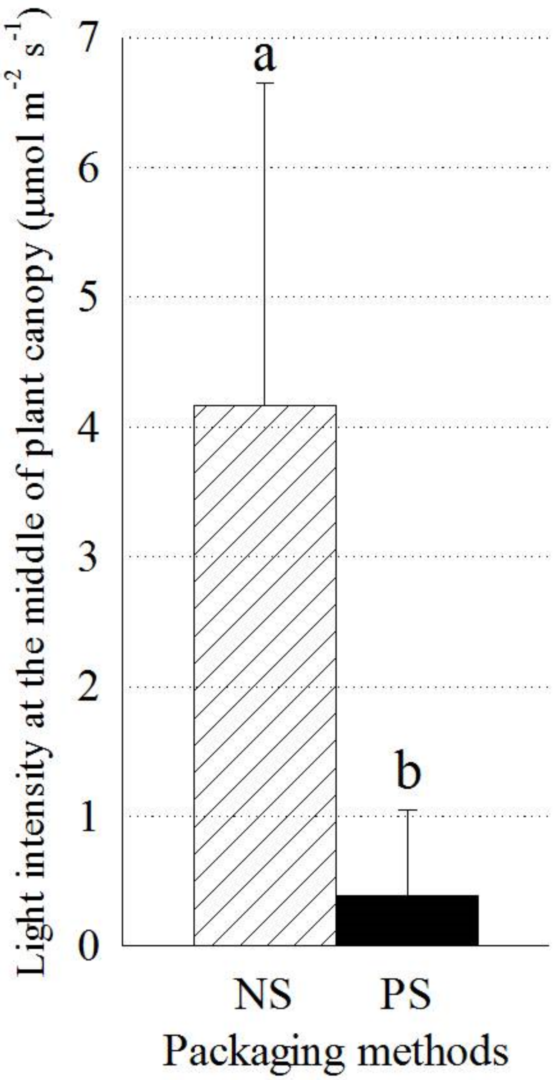

Fig. 3.9. Effects of two packaging methods [no sleeve (NS), and plastic sleeves (PS)] on light intensity measured at the middle of the plant canopy during week 49 for ‘Christmas Eve Red’ in 2017 experiment. Means separation within the group by Student-t test at $P \leq 0.05$ (Guo et al., 2018b).

3.4.6 Postproduction irrigation and associated economic implications

The ‘Freedom Red’ postproduction irrigation was not affected by any treatment in 2016 with average of 4.4 times of irrigation events, and 1.3 L per pot. During postproduction of ‘Christmas Eve Red’, the amount of irrigation water applied was reported as ml/pot since the volume is much lower than the volume used during the production stage. There were no interactions between SMC treatments and PM during postproduction for total irrigation events and total irrigation amount. At the end of the early postproduction (week 47-48), the PS packaging saved 46.7% in retail display space and saved 20% in watering labor and irrigation water volume applied compared with the NS packaging. Watering using the 20/40, 40/20 and 20/20 methods saved 15.1%, 26.6% and 32% in retail display space, respectively; 6.3%, 42.1% and 30.9% irrigation-related labor and irrigation water usage, respectively, compared with the 40/40 method (Table 10). At the end of the late harvest postproduction (week 48-49), PS saved 48.7% in display space and 54.5% in labor and irrigation amount compared with NS. The 20/40, 40/20 and 20/20 watering methods saved 15.1%, 20.3% and 26% in retail display space needed, -27%, 55.6% and 55.6% irrigation-related labor and irrigation usage, respectively, compared with the 40/40 method (Table 3.10).

These results show that costs of production are reduced by using the alternative irrigation methods compared to the traditional 40/40 method. The reductions in costs resulted from the reduced bench space required (which reduced the residency costs expressed by overhead cost per square foot per week), the reduction in the amount (and associated costs) of water and fertilizer applied, and the reduction in irrigation-associated labor (e.g. checking emitters, etc.).

Table 3.10. Irrigation and associated economic implications of 'Christmas Eve Red' to four substrate moisture content treatments (40/40, 20/20, 40/20, 20/40% SMC) and two packaging methods [(no sleeve (NS) or plastic sleeve (PS)] in two weeks of early and late harvest postproduction in simulated retail environment (Guo et al., 2018b).

2017 Postproduction wk 49 early harvest

Trt	Aver bench size need (m^2)	Space saved (%)	Total number of irrigation event	Labor saved (%)	Total irrigation amount (mL/pot)	Irrigation amount saved (%)
NS	0.2	0.0[z]	1.1[y] a[x]	0.0[v]	346.9[u] a	0.0[t]
PS	0.1	46.7	0.9 b	20.0	271.0 b	20.0
40/40	0.2	0.0	1.3 a[w]	0.0	380.0 a	0.0
20/40	0.2	15.1	1.2 a	6.3	356.3 a	6.3
40/20	0.1	26.6	0.7 b	42.1	220.0 b	42.1
20/20	0.1	32.0	0.9 b	30.9	262.5 b	30.9

2017 Postproduction wk50 late harvest

Trt	Aver bench size need (m^2)	Space saved (%)	Total number of irrigation event	Labor saved (%)	Total irrigation amount (mL/pot)	Irrigation amount saved (%)
NS	0.2	0.0	1.1 a	0.0	333.3 a	0.0
PS	0.1	48.7	0.5 b	51.5	161.5 b	51.5
40/40	0.2	0.0	1.1 a	0.0	337.5 a	0.0
20/40	0.2	15.1	1.4 a	-27.0	428.6 a	-27.0
40/20	0.1	20.3	0.5 b	55.6	150.0 b	55.6
20/20	0.1	26.0	0.5 b	55.6	150.0 b	55.6

[z] Space saved is calculated based on final spacing difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).
[y] Total number of irrigation event during 14 weeks of production.
[x] Means separation by Student t-test at $P \leq 0.5$ Means with same letter are not different.
[w] Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different
[v] Labor saved is calculated based on irrigation evens number difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).
[u] Total irrigation amount per pot was the sum of each irrigation water input during 14 weeks of greenhouse production.
[t] Irrigation amount saved is calculated based on total irrigation amount difference between the alternative irrigation methods (20/40, 40/20, 20/20) and the traditional irrigation method (40/40).

3.5 Conclusions

In our research, reducing SMC during production of poinsettias, particularly during the reproductive development stage, was beneficial for keeping plants compact throughout production and postproduction (potentially reducing overhead costs associated with bench space requirements) and served to reduce production inputs and related costs without detrimental effects on poinsettia postproduction quality. Poinsettia showed physiological adaptation and acclimation to the water deficit environment that also reduced inputs (thereby reducing potential costs) during postproduction. Plants grown under 20% SMC during reproductive production had 20-30% lower irrigation requirement during postproduction and earlier bract coloring compared with 40% SMC. Earlier bract coloring would allow growers to market poinsettias in a shorter period of time which also contributes to decreased costs.

Using 20% SMC during the reproductive development stage produced more compact plants with 19% less bract internode length on both cultivars tested. Our results show reduced SMC in the reproductive production could help prevent late stretch and postharvest losses associated with this physiological disorder.

The alternative irrigation methods used in these experiments did not differ from the traditional irrigation methods in postharvest longevity except that lower SMC caused increased closed cyathia abscission. However, this was offset by the traditional irrigation method causing higher number of bracts with BEB and more bract abscission. Even though sleeving during postproduction could save shelf space and postproduction irrigation related labor, our results also show prolonged use of sleeves during postproduction caused leaf yellowing and leaf abscission, therefore this practice should be limited to shipping followed by removal during retail.

‘Christmas Eve Red’ plants harvested after pollen shed had better postproduction longevity than those harvested before pollen shed, another possible practice to improve postharvest quality.

In conclusion, using 20% SMC during reproductive production produced compact poinsettias with lower postproduction irrigation requirement and higher postproduction quality.

CHAPTER IV

SIX BEDDING PLANT SPECIES/CULTIVARS RESPONSE TO REDUCED SUBSTRATE MOISTURE CONTENT (SMC) DURING GREENHOUSE PRODUCTION CONCERNING GROWTH, DEVELOPMENT, PRODUCTION QUALITY AND ECONOMIC EFFECT

4.1 Abstract

This study analyzed the effect of two substrate moisture contents (SMC) (20% or 40% SMC) during greenhouse production of six bedding plant species/cultivars [*Solenostemon scutellarioides* 'French Quarter' (coleus), *Petunia* x *hybrida* 'Colorworks Pink Radiance' (petunia), *Lantana camara* 'Lucky Flame' (lantana), *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' (SCC) and ‘Sunpatiens Spreading Lavender’ (SSL) (impatiens), and *Salvia splendens* ‘Red Hot Sally II’ (salvia)] on growth and development, plant production and postproduction quality, and economic value. Compared with 40% SMC, at the end of production, petunia, lantana, impatiens SCC and salvia shoot dry weight was reduced with 20% SMC. With 20% SMC, petunia and impatiens SCC root ball coverage percentage was greater on the bottom of the container, whereas impatiens SSL and salvia root ball coverage were reduced. The 20% SMC increased petunia postproduction quality by increasing flower number and shoot coloring percentage. Lantana and impatiens SCC flower and/or bud number and shoot coloring percentage were reduced by 20% SMC. Impatiens SSL shoot coloring percentage and flower number were not affected by SMC. Salvia with 20% SMC had increased postproduction quality. The 20% SMC reduced postproduction water potential in petunia, lantana and coleus, suggesting that plants with 20% SMC during production were acclimated to reduced irrigation administered during postproduction. The 20% SMC saved labor due to less frequent watering and overhead associated costs due to reduced bench space, with the exception of coleus and impatiens SSL,

which used the same bench space as the 40% SMC. Considering production and /or postproduction quality, using 20% SMC during greenhouse production is beneficial as an alternative irrigation method for these cultivars of coleus, petunia, impatiens SSL and salvia, but not for impatiens SCC or lantana.

4.2 Introduction

The wholesale value of bedding and garden plants was 1.86 billion dollars in 2015, 44% of the total wholesale value of floriculture crops in the U.S., making bedding and garden plants the largest crop segment in this industry. Annual bedding plants generated 1.3 billion dollars, representing 69% of the total bedding and garden plant segment. Although the wholesale value of bedding and garden plants was down 1% from the previous year, those sold in hanging baskets and five inches or larger containers increased while those sold in smaller containers or flats was reduced compared to the previous year (USDA, 2016).

Considering the economic value of potted bedding plants and the economic and environmental needs to save irrigation water, many studies have been conducted on bedding plants' responses to water deficits (Islam and Joyce, 2015; Jacobson et al., 2015; Starman et al., 2007). Reduced irrigation during greenhouse production increased water use efficiency in American alumroot (*Heuchera americana*), gaura (*Gaura lindheimeri*), impatiens (*Impatiens walleriana*), salvia (*Salvia splendens*), and vinca (*Catharanthus roseus*) (Burnett and van Iersel, 2008; Garland et al., 2012; Jaleel et al., 2008; Nemali and van Iersel, 2008).

Another greenhouse production challenge to growing bedding plants is height control typically managed with several plant growth regulator applications to produce compact plants with shorter internodes (Dole and Wilkins, 1999). Reduced irrigation inhibited petunia (*Petunia* x *hybrida*) shoot growth, which implied lower substrate moisture content (SMC) could be used as an effective growth control method during greenhouse production of petunia cultivars 'Hurrah White’ and 'Wave Purple' (Blanusa et al., 2009; Niu et al., 2006). Water deficit, induced by amending substrate with osmotic compounds, produced more compact salvia (*Salvia splendens* 'Bonfire') with greater leaf area:height (Burnett et al., 2005). Lowering SMC to constant 20% from 40% combined with lower fertilization increased flowering in petunia 'Dreams White', which increased their visual quality, while lowering production costs (Alem et al., 2015). Conversely, it was reported petunia ‘Hurrah White’ grown at constant 10% SMC and impatiens (*Impatiens walleriana* 'Cajun Violet') grown at 30% SMC using the dry-down method had reduced flower number (Blanusa et al., 2009; Chyliński et al., 2007).

Sensor-based irrigation systems are being used to reduce irrigation water usage and produce more compact plants, with less cost, while increasing or maintaining their aesthetic quality. The sensor-based irrigation system was first developed by Nemali and van Iersal in 2006 to reduce water consumption by maintaining a distinct and constant SMC (Nemali and van Iersel, 2006). Earlier research showed 40% SMC to be similar to the traditional, well-irrigated method commonly used in the industry, while 20% SMC was an alternative irrigation method that saved water without detrimental effects on plant quality (Alem et al., 2015; Bayer et al., 2015; Jacobson et al., 2015, Guo et al., 2018a).

Using a sensor controlled dry-down method, two bedding plant species responses to 20% SMC varied compared to 40% SMC. Twenty percent SMC produced more compact angelonia (*Angelonia angustifolia* 'Angelface Blue'), whereas, it did not impact heliotrope (*Heliotropium arborescens* 'Simply Scentsational') shoot growth. However, plants with 20% SMC had more root growth. Twenty percent SMC increased both angelonia and heliotrope postproduction visual quality by increasing the percentage of plant shoots covered with flowers, and reduced water input during production therefore, reducing production costs (Guo et al., 2018a).

Even though studies have been performed on plants' responses to water deficit during greenhouse production, the effect of water deficit on postproduction quality remains unclear (Islam and Joyce, 2015). The objective of this study was to ascertain the effect of traditional (40% SMC) vs. alternative (20% SMC) irrigation methods on growth and development and physiological parameters during production of coleus, petunia, lantana, impatiens, and salvia. We used the same dry-down method as described previously (Guo et al., 2018a) to apply SMC treatments, irrigating plants to container capacity (CC) after target SMC levels were indicated by sensor readings. The root substrate was then allowed to dry back down to the target SMC and was re-watered to CC, repeatedly as needed. We determined whether plants produced at 20% SMC acclimated to infrequent irrigation during simulated shelf life and analyzed the economics of these irrigation methods considering production inputs and shrinkage through the market channels. Finally, we quantified plant quality before and after simulated shelf life. Our hypothesis was that 20% SMC during production would lower irrigation-associated costs, control growth, better acclimate plants to the postproduction environment, and allow plants to maintain higher visual quality during postproduction

4.3 Materials and Methods

4.3.1 Plant materials and growing conditions

Rooted cuttings of coleus (*Solenostemon scutellarioides*) 'French Quarter', petunia (*Petunia* x *hybrida*) 'Colorworks Pink Radiance', lantana (*Lantana camara*) 'Lucky Flame', and impatiens (*Impatiens* x *hybrida*) 'Sunpatiens Compact Hot Coral' (SCC) grown in 102 liner trays were received and transplanted on 30 Jan. 2017. 'Sunpatiens Spreading Lavender' (SSL) grown in 102 liner trays, and salvia (*Salvia officinalis*) ‘Red Hot Sally II' seedlings grown in 128 plug trays with four seedlings per plug were received and transplanted on 15 Mar. 2018. All plants were purchased from Tagawa Greenhouses, Inc. (Denver, CO), and graded for uniformity on arrival. Each plant was transplanted into a 1.67 L (6.5 inch azalea) container (The HC Companies, Inc., Middlefield, OH) with commercial peat based soilless root substrate (85% Canadian sphagnum peat moss and 15% perlite; BM 6, Berger, Saint-Modeste, Canada). During the greenhouse production period, a water-soluble fertilizer (20N-4.4P-16.6K Peters 20-10-20; Scotts Miracle-Gro Company, Marysville, OH) was applied with each irrigation event, with a nitrogen concentration of 200 $mg \cdot L^{-1}$. Plants were treated with an etridiazole and thiophanate-methyl (Banrot, Everris NA Inc. Dublin, OH) root substrate drench after transplanting to prevent root rot. Plants were then allowed 14 days for root establishment before initiation of SMC treatments on 20 Feb. 2017 and 26 Mar. 2018. SMC treatments were continual throughout the production weeks.

Plants were grown in a glass wall and polycarbonate roof greenhouse in College Station, TX. for two experiments: 1) 30 Jan. to 5 May 2017; and, 2) 15 Mar. to 18 May 2018. Environmental data was measured at plant canopy level by WatchDog 450 data loggers and LightScout quantum light sensors (Spectrum Technologies Inc., Aurora, IL). The average temperature and light intensity in the greenhouse during the experiment was 22.8 ºC day/18.4 ºC night in 2017 and 24.5 ºC day/18.4 ºC night in 2018. During production, average daily light integral (DLI) and relative humidity were 14.6 $mol \cdot m^{-2} \cdot d^{-1}$ and 64.8% in 2017 and 16.5 $mol \cdot m^{-2} \cdot d^{-1}$ and 54.8% in 2018.

