Effects of anti-gibberellin plant growth regulators on *Tradescantia*, *Epipremnum*, and *Philodendron g*rowth in interior green walls

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Abstract

Interior green walls have been growing in popularity and understanding ways to manage growth of species used in these installations. Popular plants used in green walls include species from the genera *Tradescantia*, *Epiremnum*, and *Philodendron*. In commercial interior green walls, plant trimming and replacement necessitated by stem elongation under low light levels is labor intensive and costly. Anti-gibberellin plant growth regulators (PGRs) may slow stem elongation and thus reduce maintenance costs in this environment. Additionally, aroid species with chartreuse leaves will darken under low light levels. With this research, we examined stem elongation and leaf darkening of these three genera through the use of anti-gibberellin plant growth regulators and differences in light levels. Two experiments were conducted with spiderworts and two were conducted with aroids.

In Expt. 1, two PGRs were applied as foliar spray or drench to three spiderwort selections (zebra plant, *Tradescantia zebrina* and inch plant, *T. fluminensis*) just prior to installation in a green wall, each at three rates: ancymidol (ANC) foliar spray at 25, 100, and 200 mg•L^{-1}; paclobutrazol (PBZ) foliar spray at 20, 80 and 160 mg•L^{-1}; and PBZ drench at 1, 4, and 8 mg•L^{-1}, along with an untreated control. In Expt. 2, 80 mg•L^{-1} PBZ foliar spray, 1 mg•L^{-1} PBZ applied via subirrigation four times, and the combination of these two treatments, was evaluated on ‘Burgundy’ zebra plant. In both experiments, plants were placed in a vertical modular tray interior green wall. Change in total stem and specific internode length were measured every 14 days after installation for three months, the typical longevity of plants in green walls, to calculate growth per month. Anti-gibberellin application slowed internode elongation of spiderwort selections during the first month after installation. Anti-gibberellins were more effective in zebra

plant at reducing overall stem growth rate and less so on inch plant. Across varieties, 25 mg•L^{-1} foliar spray of ANC resulted in no difference in growth rate when compared to the control, though 100 to 200 mg•L^{-1} foliar spray was effective. Based on the results of both experiments, moderate and high rates of PBZ, applied both as a foliar spray and drench, resulted in similar reduction in stem elongation. PBZ applied as 20 to 80 mg•L^{-1} foliar spray, 4 mg•L^{-1} drench before installation in the wall, or a combination of an 80 mg•L^{-1} PBZ pre-installation foliar spray and recurring 1 mg•L^{-1} via subirrigation (4 times) were effective at growth suppression of spiderworts for at least three months. Even rates of PBZ of 160 mg•L^{-1} or 8 mg•L^{-1} drench did not show phytotoxicity in treated plants and could be considered for use. We recommend a pre-installation foliar spray of 80 mg•L^{-1} foliar spray or 4 mg•L^{-1} drench for controlling stem growth across spiderwort selections. Application of anti-gibberellin PGRs to plants before installation in green walls slows stem growth and can contribute to reduced maintenance costs.

Two popular aroid species used in green walls are pothos (*Epipremnum aureum*) and philodendron (*Philodendron scandens*). In two experiments, pothos ‘Neon’, pothos ‘Marble Queen’, and philodendron ‘Lemon Lime’ were evaluated. In Expt. 1, chemical treatments were a 0 mg•L^{-1} control, 80 mg•L^{-1} PBZ foliar spray, a 1 mg•L^{-1} PBZ subirrigation treatment applied four times, and a combination of 80 mg•L^{-1} PBZ and 1 mg•L^{-1} subirrigation treatment. In Expt. 2, chemical treatments were a 0 mg•L^{-1} control and PBZ media drenches at 4 mg•L^{-1}, 12 mg•L^{-1}, and 24 mg•L^{-1}. Light treatments of low, medium, and high levels were also included in Expt. 2. In Expt. 1, only SPAD measurements were taken to measure leaf darkening, while in Expt. 2, both stem length and SPAD measurements were taken over time. In Expt. 1, treated pothos ‘Neon’ were slightly greener than the untreated controls; however, plants in the three treatments were not different from one another. In Expt. 2, no chemical treatment slowed leaf darkening.

Pothos ‘Neon’ leaf color darkened faster than philodendron ‘Lemon Lime’. Plants in the low light treatment had lighter green leaves than those in medium and high light treatments. Light level was only a significant factor during the first month of the experiment. No chemical or light treatment reduced stem length. No chemical treatment or interior light level had meaningful effects on slowing leaf darkening and managing stem length.

This research demonstrates that anti-gibberellin PGRs can be useful tools to help manage stem elongation of spiderwort selections, but not in aroid plant species commonly used in green walls.

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Chapter 1 - Literature Review

Foliage Industry Overview

In recent years, interest in foliage plants for indoor and patio use has increased immensely. In 2020, value of wholesale foliage plant sales increased to $756 million, an increase of $140,342,000 or 23% from 2019 (2020 USDA Floriculture Crops Summary). Because of this surge, Florida has surpassed California as the number one producer of floriculture crops.

This dramatic increase in foliage is due to many factors. Younger generations of Millennials and Gen-Zers have put off buying homes and starting families, in part because of increased home prices and student loan debt (Houseplant Resource Center 2020, Garden Pals 2021). The pandemic has also increased interest in indoor foliage plants. In quarantine or confined to homes, people felt unsafe leaving their living space. People wanted to be closer to nature, so they brought it indoors in the form of foliage plants. In 2020, Garden Center Magazine interviewed 250 independent garden centers about their foliage plant sales. 64% of respondents said that foliage plant sales had increased by at least 15%, and 96% of these IGCs expected these sales to increase further in the 2021 season (Garden Center Magazine 2021).

The foliage production and interior plantscaping industries are two separate segments of horticulture businesses; that is, foliage producers and interior plantscaping companies are not vertically integrated. The primary business of interiorscaping companies is to design, install, and maintain foliage plants in interior spaces. The interiorscaping sector is served by two types of companies: large, national companies such as Ambius or Planterra, or smaller, local horticultural businesses. Examples include retail florists (e.g. Kistner's Flowers in Manhattan, Kansas) or local companies that focus primarily on interiorscaping (e.g. Thriving Botanicals in Houston, Texas, and Plantmasters in Wichita, Kansas).

Because interiorscaping companies are often separate from the production facilities that propagate and produce the foliage plant materials, there is a need to bridge knowledge of plant growth manipulation between the production and interiorscaping sectors. For example, while plant growth regulation with anti-gibberellin chemicals is common in the greenhouse production industry, interiorscaping and landscape architecture firms and their green wall designers, who generally buy plants in and don't grow them in-house, are less familiar with these growth management techniques.

Green Wall Description, Benefits, and Maintenance

Definitions and types

Green walls are vertical gardens found on the exterior or in the interior of a building. In such systems, plants obtain water and nutrients from an irrigation system in the wall. The wall itself provides an anchor for the plant roots (Weinmaster 2009).