In 2017, plants were deemed marketable after seven weeks of production (7 April) for coleus, eight weeks (14 April) for petunia and nine weeks (21 April) for lantana and impatiens

SCC. At this time, plants went through a simulated shipping process consisting of hand-watering to container capacity (CC) before moving plants by cart into a dark lab for 48h at 22.4°C and 42.4% relative humidity. In 2018, impatiens SSL and salvia were deemed marketable after six weeks of production (3 May), and then went through a simulated shipping process similar to that in 2017 with the exception of a reduced dark period of 12 h at 21.4°C and 62.7% relative humidity and the cart was wrapped with plastic polyethylene film. After shipping, plants were returned to the greenhouse by cart and held under 50% shade cloth for two weeks for simulated shelf life, during which plants were only watered with RO water when wilting began to occur. During postproduction, the average temperature, DLI, and relative humidity in the greenhouse were 22.3ºC day/19.5ºC night, 6.2 $mol \cdot m^{-2} \cdot d^{-1}$ and 64.8% in 2017 and 21.7ºC day/20.0ºC night, 8.5 $mol \cdot m^{-2} \cdot d^{-1}$ and 52.3% in 2018.

4.3.2 Substrate moisture content (SMC) treatment.

Two irrigation treatments (20% and 40% SMC) were applied in six experiments (one species/cultivar per experiment) during the production weeks. SMC was defined as V_w/V_T (V_w is the volume of water; V_T is the total volume of substrate particles, water, and air space). The 40% SMC (well-watered, traditional irrigation method) consisted of allowing the substrate to dry down to 40% SMC before hand-watering to container capacity (CC) (52.2% SMC in 2017 and 54.5% SMC in 2018) which was until the initiation of drainage. The 20% SMC (alternative irrigation method) consisted of allowing substrate to dry down to 20% SMC before hand-watering to CC. Substrate moisture contents were monitored by a watchdog 1000 series Micro Station and SM 100 WaterScout soil moisture sensors (Spectrum Technologies, Inc. Aurora, IL). There was one sensor per treatment per species inserted in the root substrate of a container that was closer to the center of the greenhouse bench to reflect the average SMC of the treatment and avoid the drying effect of the bench edges. Sensors recorded SMC every 30 minutes and each irrigation event was determined based on the sensor readings (observed daily) and the calibration of the sensor.

4.3.2 Data collection

For the economic analysis of water usage, containers were weighed before each irrigation event during the production and postproduction stage of the experiments. After irrigation, containers were allowed to drain for 1 h and then reweighed. The weight difference was calculated and recorded to determine total irrigation volume. Each irrigation event was documented and summed to determine total number of irrigation events during production and/or postproduction.

Plant height and width were recorded weekly starting at production week 1 on all six species/cultivars. Plant height was measured from the root substrate surface to the plant growing point. Two plant widths were measured across the greatest plant width and the perpendicular width. Growth index (GI) was calculated as: GI = plant height/2 + (plant width1+plant width2)/4 (Niu et al., 2007). Stem caliper on petunia, lantana, impatiens SCC, impatiens SSL, and salvia were collected at the end of production and the end of two weeks of postproduction. Bud, flower, and senesced flower number were measured weekly on petunia, lantana and impatiens SCC. The same data were collected on impatiens SSL and salvia only at the end of production and postproduction.

Instantaneous leaf gas exchange parameters [net carbon assimilation rate (P_n), stomatal conductance (g_s), and transpiration rate (E)], and relative greenness of leaves (SPAD, SPAD-502 Minolta Camera Co., Osaka, Japan) were measured weekly starting week 4 or 5 on all species with the exception of coleus, due to its characteristic multi-colored, patterned leaves. A young fully expanded leaf was put into the leaf chamber (cuvette) of a portable photosynthesis system (LI-6400XT, LI-COR Inc., Lincoln, NE) between 1000 and 1200HR, with the cuvette conditions set at 25 ºC, 1200 µmol m^{-1} s^{-1}, and 400 µmol CO_2. Coleus, lantana, petunia and salvia were subjected to mid-day water potential weekly staring at week 5 with a pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, CA). At the end of production, stem caliper were measure under the node of the third fully expanded leaf with a digital caliper on all six species/cultivars. At the end of postproduction, all species were destructively harvested and total plant shoot DW was determined after being oven-dried at 80 °C for 48 h to constant weights.

In order to measure salvia quality, five replications were dissected at the end of production, and the rest were dissected at the end of postproduction. Data collected on four salvia main stems were averaged to determine total stem height, vegetative stem height with leaves or abscised leaves, inflorescence height with fresh flowers or abscised flowers, immature, flowering and senesced inflorescence number and chlorotic leaf number.

Photos of shoots were taken from above at the end of production and postproduction to determine the shoot coloring percentage (the percentage of the plant canopy covered by flowers) on all species/cultivars except coleus and salvia, due to their lack of inflorescences and vertical inflorescences, respectively. To determine how SMC affected root orientation in the container, root ball photos were taken at the end of postproduction from the bottom of the root ball and both sides of the root ball. Root ball covering percentage was the percentage of the substrate surface covered by roots after removal from the container. The shoot coloring percentage and root ball coverage percentage were analyzed with Photoshop CS6 (Adobe Systems Inc. San Jose, CA). Photoshop quantified the colored area (flowers) and green area (leaves), and the total shoot area was calculated as colored area + green area. The shoot coloring percentage was then calculated as colored area divided by total shoot area. To determine root ball coverage percentage Photoshop quantified the total root ball area as root area + substrate area. The root ball coverage percentage was calculated as root coverage area divided by total area.

4.3.3 Experimental design and data analysis

The experiment was a randomized complete design (RCD) with two treatments (20% and 40% SMC) with15 replications and in 2017 and 10 replications in 2018. Each species was analyzed separately. The data were analyzed by JMP (SAS Institute, Cary, NC). Mean separation was conducted using student t-tests, if significant at the 5% level.

4.4 Results and Discussion

4.4.1 Plant morphology

Coleus and impatiens SSL growth index (GI; 32.4 cm, SD = 6.6 cm; and 31.6 cm, SD = 0.9 cm, respectively) and shoot dry weight (DW) were not affected by SMC (Table 4. 1). Petunia and salvia GI were greater with 40% SMC one or two weeks after SMC treatments began and continued throughout the production weeks (Fig. 4.1). Petunia GI continued to be greater whereas salvia was the same between treatments during postproduction (Fig. 4.1). Petunia, lantana, impatiens SCC and salvia had higher shoot DW with 40% SMC (Table 1) although there were no differences in GI between SMC for lantana (34.2 cm, SD = 2.2 cm) and impatiens SCC (26.6 cm, SD = 0.6 cm). The 20% SMC reduced stem caliper of lantana, impatiens SCC and salvia (Fig. 4.2).

Root ball coverage percentage varied with species. Coleus and lantana root coverage percentage was not affected by SMC (Table 4.1). Petunia and impatiens SCC with 20% SMC had more roots at the bottom of the container but not at the sides of the container (Table 4.1). Impatiens SSL and salvia had higher root ball coverage at the bottom and the sides of the container with 40% SMC (Table 4.1).

The level of adaptation is highly dependent on species and cultivar drought tolerance. Impatiens SCC is a hybrid with the strong root system, adapted to full sun or part shade, compact, and drought tolerant (Dole and Wilkins, 1999; Sato and Minemura, 2014; Sakata Seed America, 2017). This could explain why impatiens SCC with 20% SMC produced more roots, without affecting shoot GI. In contrast to impatiens SCC, impatiens SSL was bred to have a spreading habit (Sato and Minemura, 2016). In our present study, impatiens SSL shoot DW, GI and stem caliper were not affected by SMC treatments, and only root growth was inhibited. This indicated that with 20% SMC, impatiens SSL redirected more energy to support shoot growth and flowering than root development. Coleus has a high-water use requirement and was irrigated more than the other species. This trait made the difference between irrigation amount and frequency between 20% and 40% SMC diminutive compared with the other species tested and thus, coleus morphological variables were not affected.

Water deficit during production caused shoot growth inhibition including reduced leaf surface area, plant height and shoot DW. Previous studies reported lantana, petunia and salvia shoot DW decreased as the SMC level decreased (Alem et al., 2015; Eakes et al., 1991; Kim and van Iersel, 2009). Lower SMC inhibited shoot growth of other bedding plant including vinca (*Catharanthus roseus*), carnation (*Dianthus caryophyllus*), angelonia (*Angelonia angustifolia*), alumroot (*Heuchera americana*) and gaura (*Gaura lindheimeri*) (Alem et al., 2015; Burnett and van Iersel, 2008; Garland et al., 2012; Guo et al., 2018a; Jacobson et al., 2015; Jaleel et al., 2008; Kim and van Iersel, 2009).

In a water deficit environment, root growth is favored over shoot growth (Taiz et al., 2015). This was considered beneficial for adaptation and surviving a water stress situation (Blum, 1996). Angelonia, heliotrope, carnation, crimson bottlebrush (*Callistemon citrinus*), geranium (*Pelargonium* × *hortorum*), impatiens and oleander (*Nerium oleander*) were reported to have higher root density or root to shoot ratio under lower SMC (Álvarez et al., 2013; Álvarez et al., 2009; Álvarez et al., 2011; Álvarez and Sánchez-Blanco, 2013; Chyliński et al., 2007; Guo et al., 2018a; Niu et al., 2008; Sánchez-Blanco et al., 2009).

Petunia grown in 40% SMC had higher flower and bud number six weeks after SMC treatments began. However, petunia grown in 40% SMC had higher senesced flower number and therefore had less flower and bud numbers during the two weeks of postproduction (Table 4.2).

Lantana and impatiens SCC bud, flower, and senesced flower number were not affected by SMC treatments at the end of production, with an average of 13.8 (SD = 1.4), 0.1 (SD = 0.1) and 0 for lantana and 46.6 (SD = 2.0), 5.8 (SD = 0.8) and of 3.1 (SD = 0.5) for impatiens SCC, respectively.

At the end of postproduction lantana with 40% SMC had greater bud and flower numbers, because plants with 40% SMC produced more buds at the end of production (Table 3). During postproduction, impatiens SCC bud number was greater with 40% SMC (Table 3), but the flower number was not affected by SMC, with an average of 4.1 (SD = 1.1) the first week and 16.0 (SD = 1.8) the second week. Impatiens SSL flower and bud number were not different between SMC treatments during production and postproduction, with an average of 5.3 (SD = 1.0) and 44.0 (SD = 2.3) for production, and 18.2 (SD = 2.2) and 46.9 (SD = 4.1) for postproduction.

During flowering, plants are more susceptible to water stress. Research indicates that, under water deficit, root growth into deeper soil required allocation of photosynthetic products to root tips. However, during flowering, root growth is less pronounced than in the vegetative stage due to the energy being redirected to the reproductive organs (Taiz et al., 2015). Previous research also indicated that higher SMC combined with higher fertilization increased petunia shoot growth and reduced flowering (Alem et al., 2015). Thus, when facing water deficit during postproduction, the competition for photosynthetic products between root and flower could cause more flower senescence in petunia with 40% SMC in our presented research.

On the other hand, impatiens SCC and SSL flowers were less affected by the SMC treatments used in this experiment. Even though our research reported impatiens SCC with 40% SMC had more buds, the flower number was not different between SMC. *Impatiens* x *hybrida* is a hybrid between *Impatiens walleriana* and *Impatiens hawkeri* with better drought tolerance than *Impatiens walleriana*, which is more sensitive to drought and was reported to have reduced plant height and flower number under water-deficit conditions (Sato and Minemura, 2014; Sato and Minemura, 2016; Wegley, 2007).

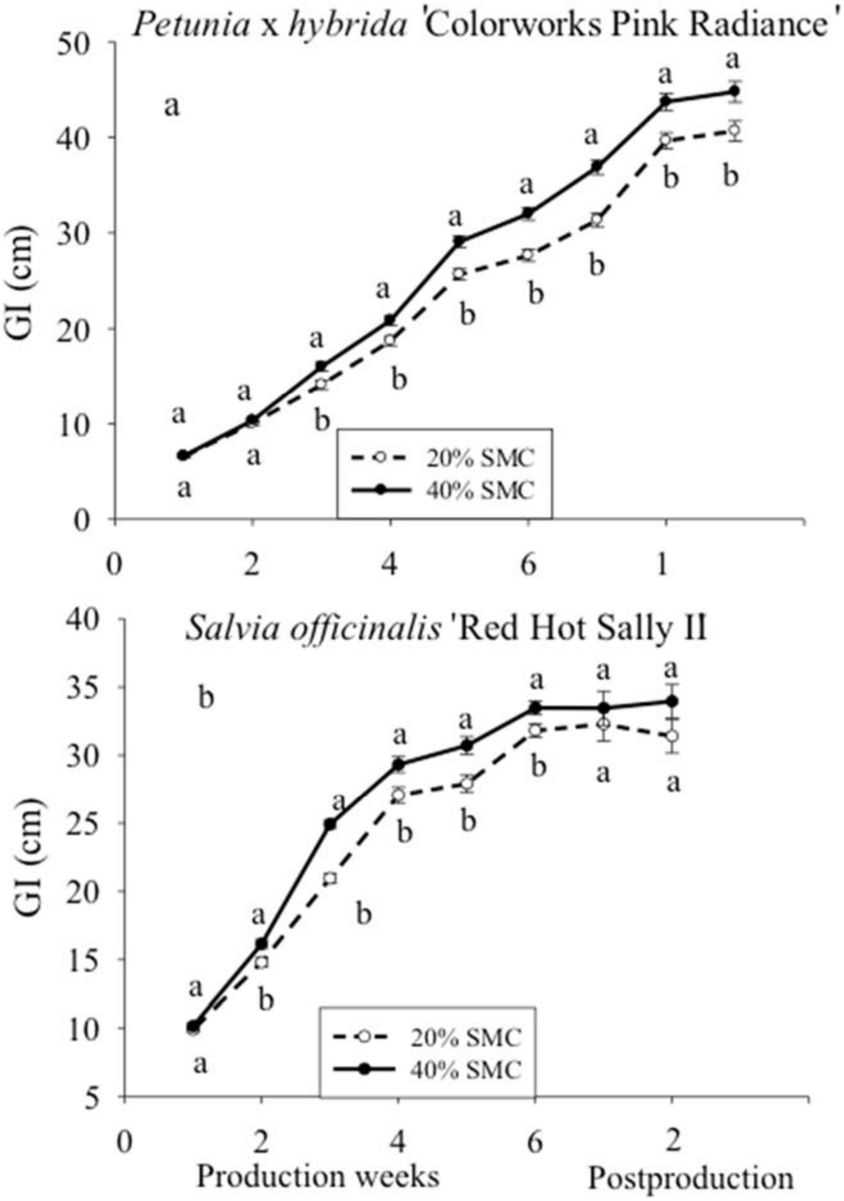

Figure 4.1. Effect of 20% and 40% substrate moisture content (SMC) on weekly growth index (GI = plant height/2 + (plant width 1 + plant width 2)/4.) production weeks 1 to 8, and two weeks of postproduction of a) *Petunia* x *hybrida* 'Colorworks Pink Radiance' in 2017; and GI of production weeks 1 to 6, and two postproduction weeks of b) *Salvia officinalis* 'Red Hot Sally II' in 2018. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000.

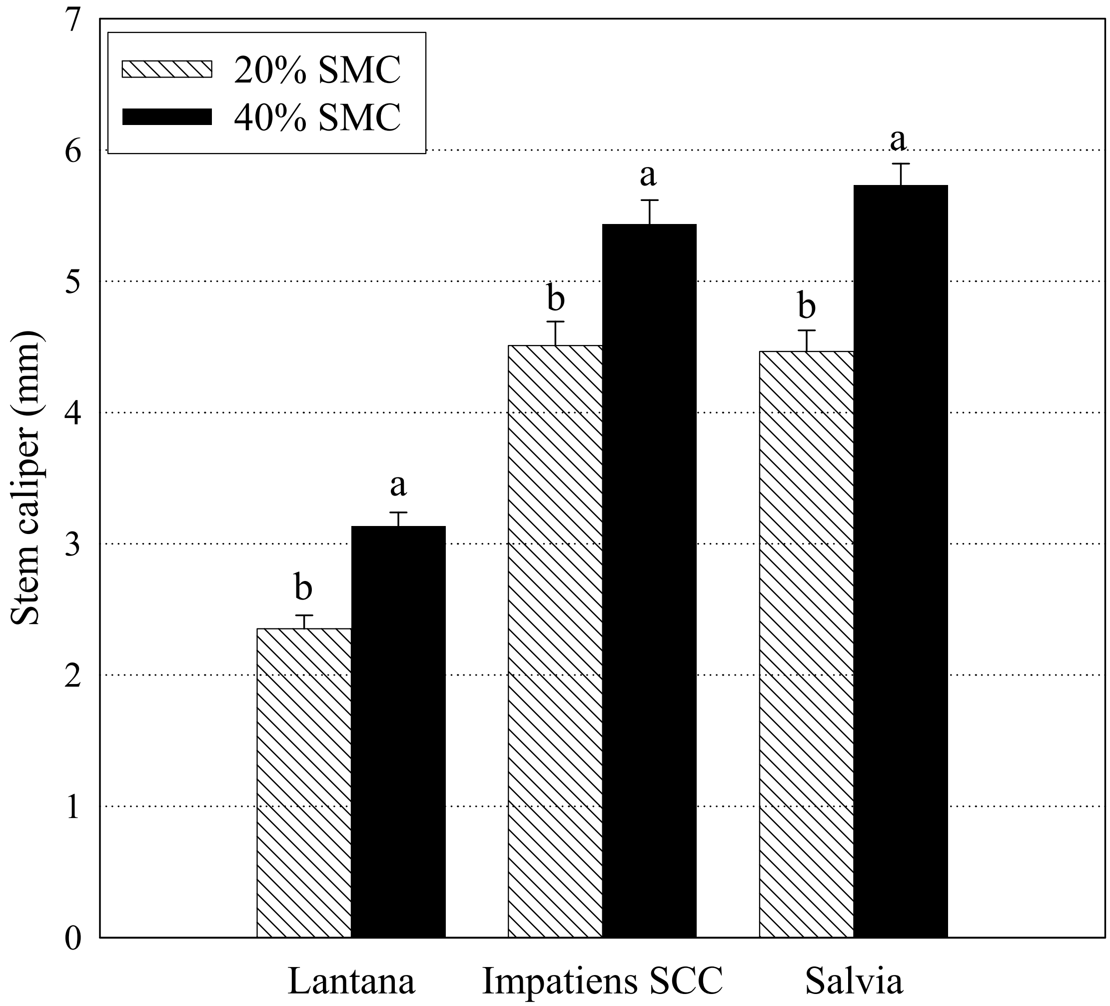

Figure 4.2. Effect of 20% and 40% substrate moisture content (SMC) on stem caliper at the end of the SMC treatment of *Lantana camara* 'Lucky Flame' and *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' (SCC) in 2017, and *Salvia officinalis* 'Red Hot Sally II' in 2018. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000.

Table 4.1. Effect of 20% and 40% substrate moisture content (SMC) on shoot dry weight (DW) and root ball coverage percentage on the bottom and side of *Solenostemon scutellarioides* ‘French Quarter’, *Petunia* x *hybrida* ‘Colorworks Pink Radiance’, *Lantana camara* ‘Lucky Flame’, and *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral’ (SCC) in 2017, and 'Sunpatiens Spreading Lavender’ (SSL) and *Salvia splendens* ‘Red Hot Sally II’ in 2018.

	Shoot DW		Root ball coverage %			
Coleus			Bottom		Side	
20% SMC	34.6	a[z]	39.7	a	52.5	a
40% SMC	33.0	a	40.1	a	50.0	a
ANOVA	ns[y]		ns		ns	
Petunia						
20% SMC	11.8	b	44.3	a	81.8	a
40% SMC	17.8	a	33.4	b	76.8	a
ANOVA	**		*		ns	
Lantana						
20% SMC	8.0	b	30.5	a	49.8	a
40% SMC	12.6	a	32.3	a	44.8	a
ANOVA	***		ns		ns	
Impatiens SCC						
20% SMC	7.1	b	21.4	a	60.2	a
40% SMC	8.5	a	13	b	56.5	a
ANOVA	**		**		ns	
Impatiens SSL						
20% SMC	12.5	a	63.5	b	35.8	b
40% SMC	13.0	a	81.1	a	45.1	a
ANOVA	ns		*		*	
Salvia						
20% SMC	11.7	b	56.9	b	51.9	b
40% SMC	16.6	a	75.5	a	68.3	a
ANOVA	***		**		**	

[z] Means separation by student t-test at $P \leq 0.05$.

[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

Table 4.2. Effect of 20% and 40% substrate moisture content (SMC) on bud, flower, and senesced flower number of *Petunia* x *hybrida* 'Colorworks Pink Radiance' from production week 5 to 7 and two postproduction weeks in 2017.

	Production						Postproduction			
Bud number	wk 5		wk 6		wk 7		wk 1		wk 2	
20% SMC	19.4	a[z]	17.3	b	17.3	b	14.7	a	15.4	a
40% SMC	22.0	a	26.7	a	28.2	a	7.5	b	10.6	b
ANOVA	ns [y]		***		***		**		*	
Flower number										
20% SMC	18.3	b	21.0	b	29.8	b	22.1	b	32.6	a
40% SMC	24.7	a	24.5	a	37.4	a	33.0	a	23.4	b
ANOVA	**		*		*		**		**	
Senesced flower number										
20% SMC	1.9	a	13.2	a	26.1	a	29.6	b	49.4	b
40% SMC	1.5	a	14.6	a	31.3	a	52.8	a	89.9	a
ANOVA	ns		ns		ns		***		***	

[z] Means separation by student t-test at $P \leq 0.05$.

[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

Table 4.3. Effect of 20% and 40% substrate moisture content (SMC) on bud and flower number of *Lantana camara* ‘Lucky Flame’ and bud number of *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral’ (SCC) during two weeks of postproduction in 2017.

	Postproduction			
Lantana bud number	wk 1		wk 2	
20% SMC	15.1	b[z]	7.3	b
40% SMC	26.5	a	15.6	a
ANOVA	**[y]		***	
Lantana flower number				
20% SMC	7.3	a	6.7	b
40% SMC	7.9	a	13.7	a
ANOVA	ns		**	
Impatiens SCC bud number				
20% SMC	38.2	b	37.4	b
40% SMC	52.1	a	47.2	a
ANOVA	***		*	

[z] Means separation by student t-test at $P \leq 0.05$.

[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

4.4.2 Plant physiology

During greenhouse production, plant leaf gas exchange, SPAD reading, and midday water potential varied among species. Petunia P_n, E, and g_s were not affected by SMC (data not shown). Lantana, impatiens SCC and SSL, and salvia had greater P_n, E and g_s with 40% SMC (Fig. 4.3).

Plants respond to water deficit by closing stomata progressively to reduce evaporation water loss hence reducing P_n, g_s, and E (Tezara et al., 1999). Studies have shown that carnation, crimson bottlebrush, salvia, rose (*Rosa spp*.), and geranium leaf gas exchange rate decreased as SMC level decreased (Álvarez et al., 2009; Álvarez et al., 2011; Álvarez and Sánchez-Blanco, 2013; Cai et al., 2014; Cai et al., 2012; Eakes et al., 1991; Sánchez-Blanco et al., 2009). In our research, lower photosynthesis rate with 20% SMC in lantana, impatiens SCC and SSL, and salvia led to a reduction of their shoot and/or root growth. Even though other studies have shown petunia gas exchange rate decreased as the SMC level decreased, this discrepancy from our results could be due to the experimental methods or the lower SMC levels used in other studies (10% and/or lower SMC) (Kim et al., 2012; Nemali and van Iersel, 2008; Niu et al., 2006). Under water deficit, shoot inhibition has occurred in some species before the photosynthetic activity is affected in order to redirect energy to support further root growth (Boyer, 1970; Taiz et al., 2015). Our results on leaf gas exchange indicated that 20% SMC inhibited petunia shoot growth before affecting its photosynthetic activity, and stimulated petunia to have more root growth.

The leaf chlorophyll index was quantified with SPAD reading and no difference between SMC treatments for the two impatiens cultivars was found. Petunia and salvia with 20% SMC had higher SPAD readings, but lantana with 20% SMC had lower SPAD reading at the end of production and postproduction (Fig 4.4). SPAD is directly related to leaf thickness, nitrogen concentration, chlorophyll level or water status (Basyouni et al., 2015; Dole and Wilkins, 1999; Martínez and Guiamet, 2004). In our study, the higher SPAD with 40% SMC for lantana could be related to the higher leaf nitrogen concentration associated with higher frequency watering and therefore fertilization with each irrigation event since no difference in leaf thickness was detected in any of the species (data not shown). The higher SPAD reading for petunia and salvia with 20% SMC could be due to lower leaf water content or increased leaf chlorophyll content (Martínez and Guiamet, 2004).

Coleus, petunia, lantana and salvia water potential was greater with 40% SMC during production. During postproduction, coleus, petunia, and lantana water potential was greater with 20% SMC, whereas salvia water potential was not affected by SMC (Table 4.4), indicating that 20% SMC during production increased water stress for all four species but only reduced water stress during postproduction for coleus, petunia, and lantana. Mid-day water potential is commonly used as a reliable indicator of plant water stress severity (Jones, 2006; Kim et al., 2012; Shackel et al., 1997). During production weeks, plants with 20% SMC had a higher stress level. Similar results were reported for petunia, vinca, and rose (Kim et al., 2012; Kim and van Iersel, 2011). The significance of our study is that 20% SMC decreased coleus, lantana and petunia water stress level during postproduction. This indicated a possible acclimation to water stress with 20% SMC during the production.

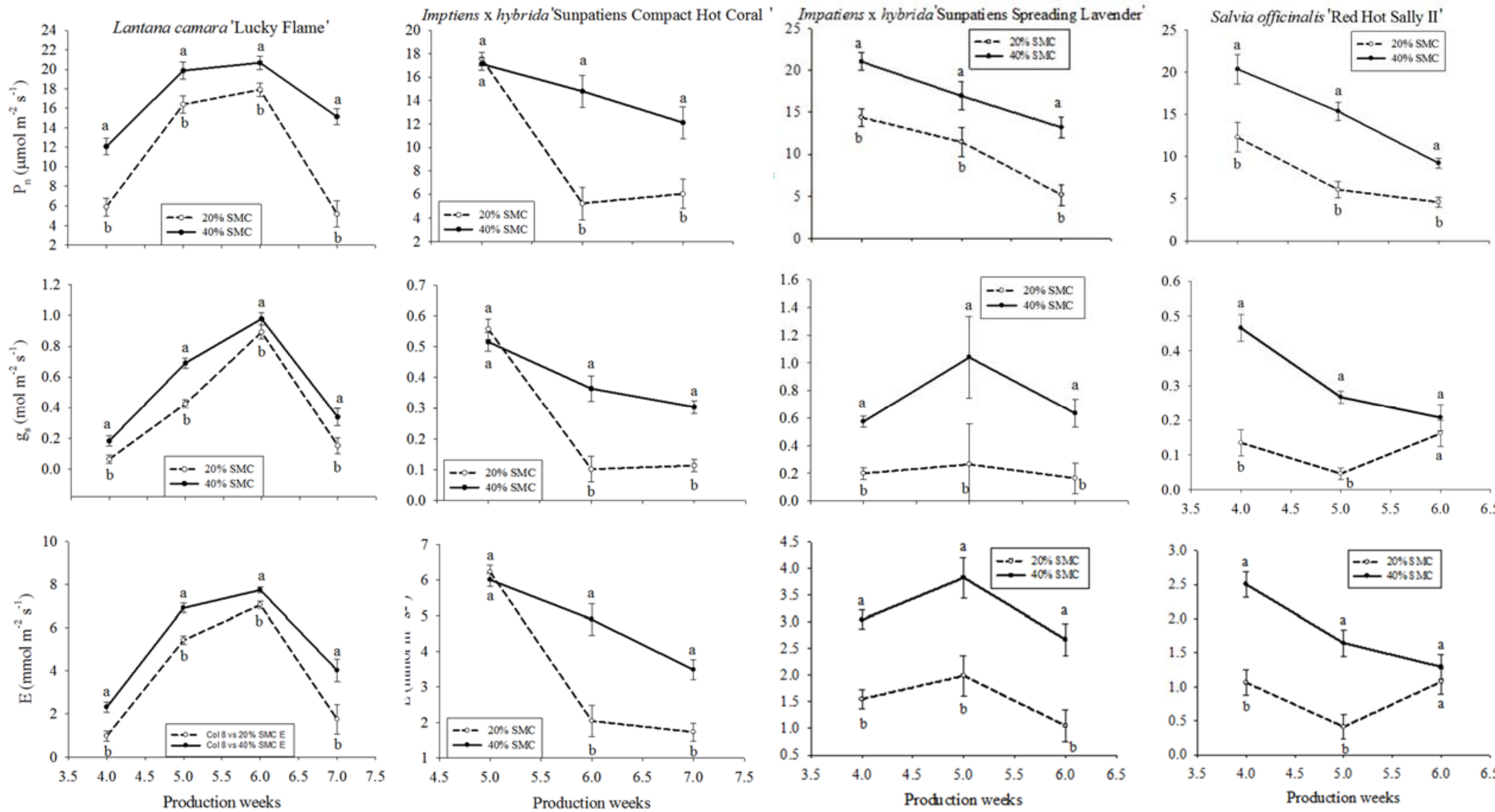

Figure 4.3. Effect of 20% and 40% substrate moisture content (SMC) on leaf net photosynthetic rate (P_n), stomatal conductance (g_s), and transpiration rate (E) from production week 4 to week 7 of *Lantana camara* 'Lucky Flame', *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' in 2017; and 'Sunpatiens Spreading Lavender' and *Salvia officinalis* 'Red Hot Sally II' in 2018. Means separation within the group by Student-t test at $P \leq 0.05$. Means with same letter are not different. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000.

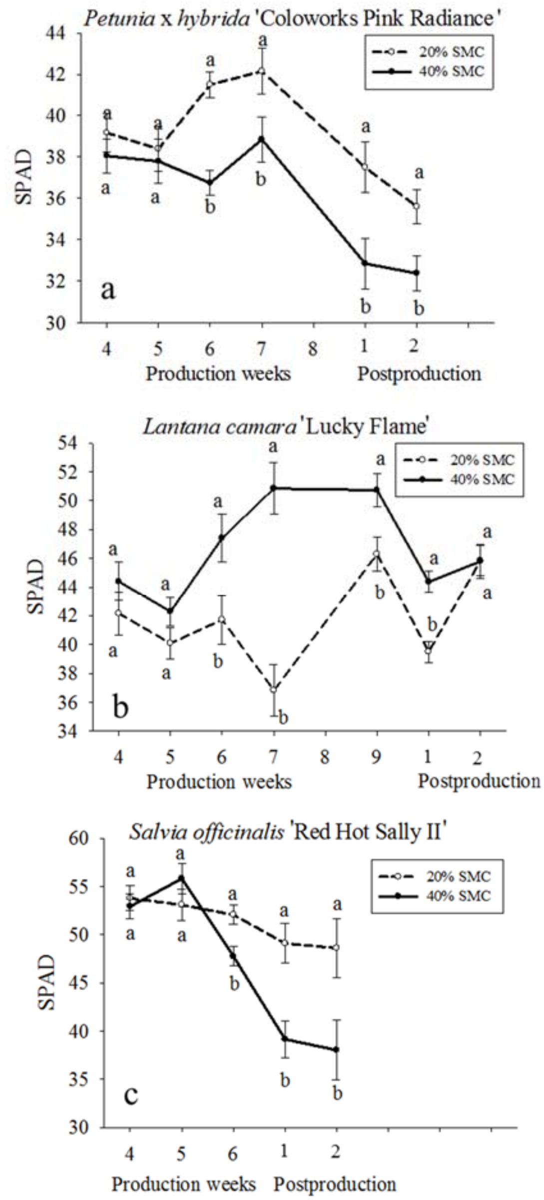

Figure 4.4. Leaf chlorophyll index [Special Products Analysis Division (SPAD) values] for two soil moisture content (40 and 20% SMC) treatments for a) *Petunia x hybrida* 'Colorworks Pink Radiance' and b) *Lantana camara* 'Lucky Flame' during production weeks 4 to 9 and two weeks of postproduction in 2017; and c) *Salvia officinalis* 'Red Hot Sally II' from production weeks 4 to 6 and two weeks of postproduction in 2018. Means separation by Student t-test at $P \leq 0.05$. Means with same letter are not different. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000.