On the exterior of buildings, one of the most common forms of a green wall is known as a green façade. In such systems, plants are planted at the base of a wall, either in the soil or a planter box, and allowed to grow vertically, using the wall itself or a trellis placed on the wall for support (Hadba et al. 2017, Manso and Castro-Gomes 2015).

Living wall systems are common in both exteriors and interiors. Such systems are classified as continuous or modular. Continuous living walls are frames that are installed on a wall that creates a void between the support wall and the living wall. There are multiple layers of waterproofing materials to protect the support wall. The void is filled with a substrate in which plant roots will thrive, such as rockwool. The last layer is a type of screen that is cut in order to hold the plants in place.

Modular walls are similar to continuous living walls, but in place of screen to hold the plants, plants are held in trays, planting tiles, and flexible bags (Manso and Castro-Gomes 2015, Fediw 2015). Brands of tray-based modular walls are LiveWall (Nunica, MI) and GSky (Delray Beach, FL). GSky is a popular modular wall in the United States as it is used by Ambius, a large multi-national interior plantscaping company. A brand of modular walls based on planting tiles is ELT (Maharashtra, India). An example of a green wall built with flexible bags is Florafelt (Norcross, GA). Modular green walls based on trays and planting tiles are more common in commercial business settings, while flexible bags are common in private applications and for homeowners.

Biofiltration walls are the final main type of green wall. These walls are plumbed directly into a building's heating, ventilation, and air conditioning systems (HVAC). In such a green wall, air is pulled through plant canopy and root medium where microbes in the root medium and the plants themselves can turn volatile organic compounds (VOCs) into less harmful compounds. Similar to other indoor systems, these walls must be completely watertight so as to not leak into the client's home or business. This type of green wall is patented by NedLaw (Ontario, Canada), a Canadian living wall company (Fediw 2015).

While green walls of many varieties can be found in exterior spaces, from this point forward, the focus will be on modular living wall systems found in the interior environment.

History of interior green walls

Green walls, or the concept thereof, are not a new idea. The concept can be traced back to the era of Romans and Babylonians. The Hanging Gardens of Babylon, one of the seven wonders of the ancient world, can be considered a type of green façade, having had plants that grew on the outside of walls. The Romans were known to have trained vining plants up the sides of walls

and trellises, and these techniques are still practiced today in the outdoor landscape through the use of pergolas and trellises (Jain and Janakiram 2016).

Modern green walls are the brainchild of French botanist Patrick Blanc. In the late 1980's, he filed the patent for his "Device for growing plants without soil on a vertical surface" (patent number FR26344971A1). This consisted of two pieces, a wall with a waterproof backing to prevent damage to the interior infrastructure and a water retention tank with a pump to get water to the plants, then return it back so it can be recirculated.

As horizontal space in commercial settings is often limited, placing plants on vertical spaces seems the next logical step. Large expanses of vertical space converted to plant cover can bring numerous benefits to a space (FMLink 2017, Forbes 2020). Green walls bring visual interest to a space. By using different species, foliage texture, growth habit, and foliage color it is possible to draw client and employee eyes to areas of interest. Green walls can also serve as a type of marketing by placing the company logo on the wall or making the logo out of plant materials.

Benefits of green walls

Green walls bring both physiological and psychological benefits to people in interior environments. Among the physiological benefits are the ability to passively raise relative humidity (RH), removal of VOCs, and carbon sequestration. Psychological benefits include shorter medical stays and improved performance by students or employees (Fediw 2015). Green walls and interiorscaping may also help a site achieve Leadership in Energy and Environmental Design (LEED) certification (Oberti and Plantamura 2017).

Plants placed in interior environments can passively raise relative humidity (RH) when HVAC heating systems are in operation (Kerschen et al. 2016). This research at Kansas State

University showed that 32,300 cm^2 of spider plant (*Chlorophytum comosum*) foliage in a small room ($22m^3$) was enough to raise the RH from 20% to a more comfortable 30%. This study also reported on use of jade plant (*Crassula argentea*) which, as a species that has a crassulacean acid metabolism (CAM) photosynthetic pathway, increased RH during the night.

Volatile organic compounds are a type of air pollution that come from many industrial processes and are carcinogenic over the long term (Lee et al. 2002). VOCs can be released from a variety of products, including cleaners, adhesives, fabrics, and even building materials. Modern construction methods lead to very tightly sealed buildings, without the ability to exchange air with the outdoor environment. This lack of air exchange can lead to sick building syndrome (Norhidayah et al. 2013). Many species of foliage plants have the ability to take up and sequester VOCs, removing them from the interior environment. Plants absorb these pollutants through a variety of mechanisms, including root uptake, absorption through stomates via gas exchange, and shoot uptake (Bandehali et al. 2021). However, multiple studies have shown that the amount of each volatile organic compound that can be taken up by a plant dependent on the plant species (Matsumoto and Yamaguchi 2007, Wolverton et al. 1989).

Carbon sequestration has been recorded with foliage plants in interiorscapes. Studies have shown that different species can fix varying amounts of carbon from their environment based on light compensation point of the species and light levels provided (Pennisi and van Iersel 2012). Torpy et al. (2007) investigated many species of foliage plants. Their research showed that the palm *Chamaedorea elegans*, when acclimated to a high light environment, can remove 118 mg CO_2 /plant/hour at 350 µmol/m^2/s photosynthetically active radiation (PAR), but the same plant at 10 µmol/m^2/s PAR adds 402 mg CO_2/ plant/hour to the environment. In the same study, the aroid *Aglaonema commutatum*, when acclimated to low light of 10 µmol/m^2/s PAR,

adds 62.4 mg CO_2/plant/hour; however, the plant removes 73.5 mg CO_2/plant/hr at 350 µmol/m²/s PAR. Larger, woody species demonstrate more efficient carbon fixation as time passes.

Benefits of plants and natural settings on human health have been found. A seminal study by Ulrich (1984) demonstrated that patients with a view to nature experienced hospital stays that were shorter than those who had a view of a non-descript wall. Direct and indirect exposure to the natural world has been shown to increase the benefits stated previously, such as shorter hospital stays, less reliance on pain medication, and increased morale of hospital workers (Bowler et al. 2010, Park et al. 2004, Grinde and Patil 2009). Direct exposure to nature refers to experience of nature directly, such as viewing or being near plants, animals, or natural settings. Indirect exposure refers to viewing pictures or paintings of nature, the use of natural materials and colors in architecture, or the use of organic shapes and forms in design (Kellert and Calabrase 2015)

Plants have also been found to have a positive effect on student and worker productivity and mood. Numerous studies have shown that offices with foliage plants make people feel more productive, less stressed, and healthier at work (Smith et al. 2011, Lohr et al. 1996, Shibata and Suzuki 2002). Interior plants have also been shown to help increase test scores for students. These benefits have been linked to plants' ability to passively humidify the air and remove toxins and microbes from the air (Daly et al. 2010). Another explanation for these benefits could be based in the principle of "biophilia" or the desire of people to remain connected with the nature.