Table 4.4. Effect of 20% and 40% substrate moisture content (SMC) on mid-day water potential of *Solenostemon scutellarioides* 'French Quarter', *Petunia* x *hybrida* 'Colorworks Pink Radiance', and *Lantana camara* 'Lucky Flame' in 2017; and *Salvia splendens* 'Red Hot Sally II' in 2018 during production weeks and postproduction weeks.

	Water potential (bar)	
	Production	Postproduction
Coleus	wk 7	wk 1
20% SMC	-1.5 b[z]	-0.6 a
40% SMC	-0.5 a	-1.4 b
ANOVA	* [y]	*
Petunia	wk 6	wk 2
20% SMC	-0.9 b	-0.5 a
40% SMC	-0.2 a	-0.9 b
ANOVA	*	*
Lantana	wk 8	wk 2
20% SMC	-1.6 b	-1.6 a
40% SMC	-0.7 a	-2.5 b
ANOVA	*	*
Salvia	wk 5	wk 2
20% SMC	-1.9 b	1.12 a
40% SMC	-0.9 a	2.12 a
ANOVA	*	ns

[z] Means separation by student t-test $P \leq 0.05$.
[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*).

4.4.3 Visual quality

At the end of production, petunia, lantana and impatiens SSL shoot coloring percentage was not affected by SMC, but was greater with 20% SMC for impatiens SCC (Table 4.5). However, at the end of postproduction petunia with 20% SMC had greater shoot coloring percentage, whereas, lantana and impatiens SCC with 40% SMC had greater shoot coloring percentage, and impatiens SSL shoot coloring percentage was not affected (Table 4.5; Fig. 4.5).

Petunia with 20% SMC had higher shoot coloring percentage during postproduction because of increased flower number. Lantana with 20% SMC had lower shoot coloring percentage due to the lower flower number during postproduction. Impatiens SCC with 20% SMC produced fewer buds, therefore had lower shoot coloring percentage. Impatiens SSL flower and bud number was not affected by SMC, the same as its shoot coloring percentage. Shoot coloring percentage declined during postproduction for 20% SMC lantana and petunia but increased for impatiens SCC and SSL, following the same trend as their flower and bud numbers.

At the end of production, salvia visual quality was not different between SMC treatments except 40% SMC had increased vegetative stem height compared to those with 20% SMC, and therefore increased total stem height. After two weeks of postproduction, salvia with 40% SMC had increased vegetative stem height with abscised leaves, increased inflorescence height with abscised flowers, and increased number of senesced inflorescences and chlorotic leaves (Table 4.6; Fig 4.6).

Earlier research showed that using lower SMC produced *Salvia splendens* with higher visual quality, and improved tolerance to low SMC compared to untreated plants (Eakes et al., 1991). Drought-induced leaf abscission was believed to contribute to plant survival under water deficit environments by relocating nutrients to the rest of the plant, and reducing water loss through leaf transpiration. Chlorophyll degradation led to leaf chlorotic as part of the process of drought-induced leaf abscission (Munné-Bosch and Alegre, 2004). In our research, even though salvia water potential was not different between SMC treatments during postproduction, plants with 40% SMC had a higher chlorotic leaf number and increased height of vegetative stems with abscised leaves. This indicated they had a more severe response to water deficit during postproduction compared to plants with 20% SMC. When combined with lower inflorescence quality this indicated plants with 40% SMC declined faster during postproduction.

Table 4.5. Effect of 20% and 40% substrate moisture content (SMC) on shoot coloring percentage at the end of production and the end of postproduction of *Petunia* x *hybrida* ‘Colorworks Pink Radiance’, *Lantana camara* ‘Lucky Flame’, and *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral’ (SCC) in 2017 and 'Sunpatiens Spreading Lavender' (SSL) in 2018.

	Shoot color %	
	Production	Postproduction
Petunia		
20% SMC	35.7 a[z]	25.5 a
40% SMC	36.7 a	17.5 b
ANOVA	ns [y]	**
Lantana		
20% SMC	8.9 a	3.7 b
40% SMC	7.3 a	9.2 a
ANOVA	ns	*
Impatiens SCC		
20% SMC	5.8 b	31.4 b
40% SMC	17.1 a	44.3 a
ANOVA	**	*
Impatiens SSL		
20% SMC	11.3 a	19.8 a
40% SMC	11.2 a	25.2 a
ANOVA	ns	ns

[z] Means separation by student t-test at $P \leq 0.05$.

[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*) or 0.01 (**).

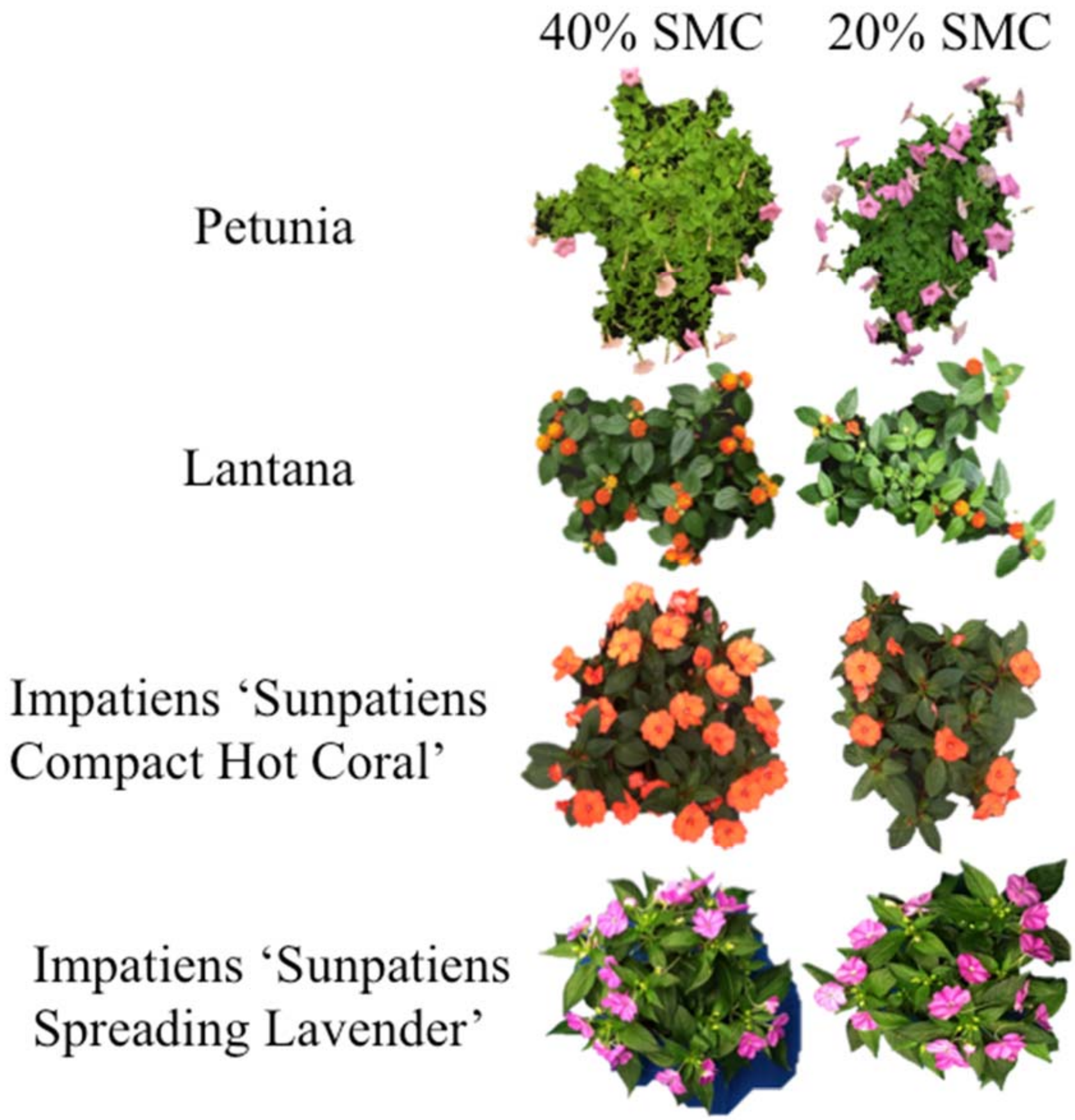

Figure 4.5. Photographs of shoot coloring percentage for *Petunia x hybrida* 'Colorworks Pink Radiance', *Lantana camara* 'Lucky Flame', *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' and 'Sunpatiens Spread Lavender' at the end of postproduction in 2017 or 2018. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) x 100% /1000.

Table 4.6. Effect of 20% and 40% substrate moisture content (SMC) on total stem height, vegetative stem height with leaves or abscised leaves, inflorescence height with fresh flowers or abscised flowers, immature, flowering and senesced inflorescence number and chlorotic leaf number at the end of production and postproduction of *Salvia officinalis* 'Red Hot Sally II' in 2018.

			Vegetative stem height (cm)				Inflorescence height (cm)				Inflorescence number							
	Total stem height (cm)		with leaves		with abscised leaves		with fresh flowers		with abscised flowers		Immature		Flowering		Senesced		Chlorotic leaf number	
End of production																		
20% SMC	38.9	b[z]	25.4	b	0	a	13.1	a	0	a	4.8	a	12.4	a	0	a	0	a
40% SMC	41.6	a	28	a	0	a	13.6	a	0	a	2.2	a	16.6	a	0	a	0	a
ANOVA	*[y]		*		ns		ns		ns		ns		ns		ns		ns	
End of postproduction																		
20% SMC	45.8	b	23.9	a	6.2	b	5.3	a	10.2	b	0.6	a	13.6	a	1	b	0.8	b
40% SMC	49.3	a	25.5	a	8.1	a	0.7	b	11.9	a	1.2	a	13	a	4	a	5.4	a
ANOVA	**		ns		*		**		**		ns		ns		**		***	

[z] Means separation by student t-test at $P \leq 0.05$.
[y] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

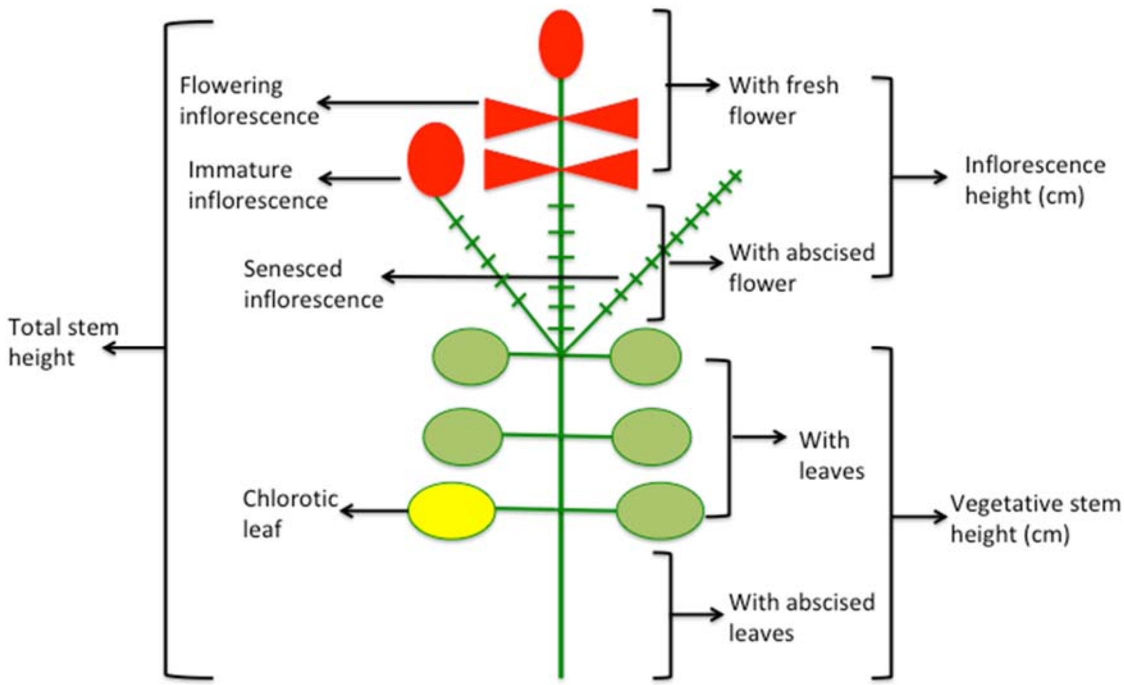

Figure 4.6. Illustration of postproduction quality parameters measured on *Salvia officinalis* 'Red Hot Sally II' at end of postproduction in 2018.

4.4.4 Irrigation and associated economic implications

In this study, we considered the 40% SMC as equivalent to the traditional, well-irrigated method that is currently used by floral industry growers. Compared with 40% SMC, lantana, impatiens SCC, petunia and salvia with 20% SMC had a smaller canopy, thus required less bench space, which may translate to lower overhead costs associated with the bench space (since they are normally applied on a per square foot per week basis). Compared to 40% SMC, coleus, petunia, lantana, impatiens SCC, and salvia saved 7.8%, 24.1%, 32.2%, 6.8%, and 13.4% on bench space, respectively, during production (Table 4.7). Impatiens SSL canopy size was not affected by SMC treatments; therefore no overhead space was saved. During the weeks in production, 20% SMC required less total number of irrigation events; thus, coleus, petunia, lantana, impatiens SCC, and salvia saved 8.3%, 27.3%, 11.1%, 22.2%, 12.5% and 36.4% on irrigation related labor, respectively. Although coleus, petunia, lantana, and impatiens SSL grown in 20% SMC required less total number of irrigation events, the irrigation amount used was not affected by SMC (Table 4.7).

During postproduction, petunia, lantana, impatiens SCC, and salvia grown in 20% SMC saved 15.5%, 33.7%, 8.8%, and 14.9% on bench space, respectively. Coleus with 20% SMC required more bench space than those in 40% SMC. Impatiens SSL bench space was not different between the two SMC treatments. Only petunia saved 25% on irrigation related labor when the total number of irrigation events for other species was not affected by SMC. In all six species, the postproduction irrigation amount was not affected by SMC (Table 4.8).

These results show that costs of production can be reduced by using an alternative watering method (20% SMC) compared with the traditional irrigation method (40% SMC). The reductions in costs are a result of the reduced bench space required (which reduced the residency costs expressed by overhead cost per square foot per week), the reduction in the amount (and associated costs) of water, and the reduction in irrigation-associated labor (e.g. to check and repair emitters). In all six species/cultivars, the total number of irrigation events was less with 20% SMC during production weeks, but the total irrigation water usage was not reduced with the less frequent irrigation, with the exception of petunia and salvia. This is because even though 20% SMC required less frequent irrigation, the 20% SMC required more water input at each irrigation event. For short season crops with a higher water-use requirement, the total water input may not be different between SMC.

Table 4.7. Irrigation and associated economic implications of *Solenostemon scutellarioides* ‘French Quarter’, *Petunia* x *hybrida* ‘Colorworks Pink Radiance’, *Lantana camara* ‘Lucky Flame’, and *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral’ (SCC) in 2017; 'Sunpatiens Spreading Lavender’ (SSL) and *Salvia splendens* ‘Red Hot Sally II’ in 2018, grown at two substrate moisture contents (SMC) (20% and 40%) in production weeks.

	Estimated pot number/bench	Space saved (%)	Total no. of irrigation event		Labor saved (%)	Irrigation amount (L/pot)		Irrigation amount saved (%)
Coleus								
20% SMC	41.0[z]	7.8[y]	11.0[x]	b[w]	8.3[v]	5.6[u]	a	-0.3[t]
40% SMC	38.0	0.0	12.0	a	0.0	5.5	a	0.0
Petunia								
20% SMC	51.0	24.1	8.0	b	27.3	3.6	a	8.1
40% SMC	39.0	0.0	11.0	a	0.0	3.9	a	0.0
Lantana								
20% SMC	71.0	32.2	8.0	b	11.1	3.1	a	11.0
40% SMC	48.0	0.0	9.0	a	0.0	3.5	a	0.0
Impatiens SCC								
20% SMC	81.0	6.8	7.0	b	22.2	2.9	b	23.2
40% SMC	76.0	0.0	9.0	a	0.0	3.8	a	0.0
Impatiens SSL								
20% SMC	67.0	-0.5	7.0	b	12.5	3.8	a	-8.2
40% SMC	67.0	0.0	8.0	a	0.0	3.5	a	0.0
Salvia								
20% SMC	78.0	13.4	7.0	b	36.4	3.9	b	33.1
40% SMC	67.0	0.0	11.0	a	0.0	5.9	a	0.0

[z] Estimated container number/bench was calculated as standard bench size (19.5’ x 5.5’)/average canopy size of the plant.
[y] Space saved was calculated based on final spacing difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[x] Total no. of irrigation events during production weeks.
[w] Means separation by student-t test multiple comparisons at $P \leq 0.05$. Means with same letter are not different.
[v] Labor saved was calculated based on irrigation events number difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[u] Total irrigation amount per container was the sum of each irrigation water input during eight weeks of greenhouse production.
[t] Irrigation amount saved was calculated based on total irrigation amount difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.