Green Wall Design and Maintenance

Plant selection

A wide variety of foliage plants are used indoors to bring beauty inside. Commercially, nearly 100 genera and 1000 species of foliage plants provide a variety of growth forms, colors, variegation, and at times, flowers. These plants originated in tropical and subtropical regions of South America, Africa, Asia, and Australia. In their native habitat, most foliage plants grow in the forest understory where there are low light levels (Henny and Chen 2020), which makes them ideal for interior environments (Chen et al. 2005). Several families that are commonly used in green walls are discussed below.

The Commelinaceae family is host to 41 genera, comprising 728 accepted species names. These species have a worldwide distribution, spanning much of Africa, North and South America, southeast Asia and northern Australia (The Plant List). The largest and most commercially used genus in this family is *Tradescantia*. Species within this genus contain a variety of colors and growth forms, including *T. virginiana*, which resemble a clump of grass, *T. zebrina* and *T. flumiensis* having a trailing growth form, and *T. spathacea*, maintaining an upright growth form. Other common genera in this family include *Callisia, Aneilima,* and *Gibasis*. The foliage color palate for this family includes greens, yellows, reds, pinks, and purples, along with variegated and striped cultivars. In their native tropical habitats, plants in this family, specifically *T. pallida* var. *purpurea*, are invasive agricultural pests due to their growth rate and ability to adapt to a variety of environments (Paiva et al. 2003). Many species in this family fall in the commercially used low or medium light ranking for interiorscaping plants (Fediw 2015).

In commercial production, *Tradescantia* species need to be grown under light conditions of at least 3,500-4,500 foot-candles and a temperature of at least 50˚F. Root medium must be kept moist, or older foliage might die. These plants are grown from stem cuttings. *Tradescantia*

plants are most often grown in hanging baskets, but they can be found in smaller pots (Griffith, 1998). While on display in an interior, *Tradescantia* can tolerate light levels between 150-250 foor candles (f.c.), though more light is preferred. Plants should be maintained at a temperature between 65-80˚F and be allowed to dry down between watering events (Griffith 1998, DelPrince 2013).

The Araceae family contains 117 genera and 3,368 accepted species. Araceae contains many of the common interiorscaping foliage plant species including anthurium (*Anthurium*), dumbcane (*Dieffenbachia*), pothos (*Epipremnum*), Swiss cheese plant (*Monstera*), arrowhead vine (*Syngonium*), philodendron (*Philodendron*), and zz plant (*Zamioculcas*) (The Plant List). Growth forms in this family are mostly limited to upright and vining plants. The foliage colors found in this family ranges from reds, oranges, and yellows to many shades of green, purple and black. A variety of leaf shapes are found in this family, including plants with and without fenestrations, as well as variegated, striped, and patterned leaves. Species in this family range in their light needs, with pothos in the low light ranking and plants like monstera in the medium-high ranking (Fediw 2015).

Under commercial production, pothos and heartleaf philodendrons (*Philodendron scandens*) grow best with light levels between 1500-3500 f.c. and a temperature between 70-90˚F. Both species benefit from regular watering and fertilization (Griffith 1998). In interior displays, both species will tolerate light levels as low as 50 f.c., but heartleaf philodendrons do best with at least 75-150 f.c. and pothos will thrive with 150-250 f.c.. These species are best suited to temperatures of 65-85˚F and need watered after the plant has time to dry between waterings (Griffith 1998, Fediw 2015).

Light levels

In most cases, interior plants, including green walls, are placed in an area where they do not receive adequate natural light for long-term survival. For ease of plant placement in different light regiments, the interiorscaping industry has developed ranges of light intensity to categorize different plant species' needs. The lowest light level is between 30–150 f.c.. This includes plants such as Janet Craig dracaena (*Dracaena deremensis* 'Janet Craig') and pothos. The medium light level is between 150-250 f.c., containing plants such as bird's nest fern (*Asplenium nidus*) and spider plant. Lastly, the high light level contains plants needing more than 250 f.c. to thrive, including pygmy date palm (*Phoenix roebellini*) and bird of paradise (*Strelitzia nicolai*) (Fediw, 2015). While most foliage plants used in interiorscapes are adapted to low-light conditions, supplemental artificial light is beneficial or necessary. Different types of light bulbs, including LEDs, incandescent bulbs, and florescent bulbs are common in office buildings. Each type of bulb differs in the quality of light they produce. With the advances in lighting efficiency, light-emitting diodes (LEDs) are becoming more prevalent in commercial sites where green walls are located. These bulbs provide more broad-spectrum light that provides the wavelengths that plants need (Fediw 2015, Seignot 2000, Stuart 1990).

When plants (e.g., *T. pallida* var. *purpurea*) are subjected to lower light levels, the thickness of the hypodermal layer is reduced to only 1-2 layers of cells (Paiva et al. 2003). In weeping fig (*Ficus benjimina*), plants placed in a low light (16 μmol/m²/s) responded by increasing leaf surface area, reducing leaf thickness, and expanding internodes (Chen et al. 2005).

Internode elongation in plants

Internode elongation in plants can be attributed to a variety of causes, including hormones within the plant (Taiz and Zieger 2006) and phytochromes (Iwamoto et al. 2011, Smith 2000).

Plant hormones, specifically gibberellins, contribute to internode elongation in plants. In the Poaceae (grass) family, exogenous application of gibberellic acid (GA) can cause rapid internode elongation (Taiz and Zieger 2006). Gibberellic acid applications to dwarf umbrella tree (*Schefflera arboricola*) resulted in taller plants and had an increased number of leaves than control plants or those sprayed with paclobutrazol (Mazher et al. 2014).

Phytochromes are proteins that plants use to determine the ratio of red (P_r) and far-red (P_{fr}) light. Phytochrome proteins have different forms for which form of light they are currently absorbing (Casal et al. 1998) and help to regulate light-responsive genes (Neff et al. 2000). In rice (*Oryza sativa*), Iwamoto et al. (2011) found that phytochromes affect multiple steps in the GA synthesis pathway, which controls internode elongation.

Irrigation and fertilization

There are many ways to irrigate plants placed in green walls. These irrigation methods are dependent on the type of green wall that is installed in a space. Most automated green wall irrigation systems are based on the principal of gravity and downward water flow. Irrigation lines are placed at the top of the green wall module and irrigation solution is delivered through emitters distributed across the modular frame. In the case of modular living wall systems, there is often an overflow pipe, allowing the tray or bag to fill with water to a specified point, then the excess irrigation solution drains to the tray or bag below. Such systems can be part of a recirculating irrigation system or a direct irrigation system. In a recirculating system, excess water not used by the plants is collected at the bottom of the green wall in a tank and is pumped

back to the top of the wall at the next irrigation event. A direct irrigation system is often plumbed into the site's water line and does not need a pump. These systems lend themselves to using a fertilizer injector in-line to provide nutrients to the plants (Ambius 2022, Perez-Urrestarazu and Urrestarazu 2018).