Table 4.8. Irrigation and associated economic implications of *Solenostemon scutellarioides* 'French Quarter', *Petunia* x *hybrida* 'Colorworks Pink Radiance', *Lantana camara* 'Lucky Flame', and *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' (SCC) in 2017; 'Sunpatiens Spreading Lavender' (SSL) and *Salvia splendens* 'Red Hot Sally II' in 2018, grown at two substrate moisture contents (SMC) (20% and 40%) in postproduction.

	Estimated pot number/bench	Space saved (%)	Total no. of irrigation event	Labor saved (%)	Irrigation amount (L/pot)	Irrigation amount saved (%)
Coleus						
20% SMC	29.0[z]	-11.2[y]	6.0[x] a[w]	0.0[v]	2.0[u] a	10.5[t]
40% SMC	32.0	0.0	6.0 a	0.0	2.2 a	0.0
Petunia						
20% SMC	31.0	15.5	3.0 b	25.0	1.3 a	7.5
40% SMC	26.0	0.0	4.0 a	0.0	1.4 a	0.0
Lantana						
20% SMC	63.0	33.7	3.0 a	0.0	1.1 a	23.6
40% SMC	42.0	0.0	3.0 a	0.0	1.4 a	0.0
Impatiens SCC						
20% SMC	73.0	8.8	3.0 a	0.0	1.4 a	-34.5
40% SMC	66.0	0.0	3.0 a	0.0	1.0 a	0.0
Impatiens SSL						
20% SMC	55.0	0.1	4.0 a	0.0	1.7 a	12.1
40% SMC	55.0	0.0	4.0 a	0.0	1.9 a	0.0
Salvia						
20% SMC	71.0	14.9	4.0 a	0.0	2.1 a	6.1
40% SMC	60.0	0.0	4.0 a	0.0	2.2 a	0.0

[z] Estimated container number/bench was calculated as standard bench size (19.5' x 5.5')/average canopy size of the plant.
[y] Space saved was calculated based on final spacing difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[x] Total no. of irrigation events during two weeks of postproduction.
[w] Means separation by student-t test multiple comparisons at $P \leq 0.05$. Means with same letter are not different.
[v] Labor saved was calculated based on irrigation events number difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.
[u] Total irrigation amount per container was the sum of each irrigation water input during eight weeks of greenhouse production.
[t] Irrigation amount saved was calculated based on total irrigation amount difference between the alternative irrigation method 20% SMC and the traditional irrigation method 40% SMC.

4.5 Conclusions

Responses and acclimation to 20% SMC varied among species/cultivars. Petunia and impatiens SCC with 20% SMC had higher root ball coverage percentage, whereas impatiens SSL and salvia with 20% SMC had lower root ball coverage percentage. The 20% SMC reduced lantana and impatiens SCC postproduction quality by reducing flower number and/or bud number. Coleus and impatiens SSL morphology was unaffected by SMC. Coleus, petunia, and lantana showed that plants with 20% SMC had decreased water stress (less negative water potential) during postproduction, indicating that plants exposed to mild water deficit during production were acclimated to the water stress.

The 20% SMC reduced total irrigation event number on all four species tested but did not affect the irrigation volume delivered to coleus, petunia, lantana, and impatiens SSL. However, 20% SMC did save labor during production for all six species/cultivars, and reduced bench space with the exception of impatiens SSL, which is bred for its spreading habit. Based on the partial budget modeling procedures we used in this experiment, 20% SMC proved to be a more cost-efficient production method for all six bedding plants species/cultivars for greenhouse growers. However, considering the crop quality and flower number, 20% SMC is not recommended for the lantana and impatiens SCC in greenhouse production. Our results suggest using 20% SMC is an alternative irrigation method for these cultivars of coleus, petunia, impatiens SSL and salvia during greenhouse production.

CHAPTER V

SUMMARY OF FINDINGS

Compared to bedding plants grown in 40% SMC, 20% SMC:

Morphological

1. Reduced shoot dry weight (DW), and growth index (GI) on angelonia, petunia, and salvia. Growth index and shoot DW were not affected on heliotrope, coleus, and impatiens ‘Sunpatiens Spreading Lavender’ (SSL).
2. Reduced shoot DW but GI was not affected on lantana impatiens ‘Sunpatiens Compact Hot Coral’ (SCC).
3. Reduced stem caliper on lantana, impatiens SCC and salvia.
4. Increased root ball coverage percentage on the bottom of the container on angelonia, impatiens SCC, and petunia
5. Increased root ball coverage percentage on the side of the container on heliotrope.
6. Increased root ball coverage percentage on both sides and the bottom of the container on impatiens SSL and saliva. Root ball coverage percentage was not affected on coleus and lantana.
7. Had no effect on angelonia flower or bud stem lengths, vegetative or flower stem node numbers, flower or bud number per stem, total flower or bud numbers, or bud stem internode length

8. Increased flower number per cyme on heliotrope at the end of postproduction.
9. Reduced petunia flower number during production but increased petunia flower number during postproduction.
10. Increased salvia main inflorescence flower height, diameter at the end of postproduction.
11. Reduced salvia senesced inflorescence number, chlorotic leaf number, and the vegetative stem height with abscised leave.

Physiological

1. Increased SPAD reading on angelonia, heliotrope, petunia, and salvia.
2. Reduced lantana SPAD reading.
3. Did not affect SPAD reading on impatiens SCC and impatiens SSL
4. Did not affect photosynthetic rate (P_n), stomatal conductance (g_s), and transpiration (E) on petunia.
5. Reduced P_n, g_s, and E on lantana, impatiens SCC, impatiens SSL, and salvia.
6. Increased postproduction water potential on coleus, petunia and lantana, indicating these plants with 20% SMC had lower water stress during postproduction.

Quality

1. Increased postproduction shoot coloring percentage on angelonia, heliotrope and petunia.

2. Decreased postproduction shoot coloring percentage on lantana and impatiens SCC Economic
3. Did not affect shoot coloring percentage on impatiens SSL.

Economic

1. Saved angelonia 25% irrigation-related labor and 16.3% irrigation amount during production; saved 8.8% irrigation amount during postproduction
2. Saved heliotrope 25% irrigation-related labor and 5.3% irrigation amount during production; saved 3.5% irrigation amount during postproduction
3. Saved coleus 8% irrigation-related labor.
4. Saved petunia 24.1% irrigation-related labor.
5. Saved lantana 11.1% irrigation-related labor.
6. Saved impatiens SSC 22.2% irrigation-related labor and 23.2 irrigation amount.
7. Saved impatiens SSL 12.5% irrigation-related labor.
8. Saved salvia 36.4% irrigation-related labor and 331.1% irrigation amount.
9. Did not affect postproduction irrigation labor and amount on coleus, lantana, impatiens SSC, impatiens SSL and salvia

Compared to poinsettia grown in 40/40 (traditional irrigation):

Morphological

1. 40/20 and 20/20 reduced GI, DW, stem length, internode length, total leaf surface area, single leaf and bract surface area, leaf thickness, and petiole thickness on 'Freedom Red' and 'Christmas Eve Red'.
2. 20/40 GI and DW were not affected by SMC treatment.
3. 20/20 reduced 'Freedom Red' root ball coverage percentage on the bottom of the container.
4. 40/20 and 20/20 reduced root ball coverage percentage on the sides of the container.
5. 40/20 and 20/20 reduced 'Christmas Eve Red' root DW.
6. Total leaf and bract numbers for both cultivars were not affected by SMC treatment.

Physiological

1. Pn, gs, and E were reduced with 20/40 and 20/20 during vegetative production, reduced with 40/20 and 20/20 during reproductive production on 'Christmas Eve Red'.
2. Midday water potential was measured from week 38 to 47 and was not affected by SMC except week 40. Midday water potential was reduced with 40/20 on 'Christmas Eve Red'.

Quality

1. 40/20 and 20/20 had higher bract coloring during production week 42-44 on 'Freedom Red' and 'Christmas Eve Red'.
2. 40/20 and 20/20 had lower SPAD reading on 'Freedom Red' before bract start to turn red.

Economics

1. Both cultivars grown in 20/40, 40/20, and 20/20 had a smaller canopy thus required less bench space, which potentially translates to lower overhead cost associated with bench space.
2. Both cultivars grown in 20/40, 40/20, and 20/20 require less irrigation and therefore saved irrigation-related labor, amount of irrigation water applied, and fertilizer usage.

Postproduction

1. 'Freedom Red' grown in 40/40 had less bracts number after five weeks of postproduction.
2. 'Freedom Red' and 'Christmas Eve Red' total leaf number and SPAD were reduced when plants were sleeved.
3. 'Christmas Eve Red' grown with 40/40 SMC and sleeving packaging during postharvest abscised more cyathia than other treatments.
4. 'Christmas Eve Red' grown in 40/40 had a greater number of stems with BEB bracts compared to those grown in 40/20 and 20/20.

5. After two weeks of postproduction late harvest 'Christmas Eve Red' had more bracts, open and closed cyathia per lateral branch, and higher SPAD reading.

Postproduction economics

1. 'Freedom Red’ postproduction irrigation was not affected by any treatment.
2. 'Christmas Eve Red' grown in 20/40, 40/20, and 20/20 required less irrigation and therefore saved irrigation-related labor.
3. Sleeved 'Christmas Eve Red' required less retail space and irrigation and irrigation related labor.

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APPENDIX A ADDITIONAL TABLES AND FIGURES

Table A1. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for total irrigation event number during production, total irrigation volume during production, total irrigation event number during postproduction, total irrigation volume during postproduction and water use efficiency (WUE) calculated as dry weight produced per gram of water used of *Angelonia angustifolia* ‘Angelface Blue’ and *Heliotropium arborescens* ‘Simply Scentsational’. Each plant species was treated as an independent experiment.

	Total irrigation event number during production	Total irrigation volume during production (L)	Total irrigation event number during postproduction	Total irrigation volume during postproduction (L)	WUE
Angelonia	***[z]	**	ns	**	ns
Heliotrope	***	*	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***)

Table A2. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for pre-dawn and midday water potential during production (week 11 and 13) and postproduction (week 14 and 15) of *Angelonia angustifolia* 'Angelface Blue' and *Heliotropium arborescens* 'Simply Scentsational'. Each plant species was treated as an independent experiment.

	Water potential production (Mpa)				Water potential postproduction (Mpa)			
	wk11 Pre-dawn	wk11 Midday	wk 13 Pre-dawn	wk 13 Midday	wk14 Pre-dawn	wk14 Midday	wk15 Pre-dawn	wk15 Midday
Angelonia	ns[z]	ns	ns	ns	ns	ns	ns	*
Heliotrope	ns	ns	ns	***	ns	ns	ns	**

[z] ns (nonsignificant) or significant at $P \leq 0.001$ (***)

Table A3. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for week 15 harvest data of *Angelonia angustifolia* ‘Angelface Blue’ including total plant shoot dry weight, total raceme number, total stem length, flower and bud stem length, vegetative, flower and bud stem node number, flower and bud number/stem, total flower and bud number, vegetative, flower and bud stem internode length.

Angelonia	Total plant shoot dry weight (g)	Total raceme number	Total stem length (cm)	Flower stem length (cm)	Bud stem length (cm)	Vegetative stem node number	Flower stem node number	Bud stem node number
	*[z]	*	*	ns	ns	ns	ns	*
	Flower number/stem	Bud number/ stem	Total flower number	Total bud number	Vegetative stem internode length (cm)	Flower stem internode length (cm)	Bud stem internode length (cm)	
	ns	ns	ns	ns	**	*	ns	

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***)

Table A4. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for total plant dry weight, total flower number, and cyme number of *Heliotropium arborescens* 'Simply Scentsational':,

Heliotrope	Total plant dry weight	Total flower number	Cyme number
	ns[z]	***	ns

[z] ns (nonsignificant) or significant at $P \leq 0.001$ (***)

Table A5. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for shoot color percentage and root ball coverage percentage of *Angelonia angustifolia* 'Angelface Blue' and *Heliotropium arborescens* 'Simply Scentsational'.

	Shoot color percentage (%)		Root ball coverage percentage (%)		
	End of production	End of postproduction	Bottom of pot	Side 1	Side 2
Angelonia	*	*	ns	*	*
Heliotrope	*	*	*	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*).

Table A6. Responses of leaf net photosynthesis (Pn), stomatal conductance (gs), and transpiration (E) to two substrate moisture contents (SMC) (20% and 40%) in *Angelonia angustifolia* 'Angelface Blue' during greenhouse production weeks 11, 12 and 13, and post-production weeks 14 and 15.

Production Pn (μ mol $m^{-2}s^{-1}$)				Post-production Pn	
SMC	wk11	wk12	wk13	wk14	wk15
20%	17.50 a[z]	14.76 b	11.73 b	11.23 a	11.88 a
40%	17.32 a	15.88 a	13.31 a	12.60 a	11.83 a
Production gs (m mol $m^{-2}s^{-1}$)				**Post-production gs**	
SMC	wk11	wk12	wk13	wk14	wk15
20%	0.41 a	0.19 b	0.20 a	0.17 a	0.29 a
40%	0.59 a	0.26 a	0.25 a	0.22 a	0.26 a
Production E (m mol $m^{-2}s^{-1}$)				**Post-production E**	
SMC	wk11	wk12	wk13	wk14	wk15
20%	3.00 b	2.30 b	1.84 a	2.41 a	1.47 a
40%	3.45 a	2.69 a	2.15 a	2.80 a	1.32 a

[z] Means separation by Student-Newman-Keuls (SNK) multiple comparisons at P ≤ 0.05. Means with same letter is not different.

Table A7. Responses of leaf net photosynthesis (Pn), stomatal conductance (gs), and transpiration (E) to two substrate moisture contents (SMC) (20% and 40%) in *Heliotropium arborescens* 'Simply Scentsational' during greenhouse production weeks 11, 12 and 13, and post-production weeks 14 and 15.

Heliotrope Production Pn (µmol·m^{-2}·s^{-1})				Post-production Pn	
SMC	wk11	wk12	wk13	wk14	wk15
20%	20.45 a[z]	16.22 a	18.74 a	16.99 a	18.93 a
40%	23.15 a	15.45 a	16.44 b	15.46 b	19.42 a
Heliotrope Production gs (mmol·m^{-2}·s^{-1})				Post-production gs	
SMC	wk11	wk12	wk13	wk14	wk15
20%	1.37 a	0.24 a	0.49 a	0.78 a	1.35 a
40%	1.45 a	0.13 b	0.31 b	0.60 b	1.31 a
Heliotrope Production E (mmol·m^{-2}·s^{-1})				Post-production E	
SMC	wk11	wk12	wk13	wk14	wk15
20%	4.83 a	1.86 a	1.86 a	4.32 a	4.57 a
40%	4.82 a	1.84 a	1.84 b	3.78 b	4.63 a

[z] Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter is not different.