Maintaining plant fertility is also important in green walls. Two common ways to fertilize plants in green walls is to fertigate at each irrigation event or to use a pre-plant incorporation and slow-release fertilizer top-dress. Fertigation involves plumbing a fertilizer injector into the irrigation system of the green wall and is somewhat common in large interior green walls (LiveWall 2022. Ambius 2022). In most cases, the concentration of fertilizer reaching the plants can be changed based on several factors, including time of year. However, this means an interiorscaper will also be responsible for maintaining the stock fertilizer solution as a part of green wall maintenance. This increase in the amount of plumbing necessary for fertigating a green wall could lead to an increase in maintenance needed for the green wall itself. For a slow-release fertilizer, products such as Osmocote (Scotts Miracle-Gro, Marysville, OH), are commonly incorporated into the growing media of the plant or placed on top of the root medium surface. Such products are commonly used to maintain fertility in other potted interiorscaping plants (Conover et al. 1991). This is a convenient way to fertilize such plants over the long term. However, annual re-applications of the fertilizer may be needed, as slow-release fertilizers break down over time, and loose fertilizer prills may block irrigation lines.

Plant rotating and trimming

Plants naturally grow toward a light source, and in some instances, can create undesirable curved growth in herbaceous plants, especially those oriented on a vertical surface. To avoid this asymmetrical growth, plants must be rotated on a regular basis. In turning the plants, the growing

point does not have enough time to develop new growth that bends towards the light source (DelPrince 2013).

As plants develop new leaves and stems in a green wall installation, they must be trimmed to maintain the original design and a professional aesthetic. Depending on the species, this growth may drape down the wall or grow outward from it. Plants should be pruned when they start to shade out the plants below them or when the aesthetic of the wall is affected (Fediw 2015).

Plant Growth Regulators

The hormone class of gibberellins (GA) have several important functions in plants, including cell elongation. Through this mechanism, GA results in internode extension and when GA synthesis is blocked, plants are shorter. Therefore, controlling GA synthesis can be a key to growth management. When its synthesis is blocked, plants are shorter.

The earliest research is reported in the 1970s. Frank and Donnan (1975) evaluated use of the anti-gibberellin ancymidol on several foliage species, including philodendron and wandering Jew. They found that rates of 0.625 to 2.5 mg a.i./ft^2 provided significant increases in market value over the control plants. R.J. Henry of the University of Florida reviewed published growth regulator research with foliage plants in the 1970s through 1980s and summarizes results. Wang and Blessington (1990) published optimal uniconazole and paclobutrazol rates for drenches on schefflera (*Schefflera actinophylla*), croton (*Codiaeum variegatum* var. *pictum*), arrowhead vine (*Syngonium podophyllum*), and plectranthus (*Plectranthus australis*).

The currently available plant growth regulators in the anti-gibberellin class that block the GA synthesis pathway to contribute these benefits to foliage plant species in green walls include ancymidol (Abide/A-Rest), chlormequat chloride (Citadel/Chlormequat E-Pro/Cycocel),

daminozide (B-Nine/Dazide), flurprimidol (Topflor), paclobutrazol (Downsize/Pac O/Piccolo 10XC/Bonzi), and uniconazole (Concise/Sumagic) (Whipker 2021). Those that are labeled for use in interiorscapes are A-Rest, Bonzi, and Downsize.

Some foliage plant species can be found in *GrowerTalks' 2021-2022 Plant Growth Regulators for Annuals*, an industry resource that is updated on an annual basis. This resource gives recommended rates of anti-gibberellin applications and is compiled by Brian Whipker. Recommended foliage plant PGR rates are as follows:

Philodendron	Ancymidol Chlormequat-Cl Daminozide	25-132 ppm spray or 2-4 ppm drench 3,000 ppm spray 2,500-7,500 ppm spray
Pothos	Ancymidol Daminozide Paclobutrazol	25-132 ppm spray or 2-4 ppm drench 2,500-7,500 ppm spray 2-4 ppm drench
Wandering Jew	Ancymidol	26-132 ppm spray

Ancymidol

Ancymidol is an anti-gibberellin chemical that is used to control growth in commercially grown plant species. It is easily absorbed and is most readily absorbed by the plant leaves and stems. Effective application methods include substrate drenches and foliar sprays (Whipker 2021). This active ingredient works to stop gibberellin production in plants by blocking the conversion of ent-kaurene to ent- kauronoic acid (Coolbaugh and Hamilton 1976).

Paclobutrazol

Two common ways paclobutrazol is applied to floriculture crops are foliar sprays and media drenches. Drenches are longer acting and provide more uniform control. One issue with sprays is that paclobutrazol is not very water soluble and not as mobile in plant tissues (Desta and Amare 2021). Similar to ancymidol, paclobutrazol blocks the gibberellic acid pathway by stopping the conversion of ent- kaurene to ent- kaurenoic acid (Hedden and Graebe 1985).

Benefits of treating plants in green walls with plant growth regulators

While no research has been done on PGR application to plants used in an interior environment with decreased light levels, PGRs have been used to reduce internode length in a wide variety of crops, leading to more compact growth (Li et. al 2009).

In *Pachira aquatica*, a combination of decreased photosynthetic photon flux density (PPFD) during production and paclobutrazol application between 50 $mg \cdot L^{-1}$ and 150 $mg \cdot L^{-1}$ has been shown to reduce the change in internode length and canopy height and also reduces net photosynthetic rates and lowers light compensation points (Li et al. 2009).

Plant growth regulators and cholorphyll concentration

An additional effect of blocking GA synthesis in foliage plants used in green walls may also be the development of darker foliage color. This phenomenon occurs for two reasons: new plant cells do not expand as much, keeping the pigments more concentrated; and chlorophyll production is up-regulated via the increased production of phytyl (Whipker 2021). While anti-gibberellins do not stop the plant from growing, they do stop the newly formed cells from expanding. This inhibition of cellular expansion leads to smaller cells, each with a similar amount of chlorophyll as an untreated leaf (Verma et al. 2010). While this process may be desirable in greenhouse and nursery production systems, this irreversible occurrence is detrimental to foliage plant cultivars with chartreuse leaves. Plant varieties with this leaf color

are frequently selected for use in green walls because of their brightly colored leaves, and darkening of leaves detracts from this aesthetic. To maintaining a design that incorporated chartreuse foliage, an interiorscaper would need to replace the whole plant, which is costly in both time and money.

Economics: Installation and Maintenance Costs of Green Walls

Installation cost can be very variable for a green wall. Factors that affect installation cost include type of green wall being installed, location (interior or exterior), size of green wall being installed, cost of plant materials, and remodeling costs to the building, including structural, water, drainage, and electrical changes. According to numerous commercial green wall installers, cost of a green wall per square foot can range anywhere from $110-$260 (TrueVert, Greenscape, Bring Nature Indoors, Plant Hardware, LiveWall).

Company	**Installation costs for a 500 sq. ft green wall**	**Maintenance Costs for a 500 sq. ft green wall**
TrueVert	$100-$225/ sq. ft.	n/a
Greenscape	$560-$1740/ sq. ft.	n/a
Bring Nature Indoors Live Green Wall	$76,150.00 ($152.30/ sq. ft.)	$10,950/ year
Bring Nature Indoors Artificial Green Wall	$35,000.00 ($70/ sq. ft.)	$1,800/ year
LiveWall Live Green Wall	$22,500-$25,000 ($45-$50/ sq. ft.)	n/a
Plant Hardware	$70-$260/ sq. ft.	$3,600-$12,000/ year

In summary, while green wall installation and maintenance is expensive, they provide many benefits in an interior environment. Using anti-gibberellin plant growth regulators offers opportunity to improve plant longevity and reduce maintenance costs over time.

Chapter 2 - Treatment of Potted Spiderwort Species with Anti-Gibberellin Plant Growth Regulators Slows Stem Elongation in an Interior Green Wall

Introduction

As more businesses recognize the many benefits of having plants in the workplace, interior green walls are becoming more common and are often used as a focal point in public spaces (McKay 2017). In most cases, professional interiorscaping firms are hired to maintain these systems. Most green walls cover a large area, making maintenance a significant expense (Fediw 2015). Plants in interior environments tend to develop unattractive growth with elongated internodes in response to low light levels, as well as low quality light, leading to a less aesthetically pleasing plant display (Collado and Hernández 2021). To maintain green wall appearance, an interiorscaper must trim specific plants or replace them all together. This frequent labor activity by the interiorscaping firm increases maintenance costs that must be passed on to clients.

Several spiderwort (*Tradescantia* species) are commonly used in interior plantscaping, including zebra plant (*T. zebrina*), purple heart (*T. pallida* 'Purple Heart'), and oyster plant (*T. spathacea*) (DelPrince 2013). In commercial production, spiderwort species are grown under light conditions of 700 to 900 $\mu mol \bullet m^{-2} \bullet sec^{-1}$ in hanging baskets or small pots (Griffith 1998). Spiderworts can tolerate light levels as low as 30 to 50 $\mu mol \bullet m^{-2} \bullet sec^{-1}$, but more light is preferred. Plants should be maintained at a temperature between 65 to 80˚F and be allowed to dry down between watering events (DelPrince 2013, Griffith 1998). In order to maintain an attractive plant, vining species should be pinched regularly.

Anti-gibberellins are a class of PGR that inhibit a plant's synthesis of the hormone gibberellic acid (GA). A variety of commercial anti-gibberellin plant growth regulators (PGRs) are available, but research is limited with their use across the wide range of spiderwort species and non-existent for their use in green walls. For potted crop production, White et al. (2005) used flurprimidol, paclobutrazol, and uniconazole on Virginia spiderwort (*Tradescantia virginiana*). They demonstrated that foliar sprays of flurprimidol between 45 to 60 mg•L^{-1}, paclobutrazol at 120 mg•L^{-1}, and uniconazole between 30 to 45 mg•L^{-1} were effective at controlling growth in this species. Latimer and Scoggins (2012) recommended daminozide foliar spray at 5000 mg•L^{-1}, a tank mixture of daminozide and chloromequat chloride at 5000 mg•L^{-1}, paclobutrazol between 40 to 80 mg•L^{-1}, uniconazole between 15 to 30 mg•L-1 and flurprimidol between 15 to 45 mg•L^{-1} to control growth in Virginia spiderwort. Whipker (2021) recommends 26 to 132 mg•L-1 foliar spray of ancymidol for zebra plant. Frank and Donnan (1975) found that 1.25 mg/ft^2 ancymidol was effective to control growth in zebra plant.

Anti-gibberellin PGRs may be applied to plants before or after their installation in a living wall. Foliar spray or drench application just before shipping for installation may be made by the commercial grower, or the chemical may be applied in the irrigation solution of the living wall *in situ*, as long as required re-entry intervals are met.

Ancimydol (A-Rest, SePRO Corp. Carmel, IN) is a nitrogen-containing heterocycle with a pyrimidine group, and this chemical inhibits GA synthesis by blocking the conversion of ent-kaurene to ent-kaurenoic acid (Coolbaugh and Hamilton 1976). Ancymidol is rated for use on ornamentals in greenhouses, nurseries, shade houses, and interiorscapes. The label limits the application to areas where the active ingredient will not contact workers or other people by direct contact or with drift residues, and there is a 12-hour reentry interval (REI). As per the current

label, A-rest could be used in an interiorscape location by applying at a time when the REI would be met with no exposure to residue, such as after a facility closes.

Paclobutrazol is also a nitrogen-containing heterocycle with a triazole group that blocks GA synthesis by inhibiting the conversion of ent-kaurene to ent-kaurenoic acid (Hedden and Graebe 1985). Several formulations of this PGR are available for commercial use. For example, the Pac-O (OHP Inc., Bluffton, SC) label does not support application to plants *in situ* in an interiorscape. The label limits applications to areas where it will not contact workers or other people by direct contact or contact with drift residues, and there is a 12-hour REI for this chemical. However, Bonzi (Syngenta, Basel, Switzerland), another paclobutrazol-containing PGR, is labeled for application in interiorscapes, provided no layperson encounters the active ingredient until after the REI. As per the current labels, Pac-O could be used prior to installing plants in a green wall, but not in the interiorscape location with the green wall; both A-Rest and Bonzi could be applied *in situ*.

Our objective was to determine whether the anti-gibberellin PGRs ancymidol (ANC) and paclobutrazol (PBZ) could be used to slow growth of spiderworts placed in a low-light interior green wall environment. Secondly, we wanted to optimize post-production application method and rate of these PGRs for use in interior green walls.

Materials and Methods

Two experiments were conducted with two species of spiderworts using the interior vertical modular tray living wall system (Versa Wall, GSky, Delray Beach, FL) in the lobby of Throckmorton Plant Sciences Center of Kansas State University. The interior green wall was installed by Ambius (Wyomissing, PA) in 2015. The green wall had 14 rows of Versa Trays with

36 plants per row, totaling 504 plants. Expt. 1 occurred from 22 November 2021 to 14 February 2022, and Expt. 2 occurred from 11 April to 4 July 2022.