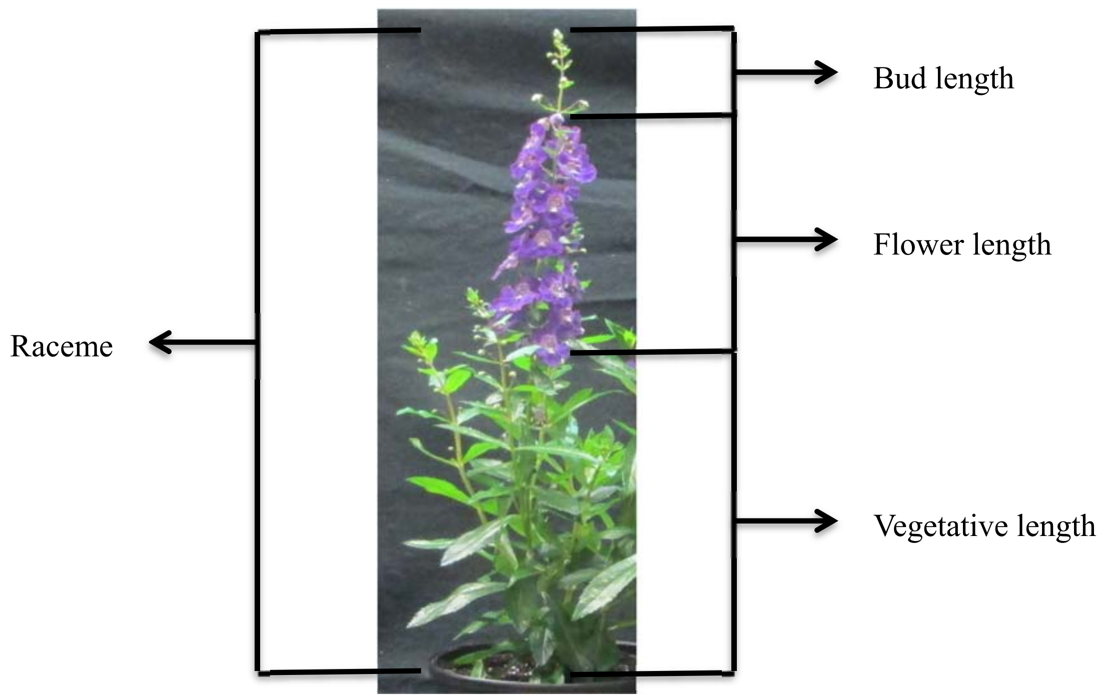

Fig. A1. Raceme, bud length, flower length and vegetative length of *Angelonia angustifolia* ‘Angelface Blue’.

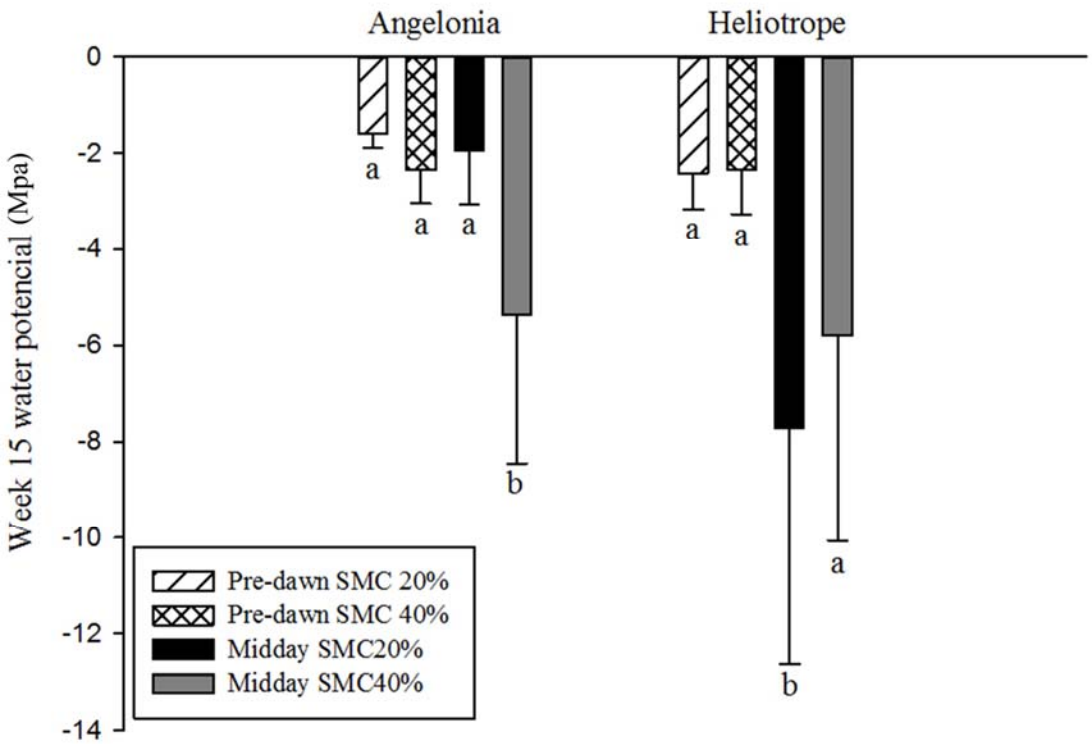

Fig. A2. Pre-dawn and midday water potential for two substrate moisture content (20 and 40% SMC) treatments on Angelonia angustifolia ‘Angelface Blue’ and Heliotropium arborescens ‘Simply Scentsational’ at production week 15. Means separation by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

Table A8. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on plant growth index (GI = plant height/2 + (plant width 1 + plant width 2) / 4), leaf thickness, petiole diameter, plant shoot dry weight (DW) leaf surface area, internode length, SPAD, photosynthesis (Pn), stomatal conductance (gs), leaf transpiration (E), predawn and midday water potential (Ψw) over 12 production weeks for *Euphorbia pulcherrima* 'Freedom Red' in 2016 experiment.

	Production weeks											
	36	37	38	39	40	41	42	43	44	45	46	47
GI	ns[z]	ns	***	***	***	***	***	***	***	***	***	***
Leaf thickness (µm)			ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Petiole diameter (µm)							ns	***	***	***	***	***
Plant shoot DW (g)	ns			ns			ns			**		***
Leaf surface area (cm^2)	ns			ns			ns			*		**
Total leaf surface area (cm^2)	ns			ns			*			**		*
Internode length (cm)				ns			ns			**		***
SPAD			ns	*	**	*	***	***	**	**	**	ns
Pn			***	ns	ns	ns	***	***	**	***	*	**
gs			ns	ns	ns	ns	***	***	ns	**	ns	**
E			ns	ns	ns	ns	***	***	ns	**	ns	**
Predawn Ψw			*	ns	ns	*	ns	ns	ns	ns	*	ns
Midday Ψw			ns	*	*	ns	*	ns	ns	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

Table A9. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bract surface area, leaf no., bract no., and total leaf + bract no. measured over two production weeks for *Euphorbia pulcherrima* 'Freedom Red' in 2016 experiment.

	Production weeks	
	45	47
Bract surface area (cm)	**	***
Leaf no.	ns	ns
Bract no.	*	ns
Total leaf + bract no.	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01 (**) or 0.001 (***).

Table A10. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bract coloring percentage measured over three weeks for *Euphorbia pulcherrima* 'Freedom Red' in 2016 experiment.

	Production weeks		
	44	45	46
Bract coloring %	*** [z]	*	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), or 0.001 (***).

Table A11. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on root ball covering percentage at the bottom and side of the pot, total no. of irrigation events, and total irrigation volume during production measured in week 47 for *Euphorbia pulcherrima* 'Freedom Red' in 2016.

Root ball covering percentage		Total no. of irrigation events during production	Total irrigation volume during production (L)
Bottom	Side		
**[z]	***	***	***

[z] Significant at $P \leq 0.01$ (**), or 0.001 (***).

Table A12. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%), and three packaging methods (PM) [pot covering and sleeves (CS), pot covering only (C), or no covering (N)] on total no. of irrigation events and total irrigation volume during postproduction for *Euphorbia pulcherrima* 'Freedom Red' in 2016 experiment.

	Total no. of irrigation events during postproduction	Total irrigation volume during postproduction (L)
SMC	ns[z]	ns
PM	ns	ns
SMC X PM	ns	ns

[z] ns (nonsignificant).

Table A13. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and three packaging methods (PM) [pot covering and sleeves (CS), pot covering only (C), or no covering (N)] on visual rating, necrotic bracts no., leaf no., necrotic stem number, stem no., SPAD, total bract no., bract no. per stem, total bract surface area, total leaf surface area, and plant shoot dry weight (DW) during postproduction (L) for *Euphorbia pulcherrima* 'Freedom Red' in 2016 experiment.

	Visual rating	Necrotic bract no.	Leaf no.	Necrotic stem no.	Stem no.	SPAD	Total bract no.	Bract no. per stem	Total bract surface area	Total leaf surface area	Plant shoot DW
SMC	ns[z]	ns	ns	ns	ns	ns	*	ns	ns	ns	***
PM	ns	ns	*	ns	*	***	ns	ns	ns	*	ns
SMC X PM	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), or 0.001 (***).

Table A14. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on plant growth index (GI = plant height/2 + (plant width 1 + plant width 2) / 4), SPAD, photosynthesis (Pn), stomatal conductance (gs), leaf transpiration (E), predawn and midday water potential (Ψw) measured over 11 production weeks for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	Production weeks										
	37	38	39	40	41	42	43	44	45	46	47
GI	ns[z]	ns	ns	ns	***	***	***	***	***	***	***
SPAD			ns	ns	ns	ns	ns	*	ns	ns	ns
Pn		***	--	**	***	***	***	***	ns		
gs		***	--	***	***	***	**	**	ns		
E		***	--	***	***	***	***	***	ns		
Predawn Ψw				ns[z]	ns	ns	ns	ns	ns		
Midday Ψw				***	ns	ns	ns	ns	ns		

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*) or 0.001 (***).

Table A15. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bract no., leaf no., leaf + bract no., bract area, leaf area, total bract area, total leaf area, stem length, leaf internode length, and bract internode length, measured week 46 and 47 and leaf thickness and petiole thickness, (week 46, only) and flower no and bud no. (week 47, only) for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

Production week 46											
Bract no.	Leaf no.	Leaf + bract no.	Bract area (cm^2)	Leaf area (cm^2)	Total bract area (cm^2)	Total leaf area (cm^2)	Stem length (cm)	Leaf internode length (cm)	Bract internode length (cm)	Leaf thickness (µm)	Petiole thickness (µm)
ns	ns	ns	***	*	*	**	***	ns	***	ns	ns

Production week 47											
Bract no.	Leaf no.	Leaf + bract no.	Bract area (cm^2)	Leaf area (cm^2)	Total bract area (cm^2)	Total leaf area (cm^2)	Stem length (cm)	Leaf internode length (cm)	Bract internode length (cm)	Flower no.	Bud no.
ns	*	ns	**	ns	*	***	***	ns	***	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$(*), or 0.001 (***).

Table A16. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on stem, leaf, bract, total shoot, root dry weight (DW), total no. of irrigation events, total irrigation volume during production measured week 46 and 47 for *Euphorbia pulcherrima* ‘Christmas Eve Red' in 2017 experiment.

Production week 46						
Stem DW (g)	Leaf DW (g)	Bract DW (g)	Total shoot DW (g)	Root DW (g)	Total no. of irrigation events during production	Total irrigation volume during production (L)
**[z]	**	**	***	ns	***	***
Production week 47						
Stem DW (g)	Leaf DW (g)	Bract DW (g)	Total shoot DW (g)	Root DW (g)	Total no. of irrigation events during production	Total irrigation volume during production (L)
***	***	***	***	***	***	***

[z] ns (nonsignificant) or significant at $P \leq 0.01$ (**), or 0.001 (***).

Table A17. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on red bract/inflorescence no. and percent of bract coloring measured over two production weeks for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	No. of red bract/inflorescence	% of bract coloring
42	***[z]	***
43	***	**

[z] Significant at $P \leq 0.01$ (**), or 0.001 (***).

Table A18. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bract coloring % measured over three production weeks for *Euphorbia pulcherrima* ‘Christmas Eve Red’ in 2017 experiment.

	Production weeks		
	44	45	46
Bract coloring%	*[z]	*	ns

[z] ns (nonsignificant) or significant at $P \le 0.05$ (*), 0.01 (**), or 0.001 (***).

Table A19. Analysis of variance (ANOVA) for two packing methods [no packaging (N), or sleeves (S)] on ethylene concentration measured over two weeks of 1st postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	47	48
1st postproduction ethylene concentration (ppb)	ns[z]	ns

[z] ns (nonsignificant).

Table A20. Analysis of variance (ANOVA) for two packing methods [no packaging (N), or sleeves (S)] on ethylene concentration measured over two weeks of 2nd postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	48	49
2nd postproduction ethylene concentration (ppb)	ns[z]	ns

[z] ns (nonsignificant).

Table A21. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two package methods (PM) [no packaging (N), or sleeves (S)] on total no. of irrigation events and total irrigation volume (L) during 1st postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

1st postproduction	Total no. of irrigation events	Total irrigation volume (L)
SMC	***[z]	***
PM	*	*
SMC X PM	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*) or 0.001 (***).

Table A22. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two package methods (PM) [no packaging (N), or sleeves (S)] on total no. of irrigation events and total irrigation volume (L) during 2nd postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

2nd postproduction	Total no. of irrigation events	Total irrigation volume (L)
SMC	***[z]	***
PM	***	***
SMC X PM	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*) or 0.001 (***).

Table A23. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two package methods (PM) [no packaging (N), or sleeves (S)] on light intensity measured at the top middle, and bottom of the plant canopy during week 49 for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

Light intensity during postproduction			
	Top	Middle	Bottom
SMC	ns	ns	ns
PM	ns	***	ns
SMC x PM	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.001$ (***).

Table A24. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) two package methods (PM) [no covering (N), or sleeves (S)] on flower no., bud no., flower + bud no., SPAD, visual rating, bract no., necrotic bract no., green leaf no., yellow leaf no., total leaf no., leaf + bract no., necrotic stem no., and total stem no. measured at the end of 1st postproduction (week 49) for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	End of postharvest wk49												
	Flower no.	Bud no.	Flower + bud	SPAD	Visual rating	Bract no.	Necrotic bract no.	Green leaf no.	Yellow leaf no.	Total leaf no.	Leaf + bract no.	Necrotic stem no.	Total stem no.
SMC	ns[z]	**	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
PM	ns	ns	ns	***	ns	ns	ns	ns	ns	ns	ns	*	ns
SMC X PM	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$(*), 0.01 (**) or 0.001 (***).

Table A25. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) two package methods (PM) [no packaging (N), or sleeves (S)] on flower no., bud no., flower + bud no., SPAD, visual rating, bract no., necrotic bract no., green leaf no., yellow leaf no., total leaf no., leaf + bract no., necrotic stem no., and total stem no. measured at the end of 2nd postproduction (week 50) for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	End of postharvest wk50												
	Flower no.	Bud no.	Flower +bud	SPAD	Visual rating	Bract no.	Necrotic bract no.	Green leaf no.	Yellow leaf no.	Total leaf no.	Leaf +bract no.	Necrotic stem no.	Total Stem no.
SMC	ns	**	ns	ns	ns	ns	*	*	ns	*	**	*	*
PM	ns	ns	ns	ns	*	ns	ns	ns	*	ns	*	ns	ns
SMC X PM	ns	ns	ns	ns	ns	ns	*	ns	*	ns	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$(*) or 0.01 (**).

Table A26. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two package methods (PM) [no packaging (N), or sleeves (S)] on flower and bud no., flower + bud no., and visual rating measured during the two weeks of 1st postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

1st postproduction	Flower no.	Bud no.	Flower + bud no.	Visual rating
PM	ns[z]	ns	*	ns
SMC	*	ns	ns	*
Week	***	***	ns	ns
Week X PM	ns	ns	ns	ns
SMC X PM	ns	ns	ns	ns
Week X SMC	ns	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$(*) or 0.001 (***).

Table A27. Analysis of variance (ANOVA) for four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) and two package methods (PM) [no packaging (N), or sleeves (S)] on flower and bud no., flower + bud no., and visual rating measured during the two weeks of 2nd postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

2nd postproduction	Flower no.	Bud no.	Flower + bud no.	Visual rating
PM	ns[z]	ns	ns	ns
SMC	ns	ns	*	ns
Week	***	***	ns	***
Week X PM	ns	ns	ns	ns
SMC X PM	ns	ns	ns	ns
Week X SMC	ns	ns	ns	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$(*) or 0.001 (***).