Plant material. For Expt. 1, tip cuttings of zebra plant (*Tradescantia zebrina*) and inch plant (*T. fluminensis*) were received in Manhattan, KS, on 12 Oct 2021 from North Carolina Farms (Indian Trails, NC). 'Burgundy' zebra plant tip cuttings were taken on 12 Oct 2021 from a stock plant originating from Costa Farms (Miami, FL). In Expt. 2, only 'Burgundy' zebra plant was used, and tip cuttings were taken on 28 Feb 2022. Cuttings were stuck into 4-in terra cotta plastic pots (375 mL; Pöppelmann Plastics USA LLC, Claremont, NC) and filled with BX General Purpose Growing Media (Premier Horticulture Inc., Quakerton, PA). Three cuttings were placed in each pot in Expt. 1, and four cuttings in Expt. 2. Cuttings were rooted and grown on in a glass-glazed greenhouse (Throckmorton Plant Sciences Center, Manhattan, KS) under 52% white shade cloth (PAK Unlimited, Inc., Cornelia, GA) for 41 days before installation in the green wall for Expt. 1 and 42 days before installation for Expt. 2. Temperature set points were 25ºC D : 22ºC N. Average daytime light levels for production were 161 $\mu mol \cdot m^{-2} \cdot sec^{-1}$. Due to the vigorous nature of 'Burgundy' zebra plant, plants used in Expt. 1 were pinched to leave two to three nodes with an average height at pinch of 6 cm and height at installation of 13 cm. The other two varieties were left unpinched and had heights of 15 to 16 cm when installed in the green wall.

During production, plants were irrigated overhead as needed with 200 $mg \cdot L^{-1}$ N from 20N-4.3P-16.6K (Compass Minerals, Overland Park, KS). Before installation, 4 g of controlled release fertilizer (15N-3.87P-9.96K; OsmocotePLUS, Scotts MiracleGro, Marysville, OH) was applied to each pot and watered in with municipal water.

Treatments. Chemicals used in Expt. 1 were ancimydol (A-Rest, SePRO Corp., Carmel, IN) and paclobutrazol (Pac-O, OHP Inc., Bluffton, SC). Ancimydol (ANC) was applied as a foliar spray. Paclobutrazol (PBZ) was applied both as a foliar spray and as a media drench. Rates of ANC applied were 0, 25, 100, and 200 mg•L^{-1}. PBZ foliar spray was applied at rate of 0, 20, 80, and 160 mg•L^{-1}. PBZ media drench was applied at rates of 0, 1, 4, and 8 mg•L^{-1}. Rates were selected based on industry PGR recommendations (Whipker 2021) and from rates used by commercial growers (personal communication, Green Circle Growers, Oberlin, OH). For foliar spray treatments, 17 mL of the treatment solution was sprayed onto each treated plant using a hand sprayer which was volume sufficient to fully cover all foliage to run-off. No adjuvant was used. For media drench treatments, 60 mL of the treatment solution was applied. Distilled water was used for 0 control treatments. PGRs were applied two days before installation into the green wall. Plants were installed on 22 November 2021 and harvested on 14 February 2022.

In Expt. 2, only PBZ was used on 'Burgundy' zebra plant. The four treatments were 0 mg•L^{-1} control, a subirrigation application of 1 mg•L^{-1} PBZ applied at each irrigation event (days 0, 23, 51, and 78 after installation); a foliar spray of 80 mg•L^{-1} PBZ applied before plant installation into the wall; and a combination of a 1 mg•L^{-1} application during subirrigation events and an 80 mg•L^{-1} foliar spray. To accomplish the subirrigation applications during Expt. 2 without affecting other treatments, selected plants were removed from the green wall and placed in a flat with 2000 mL of the treatment PGR solution, allowed to absorb for one hour, and replaced in the green wall. Care was taken to ensure leaves did not touch the PGR solution. In the foliar spray treatment, 17 mL of the treatment solution was applied to each plant two days prior to installation in the green wall.

For both experiments, plants were separated into six replications based on size and placed randomly into pre-selected blocks of the green wall. The blocks were established based on differences in light intensity and irrigation quantity (Figure 2-1). In Expt. 1, each of six blocks had one pot of each treatment (3 species x 3 PGR treatments x 4 rates) for a total of 36 plants per block and 216 experimental plants. In Expt. 2, each of six blocks had two pots of each treatment (1 species x 4 PGR + application method) for a total of 16 plants per block and 96 experimental plants. Remaining slots in the green wall were populated with filler plants of the same species, or aroid species commonly used in living wall designs. As filler plants grew to cover experimental plants, stems were removed.

Green wall light, temperature, and irrigation. Temperature and light intensity in the green wall were recorded every 15 min with a HOBO Pendant MX Temperature/ Light Data Logger MX2202 (Onset Computer Corp., Bourne, MA; light levels reported in Figure 2-1). Temperatures in the green wall ranged from 11.7 to 22.6˚C and never had a variation of more than 2.4˚C between blocks.

To determine when to irrigate the living wall, eight sentinel plants were randomly selected across the wall and the weight of each pot was measured at container capacity; pot weights were averaged (Figure 2-1). These sentinel pots were weighed weekly. Once the weights reached 70% (+/- 5%) of their weight at container capacity, the green wall irrigation system was activated for one hour. The irrigation system was controlled with a Hunter X-CORE Irrigation Controller (Hunter Industries, San Marcos, CA). Thirty minutes post-irrigation, the weights of the sentinel pots were again measured and averaged. The green wall was irrigated on days 9, 28, 52, and 66 after installation (DAI) in Expt. 1 and on days 0, 23, 51, and 78 DAI in Expt. 2.

Data collected. Selected internode length (Expt. 1) and total stem length (Expts. 1 and 2) were measured on DAI 0, 15, 29, 43, 57, and 85 after installation in Expt. 1 and DAI 0, 14, 28, 42, 56, and 84 in Expt. 2. Selected internodes and stems were marked with silicone tomato grafting clips (Hydro-Gardens, Colorado Springs, CO) for repeated measures. Internodes were selected from the stem of smallest length in each pot. The measured internodes were selected from the first two to four internodes at the apex of the stem (Figure 2-2A). Total stem lengths were taken on the stem of medium length in each pot (Figure 2-2B) from the edge of the pot to leaf tip. In Expt. 1, stem length of 'Burgundy' zebra plant was measured from the axial break just below the pinch.

In both Expts. 1 and 2, variance of the factorial treatment structure was analyzed using JMP Pro ver.16.0.0 (SAS Institute Inc., Cary, NC). All tests were conducted at the 0.05 significance level. LSMeans were separated using Tukey HSD multiple comparison procedure.

Results and Discussion

Change in internode length. During the first 29 DAI in Expt. 1, internodes elongated more for zebra plant species than the other two spiderwort selections (Table 2-1). Plants treated with ANC foliar spray had greater internode elongation during this period than those treated with PBZ foliar spray (Table 2-1). The medium and high PGR concentrations resulted in less internode elongation than the control or low rates (Table 2-1).