Table A28. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on stem length, bract internode length, total bracts surface area, total leaf surface area, bracts surface area and leaf surface area measured at the end of production week 46 for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	wk 46 Harvest											
	Stem length (cm)		Bract internode length (cm)		Total bracts surface area (cm^2)		Total leaf surface area (cm^2)		Bracts surface area (cm^2)		Leaf surface area (cm^2)	
40/40	22.3	a[z]	1.1	a	2023.9	a	2032.2	a	59.1	a	55.7	a
20/40	22.7	a	1.1	a	2039.6	a	2319.2	a	64.4	a	57.1	a
40/20	19.9	b	0.9	b	1721.5	ab	1944.4	a	45.8	b	53.4	a
20/20	18.3	b	0.9	b	1347.2	b	1598.4	b	47.1	b	46.2	b

[z] Means separation by student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

Table A29. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on stem length, bract internode length, total bracts surface area, total leaf surface area, bracts surface area and leaf surface area measured at the end of production week 47 for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	wk 47 Harvest													
	Stem length (cm)		Bract internode length (cm)		Total bracts surface area (cm^2)		Total leaf surface area (cm2)		Bracts surface area (cm^2)		Leaf surface area (cm^2)		Total leaf no.	
40/40	22.4	a[z]	0.8	a	3484.3	a	2234.1	a	74.4	a	54.9	a	39.2	a
20/40	21.4	a	0.9	a	3279.9	ab	2072.7	ab	75.3	a	52.1	a	37.3	a
40/20	19.2	b	0.7	b	2782.8	b	1674.6	bc	62.4	b	51.0	a	34.9	ab
20/20	18.0	b	0.7	b	2605.2	b	1313.7	c	63.7	b	46.9	b	26.6	b

[z] Means separation by student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

Table A30. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bracts maturity/coloring percentage measured over three production weeks for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	Bract coloring %		
Trt	wk44	wk45	wk46
40/40	23.95 b[z]	62.22 b	80.52 a
20/20	38.75 a	78.06 a	84.80 a
40/20	25.40 b	74.63 ab	86.63 a
20/40	23.22 b	62.15 b	80.59 a

[z] Means separation by student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

Table A31. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bud no., total leaf no., necrotic stem no. and leaf + bract no. measured at the end of two postproduction for *Euphorbia pulcherrima* 'Christmas Eve Red' in 2017 experiment.

	wk50			
	Bud no.	Total leaf no.	Necrotic stem no.	Leaf + bract no.
40/40	5.93 a	33.11 a	2.22 a	73.78 a
20/20	3.73 b	23.90 b	0.70 b	59.90 b
40/20	4.00 b	25.27 b	0.73 b	61.27 b
20/40	5.35 a	34.20 a	0.80 b	74.80 a

[z] Means separation by student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

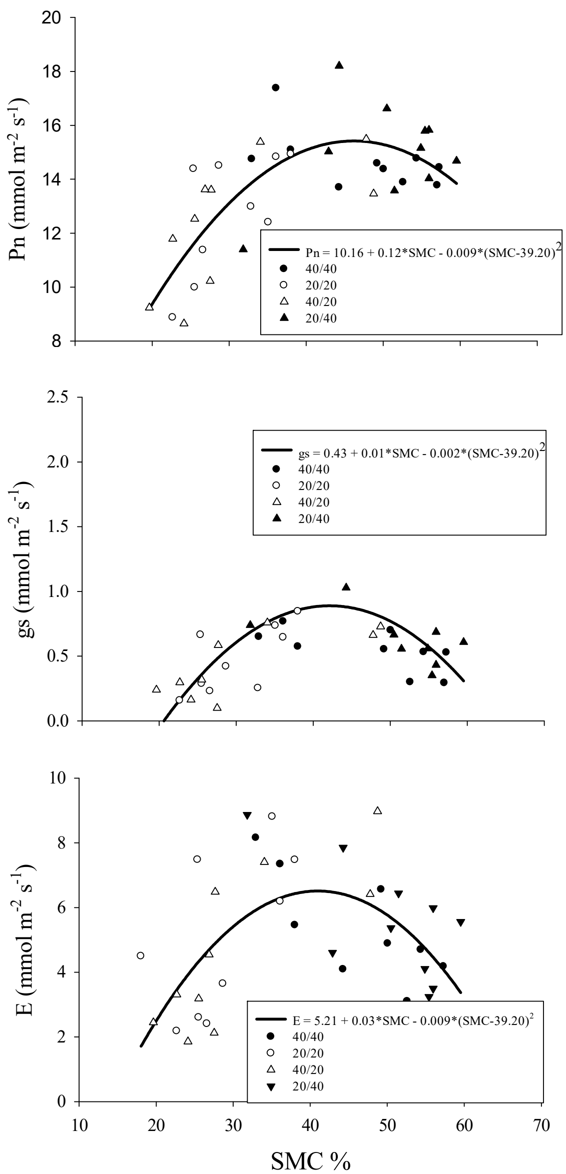

Fig. A3. Effects of four substrate moisture content (SMC) treatments (40/40, 20/20, 40/20, 20/40% SMC) on weekly leaf net photosynthesis (Pn), stomatal conductance (gs) and transpiration (E) of *Euphorbia pulcherrima* 'Freedom Red' during greenhouse production week 38 to week 47 in 2016 experiment

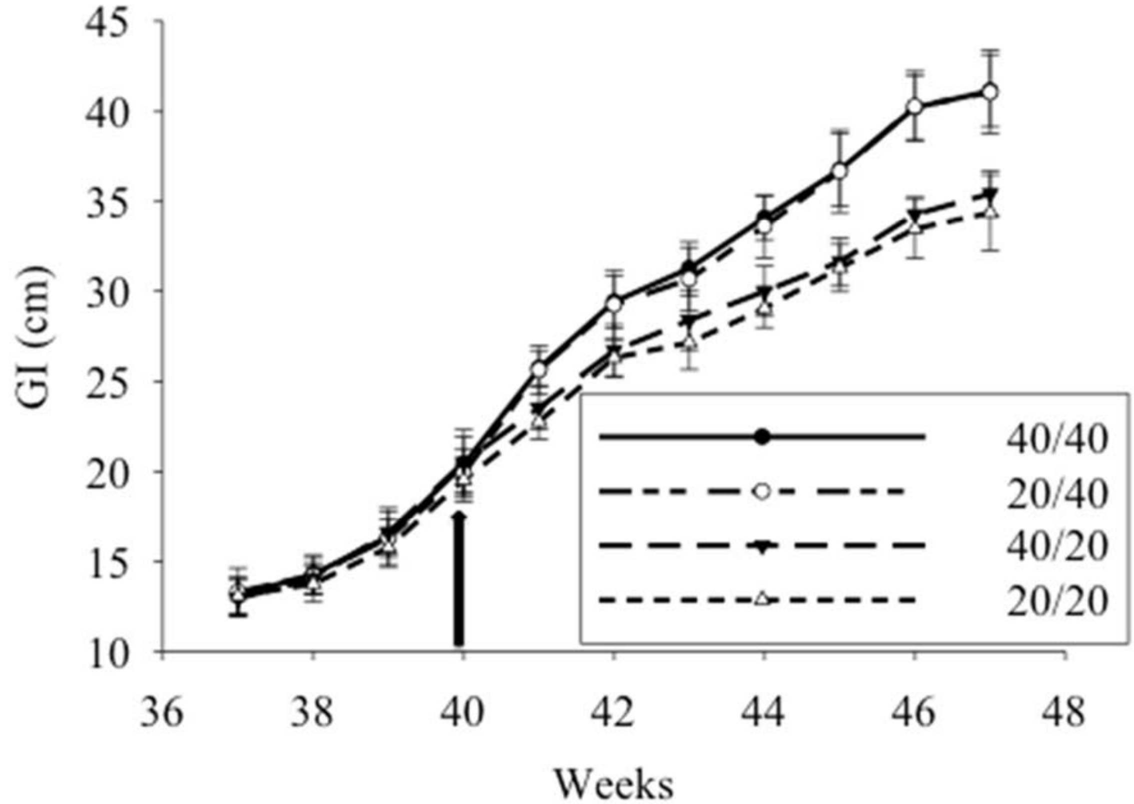

Fig. A4. Effects of four SMC treatments (40/40, 20/40, 40/20, 20/20%) on weekly growth index (GI = plant height/2 + (plant width 1 + plant width 2)/4.) from production week 37 to production week 47 of *Euphorbia pulcherrima* ‘Christmas Eve Red' in 2017 experiment. The arrow is denotes week 40 when SMC treatment changed.

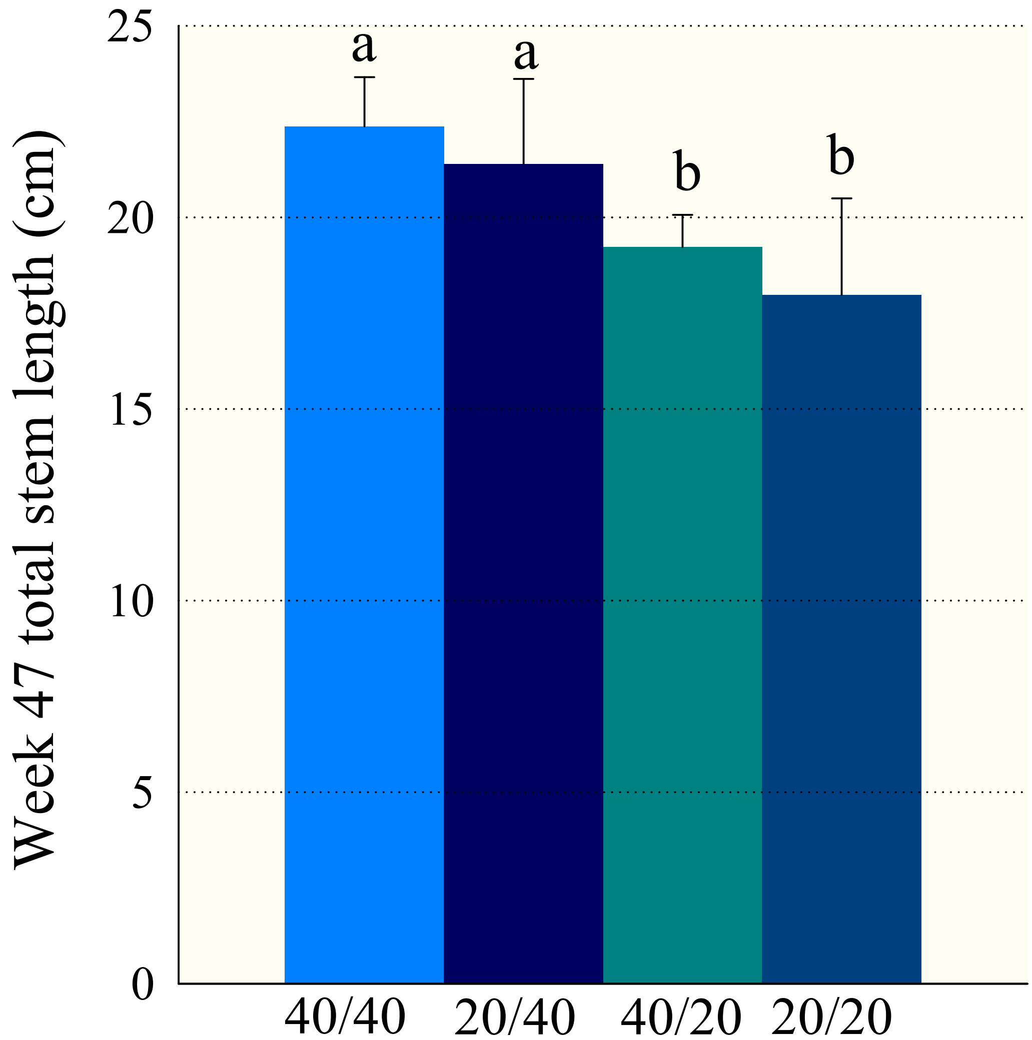

Fig. A5. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on total stem length of *Euphorbia pulcherrima* 'Christmas Eve Red' at end of greenhouse production (week 47) in 2017 experiment. Means separation within the group by Student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

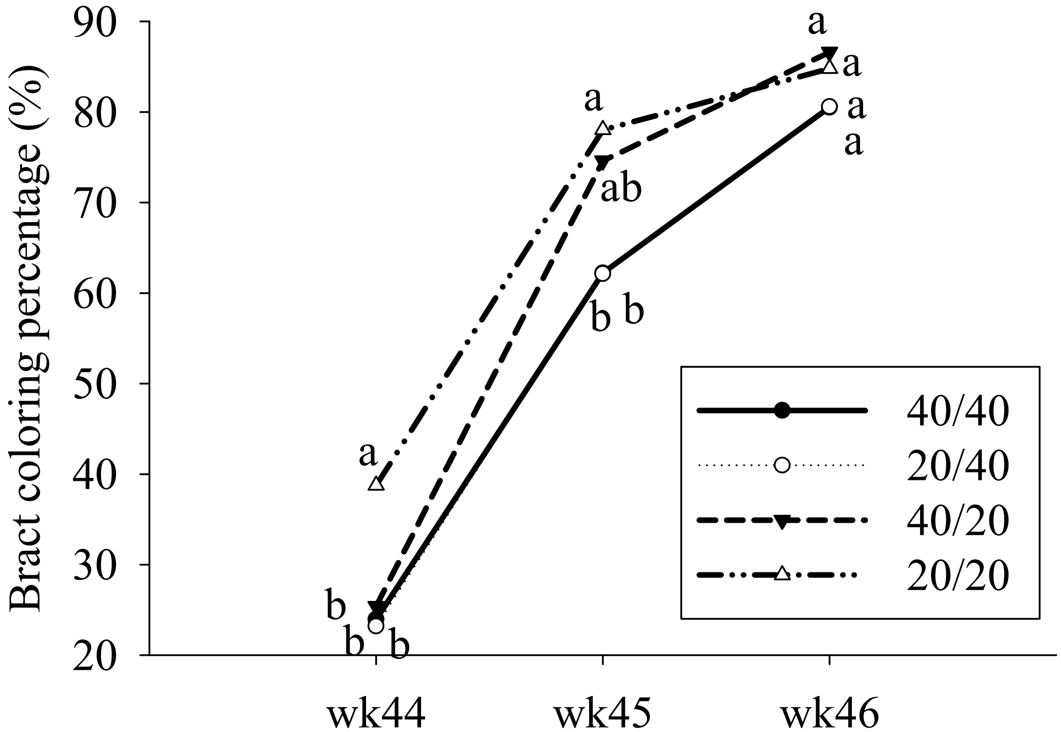

Fig. A6. Effects of four substrate moisture content (SMC) treatments (40/40, 20/40, 40/20, 20/20%) on bracts maturity/coloring percentage measured over three production weeks for *Euphorbia pulcherrima* ‘Freedom Red’ in 2016 experiment. Means separation by student-Newman-Keuls (SNK) multiple comparisons at $P \leq 0.05$. Means with same letter are not different.

Table A32. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for growth index (GI), midday water potential (ψ_w), and final shoot dry weight (DW) during the experiment weeks of *Solenostemon scutellarioides* 'French Quarter' in 2017.

	Coleus experiment weeks								
	SMC treatment							Postproduction	
	wk 1	wk 2	wk 3	wk 4	wk 5	wk 6	wk 7	1st wk	2nd wk
GI	ns [z]	ns	ns	ns	ns	ns	ns	ns	ns
Mid-day ψ_w	-- [y]	--	--	--	--	--	*	*	ns
Shoot DW	--	--	--	--	--	--	--	--	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*).

[y] Not measured.

Table A33. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for growth index (GI), SPAD, leaf and stem caliper, bud, flower and senesced flower number (#), leaf net photosynthesis (Pn), stomatal conductance (gs), transpiration (E), mid-day water potential (ψ_w), shoot coloring percentage (%), and shoot dry weight (DW) during experiment weeks of *Petunia x hybrida* 'Colorworks Pink Radiance' in 2017.

	Petunia experiment weeks									
	SMC treatment								Postproduction	
	wk 1	wk 2	wk 3	wk 4	wk 5	wk 6	wk 7	wk 8	1^{st} wk	2^{nd} wk
GI	ns[z]	ns	**	**	***	***	***	--	**	*
SPAD	--[y]	--	--	ns	ns	**	*	--	*	*
Leaf thickness	--	--	--	ns	ns	ns	ns	--	**	ns
Stem caliper	--	--	--	ns	ns	ns	ns	--	**	ns
Bud #	--	--	--	ns	ns	***	***	--	**	*
Flower #	--	--	--	ns	**	*	*	--	**	**
Senesced flower #	--	--	--	--	ns	ns	ns	--	***	***
Pn	--	--	--	ns	ns	ns	ns	--	--	--
gs	--	--	--	ns	ns	ns	ns	--	--	--
E	--	--	--	ns	ns	ns	ns	--	--	--
Mid-day ψ_w	--	--	--	--	--	*	ns	ns	ns	*
Shoot coloring %	--	--	--	--	--	--	--	ns	--	**
Shoot DW	--	--	--	--	--	--	--	--	--	**

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***).
[y] Not measured.

Table A34. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for growth index (GI), SPAD, leaf and stem calipter, bud, flower and senesced flower number (#), leaf net photosynthesis (Pn), stomatal conductance (gs), transpiration (E), mid-day water potential (ψ_w), shoot coloring percentage (%), and shoot dry weight (DW) during experiment weeks of *Lantana camara* 'Lucky Flame' in 2017.

	Lantana experiment weeks										
	SMC treatment									Postproduction	
	wk 1	wk 2	wk 3	wk 4	wk 5	wk 6	wk 7	wk 8	wk 9	1st wk	2nd wk
GI	ns[z]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SPAD	--[y]	--	--	ns	ns	*	**	--	*	**	ns
Leaf thickness	--	--	--	ns	ns	ns	ns	ns	ns	ns	--
Stem caliper	--	--	--	ns	ns	***	*	*	*	*	--
Bud #	--	--	--	--	--	--	ns	--	**	***	--
Flower #	--	--	--	--	--	--	ns	--	ns	**	--
Senesced flower #	--	--	--	--	--	--	--	--	ns	ns	--
Pn	--	--	--	**	*	*	*	--	--	--	--
gs	--	--	--	*	**	ns	ns	--	--	--	--
E	--	--	--	**	**	*	*	--	--	--	--
Mid-day ψ_w	--	--	--	--	--	--	--	*	ns	ns	*
Shoot coloring %	--	--	--	--	--	--	--	--	ns	--	*
Shoot DW	--	--	--	--	--	--	--	--	--	--	***

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***).

[y] Not measured.

Table A35. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for growth index (GI), SPAD, leaf and stem caliper, bud, flower and senesced flower number (#), leaf net photosynthesis (Pn), stomatal conductance (gs), transpiration (E), shoot coloring percentage (%), and shoot dry weight (DW) during experiment weeks of *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' (SCC) in 2017.

	Impatiens SCC experiment weeks										
	SMC treatment									Postproduction	
	wk 1	wk 2	wk 3	wk 4	wk 5	wk 6	wk 7	wk 8	wk 9	1st wk	2nd wk
GI	ns[z]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SPAD	--[y]	--	--	--	--	ns	ns	ns	ns	ns	--
Leaf thickness	--	--	--	--	--	ns	ns	ns	ns	ns	--
Stem caliper	--	--	--	--	--	ns	ns	ns	*	**	--
Bud #	--	--	--	--	--	ns	ns	ns	ns	***	*
Flower #	--	--	--	--	--	ns	ns	ns	ns	ns	ns
Senesced flower #	--	--	--	--	--	ns	ns	ns	ns	ns	ns
Pn	--	--	--	--	ns	**	**	--	--	--	--
gs	--	--	--	--	ns	**	**	--	--	--	--
E	--	--	--	--	ns	**	**	--	--	--	--
Shoot coloring %	--	--	--	--	--	--	--	--	**	--	*
Shoot DW	--	--	--	--	--	--	--	--	--	--	**

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*) or 0.01(**).
[y] Not measured.

Table A36. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for growth index (GI), SPAD, leaf and stem caliper, bud, flower and senesced flower number (#), leaf net photosynthesis (Pn), stomatal conductance (gs), transpiration (E), shoot coloring percentage (%), shoot fresh weight (FW), and shoot dry weight (DW) during experiment weeks of *Impatiens* x *hybrida* 'Sunpatiens Spreading Lavender' (SSL) in 2018.

	Impatiens SSL experiment weeks							
	SMC treatment						Postproduction	
	wk 1	wk 2	wk 3	wk 4	wk 5	wk 6	1st wk	2nd wk
GI	ns[z]	ns	ns	ns	ns	ns	ns	ns
SPAD	ns	ns	ns	ns	ns	ns	ns	ns
Leaf thickness	--[y]	--	--	--	--	ns	--	ns
Stem caliper	--	--	--	--	--	ns	--	ns
Bud #	--	--	--	--	--	ns	--	ns
Flower #	--	--	--	--	--	ns	--	ns
Senesced flower #	--	--	--	--	--	ns	--	--
Pn	--	--	--	**	*	***	--	--
gs	--	--	--	***	*	*	--	--
E	--	--	--	***	**	**	--	--
Shoot coloring %	--	--	--	--	--	ns	--	ns
Shoot FW	--	--	--	--	--	ns	--	ns
Shoot DW	--	--	--	--	--	ns	--	ns

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***).
[y] Not measured.

Table A37. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for growth index (GI), reproductive stem length, SPAD, leaf thickness, bud and flower number (#), main stem #, internode length, leaf net photosynthesis (P_n), stomatal conductance (g_s), transpiration (E), mid-day water potential (ψ_w), main stem caliper, side stem caliper, total stem length, reproductive stem length, flower and shoot fresh weight (FW) and dry weight (DW) during experiment weeks of *Salvia officinalis* 'Red Hot Sally II' in 2018.

	Salvia experiment weeks							
	SMC treatment						Postproduction	
	wk 1	wk 2	wk 3	wk 4	wk 5	wk 6	1st wk	2nd wk
GI	ns[z]	*	***	*	**	**	ns	ns
Reproductive stem length	--[y]	--	--	ns	ns	ns	ns	ns
SPAD	--	--	--	ns	ns	*	**	*
Leaf thickness	--	--	--	--	--	ns	--	ns
Bud #	--	--	--	--	--	ns	--	ns
Flower #	--	--	--	--	--	ns	--	ns
Main stem #	--	--	--	--	--	ns	--	ns
Internode length	--	--	--	--	--	ns	--	ns
P_n	--	--	--	**	***	***	--	--
g_s	--	--	--	***	***	ns	--	--
E	--	--	--	***	**	ns	--	--
Mid-day ψ_W	--	--	--	ns	*	ns	ns	--
Main stem caliper	--	--	--	--	--	***	--	ns
Side stem thick	--	--	--	--	--	--	--	ns
Total stem length	--	--	--	--	--	*	--	**
Reproductive stem length	--	--	--	--	--	ns	--	ns
Flower FW	--	--	--	--	--	ns	--	**
Shoot FW	--	--	--	--	--	***	--	***
Flower DW	--	--	--	--	--	ns	--	**
Shoot DW	--	--	--	--	--	***	--	**

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***).
[y] Not measured.

Table A38. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for root covering percentage (%) at the end of postproduction of *Solenostemon scutellarioides* ‘French Quarter’, *Impatiens* x *hybrida* 'Sunpatiens Compact Hot Coral' (SCC), *Lantana camara* ‘Lucky Flame’, and *Petunia* x *hybrida* ‘Colorworks Pink Radiance’ in 2017; *Impatiens* x *hybrida* 'Sunpatiens Spreading Lavender' (SSL), and *Salvia officinalis* ‘Red Hot Sally II' in 2018. Each plant species was treated as an independent experiment.

Root covering %		
	Bottom	Side
Coleus	ns[z]	ns
Petunia	*	ns
Lantana	ns	ns
Impatiens SCC	**	ns
Impatiens SSL	*	*
Salvia	**	**

[z] ns (nonsignificant) or significant at $P \leq 0.05$(*), or 0.01 (**).

Table A39. Analysis of variance (ANOVA) for difference between two treatments [substrate moisture content (SMC) at 40% or 20%] for main inflorescence with flower length, main inflorescence diameter, and main stem with leave length at the end of SMC treatment period and with additional parameters for main inflorescence without flower length, side inflorescence with flower length, side inflorescence diameter, stem length with senesced leaves, chlorotic leaf number (#), and senesced inflorescence # at the end postproduction of *Salvia officinalis* 'Red Hot Sally II' in 2018.

Salvia end of SMC treatment		
Main inflorescence with flower length	Main inflorescence diameter	Main stem with leaves length
ns[z]	ns	*

Salvia end of postproduction								
Main inflorescence with flower length	Main inflorescence without flower length	Side inflorescence with flower length	Main inflorescence diameter	Side inflorescence diameter	Main stem with leaves length	Stem length with senesced leaves	Chlorotic leaf #	Senesced inflorescence #
**	**	ns	**	**	ns	*	***	**

[z] ns (nonsignificant) or significant at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***).

APPENDIX B VITA

Yanjun (Cecilia) Guo

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3180 Cain Rd. APT 170, College Station, Texas, 77840

Education

PhD in Horticultural Sciences**,** Aug. 2015 - Dec. 2018
Texas A&M University (TAMU), College Station, Texas
Dissertation title: Reducing substrate moisture content (SMC) during greenhouse production and postproduction of bedding and potted plants improves crop quality and economic value. *Our finding indicated that using 20% SMC during greenhouse production improves angelonia, heliotrope, poinsettia, and petunia postharvest quality and economic value.*
Funded by a grant from the Floriculture & Nursery Crop Research Initiative (FNRI) awarded to the Floriculture Research Alliance.

Certificate in Business, Mays Business School, Texas A&M University, July 2017. The Mays Business School offers a Certificate in Business to non-business graduate students at Texas A&M University. This certificate provides a general overview of the four major functional areas of business (accounting, finance, marketing, and management) through a set of courses designed for non-business students.

M.S. in Horticultural Sciences, Aug. 2013 - Dec. 2014
Thesis title: Poinsettia and Easter lily growth and development responses to root substrate containing biochar. *We found that up to 80% fine granular biochar could be used as a substrate amendment to commercial peatmoss based substrate with acceptable growth reduction and no changes in plant quality.*

B.S. in Agronomy Science, Sep. 2007 - July 2011
Shengyang Agricultural University, Shengyang, Liaoning, P.R. China

Work Experience

Texas A&M University (TAMU), College Station, Texas
Graduate Research/Teaching Assistant, Sep. 2015 – Dec. 2018
Designed and conducted five greenhouse experiments to test economical and postproduction quality analysis of floriculture crops produced at reduced substrate moisture content.
Teaching assistant: Hort. 203 Floral design (fall 2018), Hort. 428: Greenhouse Operation and Management (fall 2015, 16, and 17), Hort. 429: Floriculture Crop Production (spring 2016),

Altman Plants, Giddings, Texas
Production Assistant, full time. Jan. 2015- June 2015

Assisted in receiving and ordering plant materials, making weekly production plans for crop production team, and conducting monthly inventory checks.

Texas A&M University (TAMU), College Station, Texas
Graduate Research Assistant, *Sep. 2013 – Dec. 2014*
IR4-project: phytotoxicity testing for new fungicides on ornamental plants.
National Strawberry Sustainability Initiative Project: strawberries cultivars selection in east TX.
Scott's New Mulch Research: Conducted substrate test using porometer on mulch, particle size testing using soil sieves.
Texas Peach Plum Pox Virus Survey (Texas Plant Disease Diagnostic Lab): Performed enzyme-linked immunosorbent assay (ELISA) tests of Plum pox virus (PPV), Prune dwarf virus (PDV), and Prunus necrotic ring spot virus (PNRSV) on peach tree within Texas area.
Tested ornamental plants growth response to Agriplier (a soil conditioner).

Unique Skills & Qualifications

Greenhouse. Management of research greenhouses including greenhouse environmental control systems, sensor-controlled irrigation system, crop production scheduling, plant propagation, transplanting, irrigation, fertilization, pesticide/fungicides application, porometer to test greenhouse substrate physical characteristics, etc.

Lab analyses. LiCor LI-6400 XT portable photosynthesis system, Pressure Bomb, Gas Chromatography, Enzyme-linked immunosorbent assay (ELISA) tests on plant leaf tissues, Adobe Photoshop, Training new student workers, etc.

Software. Microsoft Office (Word, Excel, and PowerPoint); Statistical analysis (SAS, JMP); Graphing (SigmaPlot), Endnote, etc.

Experimental design. Specialized in agriculture experimental design, data collection and statistical analysis.

Language. Bilingual and efficient communications in listening, speaking, writing both English and Mandarin Chinese.

Publications

Guo. Y, T. Starman, and C. Hall. 2018. Reducing substrate moisture content during greenhouse production of poinsettia improves postharvest quality and economic value. HortScience. 53(11): 1-11.

Guo, Y., T. Starman, and C. Hall. 2018. Reducing substrate moisture content (SMC) during greenhouse production and postproduction of angelonia and heliotrope improves crop quality and economic value. HortScience. 53(7): 1006-1011.

Guo, Y., G. Niu, T. Starman, A. Volder, and M. Gu. 2018. Poinsettia growth and development response to container substrate with biochar. Horticulturae. 4:1.

Guo, Y., G. Niu, T. Starman, and M. Gu. 2018. Easter lily growth and development response to container substrate with biochar. J. Hort. Sci. & Biotechnol. 1-7.

Li, J., M. Gu, F. Cheng, Y. Guo and K. Ong. 2014. Preliminary results of three biofungicides and MilStop for controlling basil downy mildew. Proceedings of the SNA Res. Conf. 59:159-160.

Guo, Y., T. Starman, and C. Hall. 2018. Six bedding plant species/cultivars response to reduced substrate moisture content (SMC) during greenhouse production concerning growth, development, postproduction quality and economic effect. (In preparation).

Guo, Y., T. Starman, and C. Hall. 2019. Geranium and canna growth and development response to three different substrates and reduce irrigation and the economic impact. (In preparation).

Grant and Awards

Travel award – Office of Graduate and Professional Studies ($500), Jan. 2014.

Aggies Commit Graduate Student Organization Mini-grants, Academic Year 2016-17 for Horticulture department poster competition ($510), Nov. 2016.

American Floral Endowment (AFE) Production & Postharvest Research Funding ($13,500) with Dr. Terri Starman and Dr. Charlie Hall, Jan. 2017.

29th American Society for Horticultural Science (ASHS) Conference traveling award ($500), June 2017.

Leadership

Horticulture Graduate Student Council, Texas A&M University, Vice president, Sep. 2016- Aug. 2017. Participated in and organized monthly departmental graduate student meetings and activities.
Applied and received mini grant for horticulture department annual post competition ($510) from aggies commit graduate student organization mini-grants academic year 2016-17.

Honor

Third place in student poster competition – 2013 Texas Plant Protection Associate Conference, Bryan, TX.

Pi Alpha Xi-lota Chapter - 2014 Texas A&M University

Abstracts / Poster presentations

Guo, Y., G. Niu, T. Starman, A. Volder, and M. Gu. 2013. Poinsettia growth response to container substrate amended with biochar. TX Plant Protection Assoc. Conf. (abstr.)

Guo, Y., G. Niu, T. Starman, A. Volder, and M. Gu. 2014. Poinsettia growth responses to container substrate amended with biochar. Southern Region ASHS. HortScience 49(9):S22 (abstr.).

Guo, Y., G. Niu, T. Starman, and M. Gu. 2014. The effects of biochar and fertigation regimes on Easter lily production. Annual Southern Nursery Association (abstr.).

Guo, Y., G. Niu, T. Starman, and M. Gu. 2014. Easter lily growth response to container substrate amended with biochar. TX Plant Protection Assoc. Conf. (abstr.).

Guo. Y., T. Starman, and C. Hall. 2016. Effects of reducing substrate moisture content (SMC) during greenhouse production and postproduction of bedding plants. Floriculture Res. Alliance. 2016 (abstr.).

Guo. Y., T. Starman, and C. Hall. 2016. Effects of reducing substrate moisture content (SMC) during greenhouse production and postproduction of bedding plants. Hortscience 51 (9): 389 (abstr.).

Guo. Y., T. Starman, and C. Hall. 2016. Effects of reducing substrate moisture content (SMC) during greenhouse production and postproduction of bedding plants. 28th Ann. TX Plant Protection Assoc. Conf. (abstr.).

Guo. Y., T. Starman, and C. Hall. 2017. Poinsettia grown at reduced substrate moisture content (SMC). Floriculture Res. Alliance. 2017 (abstr.).

Abstract for oral presentations

Guo, Y., G. Niu, T. Starman, A. Volder, and M. Gu. 2014. Poinsettia growth responses to container substrate amended with biochar. Southern Region ASHS. HortScience 49(9):19 (abstr.).

Guo. Y, T. Starman, and C. Hall. 2017. Effects of reducing substrate moisture content (SMC) during greenhouse production and postproduction of poinsettia. (abstr.).

Guo. Y, T. Starman, and C. Hall. 2018. Reducing substrate moisture content during greenhouse production of poinsettia improves postharvest quality and economic value. (abstr.).