Across species and chemical application in Expt. 1, the measured internode elongated for only the first 29 days and had minimal change in length during days 30 through 85 (Figure 2-3). That is, the selected internode—originally near the apex of the plant-- expanded significantly only during the first month after installation in the wall. No significant change in internode elongation occurred during months two or three (Figure 2-3) as the distance between the

measured internode and the plant's apex increased. Stem internodes near the base of the plant of many species, including soybean (*Glycine max;* Zhang et al. 2020), sunflower (*Helianthus annuus*; Garrison 1973), and bamboo (*Bambusa multiplex*; Wei et al. 2019), have been shown to stop elongating after a period of time. The growth curve of an individual internode over time is sigmoidal in shape. For this reason, internode length was not an informative measure of PGR effectiveness and was only measured in Expt. 1.

The interaction between spiderwort selection, chemical application, and concentration in Expt. 1 was not significant (Table 2-1, Table 2-2). At the onset of Expt. 1, all stem lengths were similar (Table 2-2). To evaluate treatment effects, the change in stem length was calculated in one month intervals.

Species. A difference occurred in stem growth between the two spiderwort species used in Expt. 1, but the two selections of zebra plant behaved similarly as 'Burgundy' is a cultivar of *T. zebrina*. Inch plant had greater stem growth compared to the two selections of zebra plant over each month and the entire experiment (Table 2-1). Chemical PGR application more effectively reduced stem length of zebra plant than inch plant (Fig. 2-4C, Fig, 2-4D).

Chemical. Paclobutrazol was more effective than ANC at inhibiting internode expansion (Table 2-1); however, no difference in stem length or monthly growth rate occurred between these chemicals (Table 2-1, Table 2-2). Both ANC and PBZ affect the gibberellin synthesis pathway in the same reaction step, by blocking the conversion of ent-kaurene to ent-kaurenoic acid (Coolbaugh and Hamilton 1975, Hedden and Graebe 1985). No difference in stem length occurred between a foliar spray application of PBZ and a media drench of PBZ at the rates used.

All chemical PGR applications except the lowest rate of ANC controlled stem length compared to the control throughout Expt. 1 (Table 2-1). The high rates of each chemical

application resulted in less stem elongation than the low rate, but similar control to the medium rate, for every month except the third. This result suggests that PGR efficacy may have begun to wane D57 to D85 (Table 2-1).

Rate of ANC foliar spray resulted in different internode expansion, overall change in stem length, and weekly stem growth rate over the three-month experiment between a 100 and 200 mg•L^{-1} application versus the control (Table 2-1). A high ANC foliar spray of 200 mg•L^{-1} provides the best growth regulation on both tradescantia species used (Figure 2-4). For PBZ, using the chemical as a foliar spray at 20, 80, or 160 mg•L^{-1} or a media drench at 1, 4, or 8 mg•L^{-1} provides similar growth limiting effects (Table 1, Figure 2-4).

In Expt. 2, stems of 'Burgundy' zebra plant selected for measurement again started at similar length (Table 2-3). Each of the three treatments reduced stem elongation compared to the control (Table 2-3). This effect occurred during each of the three months of the experiment (Table 3) as well as overall (Figure 2-5). Though the combination of 80 mg•L^{-1} spray and recurring 1 mg•L^{-1} subirrigation treatment appeared to maximize decrease in stem growth rate by month, results were not significantly different from the other PGR treatments. Therefore, the simplest chemical application strategy of PGR application as a foliar spray or drench prior to installation in the green wall can be recommended.

Summary. Anti-gibberellin application slowed growth in internode length of spiderwort selections during the first month after installation in a green wall. Anti-gibberellins were more effective in zebra plant at reducing overall stem growth rate and less so on inch plant. Across varieties, 25 mg•L^{-1} foliar spray of ANC resulted in no difference in growth rate when compared to the control, though 100 to 200 mg•L^{-1} foliar spray was effective. While ANC is an effective

option at foliar spray rates > 100 mg•L^{-1}, the chemical cost is higher than the cost of PBZ applications (Table 4).

Based on the results of both experiments, moderate and high rates of PBZ, applied both as a foliar spray and drench, resulted in similar reduction in stem elongation. PBZ applied as 20 to 80 mg•L^{-1} foliar spray, 4 mg•L^{-1} drench before installation in the wall, or a combination of an 80 mg•L^{-1} PBZ pre-installation foliar spray and recurring 1 mg•L^{-1} via subirrigation (4 times) were effective at growth suppression of spiderworts for at least three months. Even rates of PBZ of 160 mg•L^{-1} or 8 mg•L^{-1} drench did not show phytotoxicity in treated plants and could be considered for use. We recommend a pre-installation foliar spray of 80 mg•L^{-1} foliar spray or 4 mg•L^{-1} drench for controlling stem growth across spiderwort selections. Application of anti-gibberellin PGRs to plants before installation in green walls slows stem growth and can contribute to reduced maintenance costs.

Figure 2.1. Green wall design used for experiment 1. Blocks of treatments are denoted with red squares (with six bloocks), placement of HOBO light/temperature sensors (one per block) are shown with magenta circles, sentinel pots for irrigation are shown with blue triangles (eight around the green wall), and average light levels ($\mu mol \bullet m^{-2} \bullet sec^{-1}$) per block are reported in white boxes. Average light levels were found after measuring each pot location in each block with a light meter.

Figure 2.2. Internode (A) and stem length (B) were measured on specific stems of each plant and repeated every two weeks. Tomato grafting clips marked selected internodes or stems for repeated measurement.

Figure 2.3. Internode elongation for average of zebra plant (*Tradescantia zebrina*) (A) and inch plant (*T. fluminensis*) (B) in experiment 1. Ancymidol foliar spray applied at 25 (AL, orange), 100 (AM, light gray), and 200 (AH, yellow) mg•L^{-1}, paclobutrazol foliar spray at 20 (SL, light blue), 80 (SM, green), and 160 (SH, dark blue) mg•L^{-1}, paclobutrazol media drench at 1 (DL, burgundy), 4 (DM, dark gray), and 8 (DH, tan) mg•L^{-1}. Standard error values of the means at each date are shown.

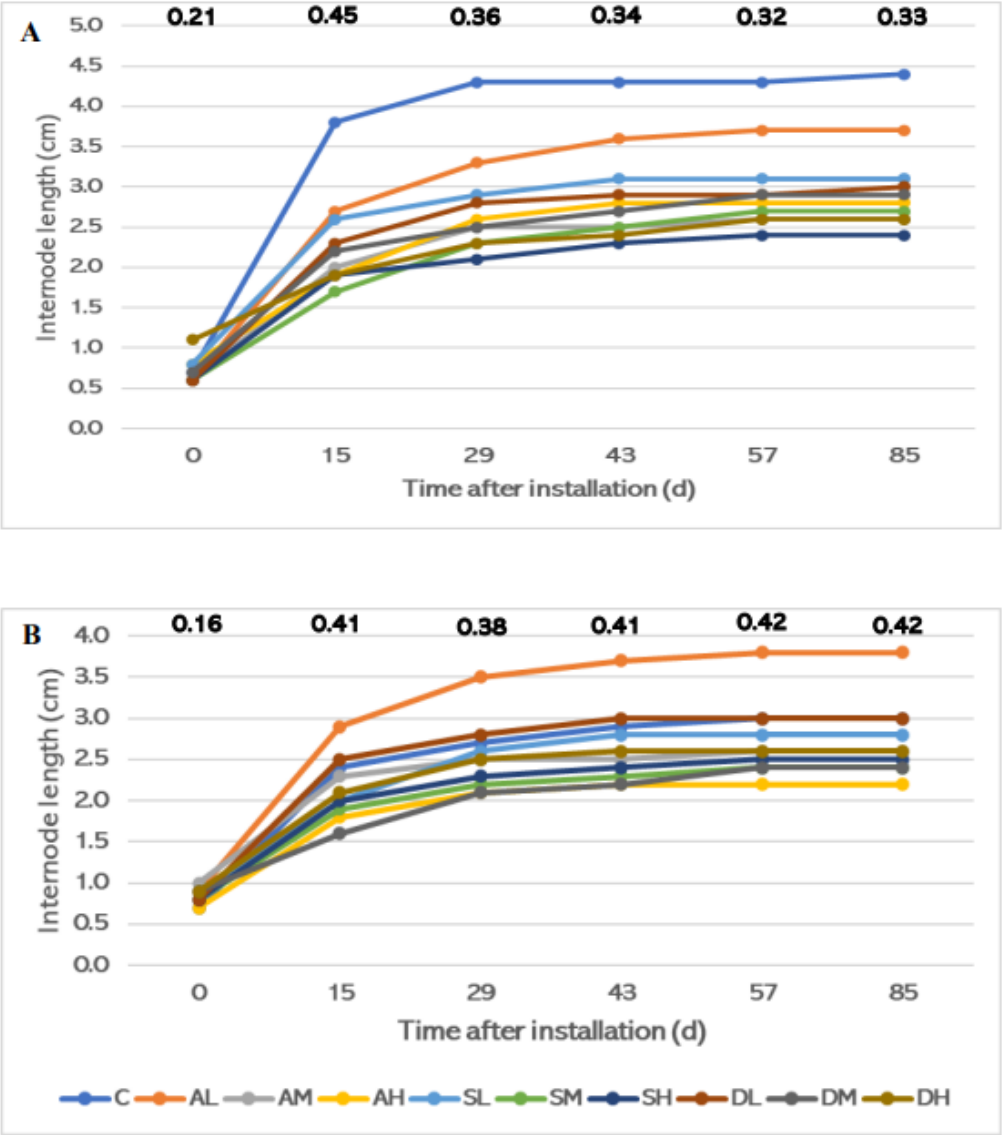


Figure 2.4. Internode (A, B) and stem growth (C, D) comparisons between average of zebra plant (*Tradescantia zebrina*) selections (A, C) and inch plant (*T. fluminensis*) (B, D) for ancymidol (ANC) foliar spray and paclobutrazol (PBZ) foliar spray and PBZ drench treatments and rate of chemical applied in experiment 1. Mean separation based on Tukey HSD $\alpha \leq 0.05$.

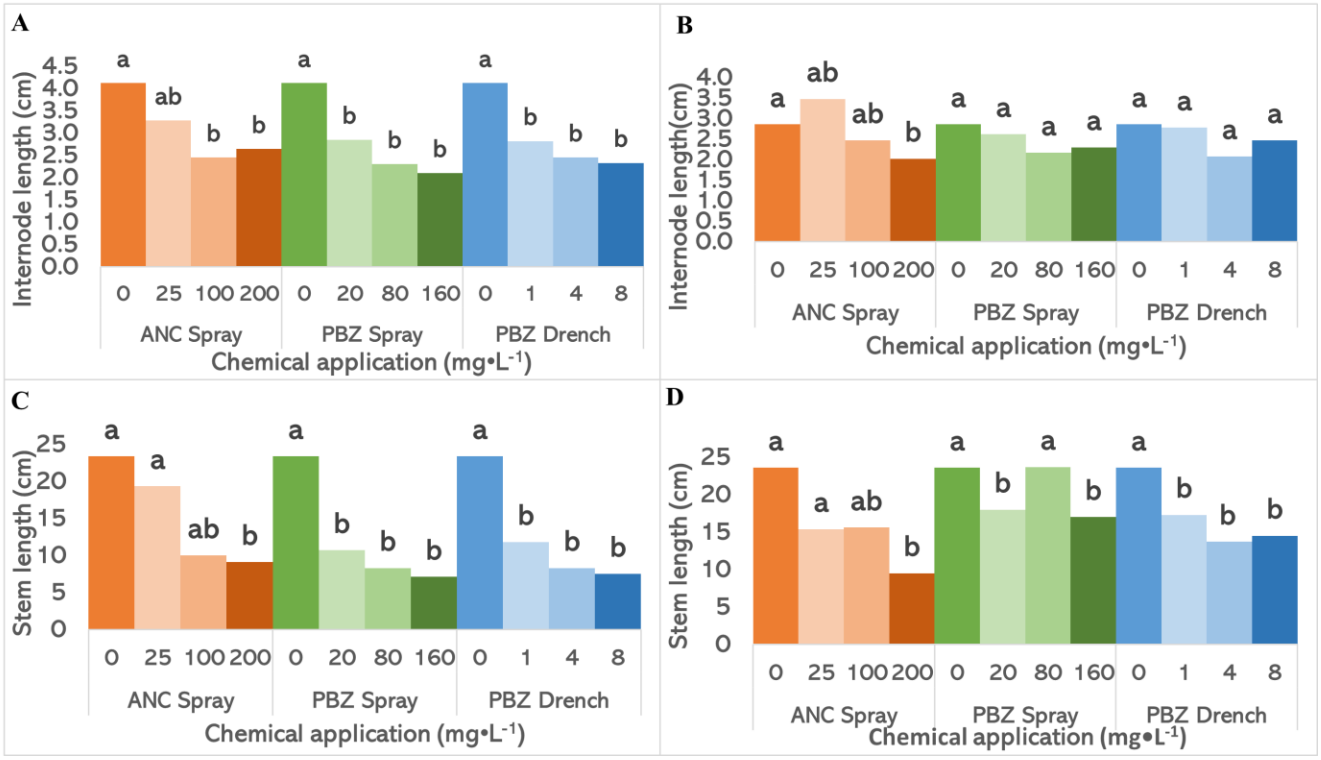


Figure 2.5. Treatment comparison of a 0 mg•L-1 control and paclobutrazol applied as a foliar spray (80 mg•L^{-1}), media application via subirrigation (1 mg•L^{-1}, applied four times), and a combination of a foliar spray and recurring media application (80 mg•L^{-1} with 1 mg•L^{-1}, applied four times) in experiment 2 of zebra plant (*Tradescantia zebrina*) 'Burgundy'. Mean separation based on Tukeys' HSD $\alpha \leq 0.05$.

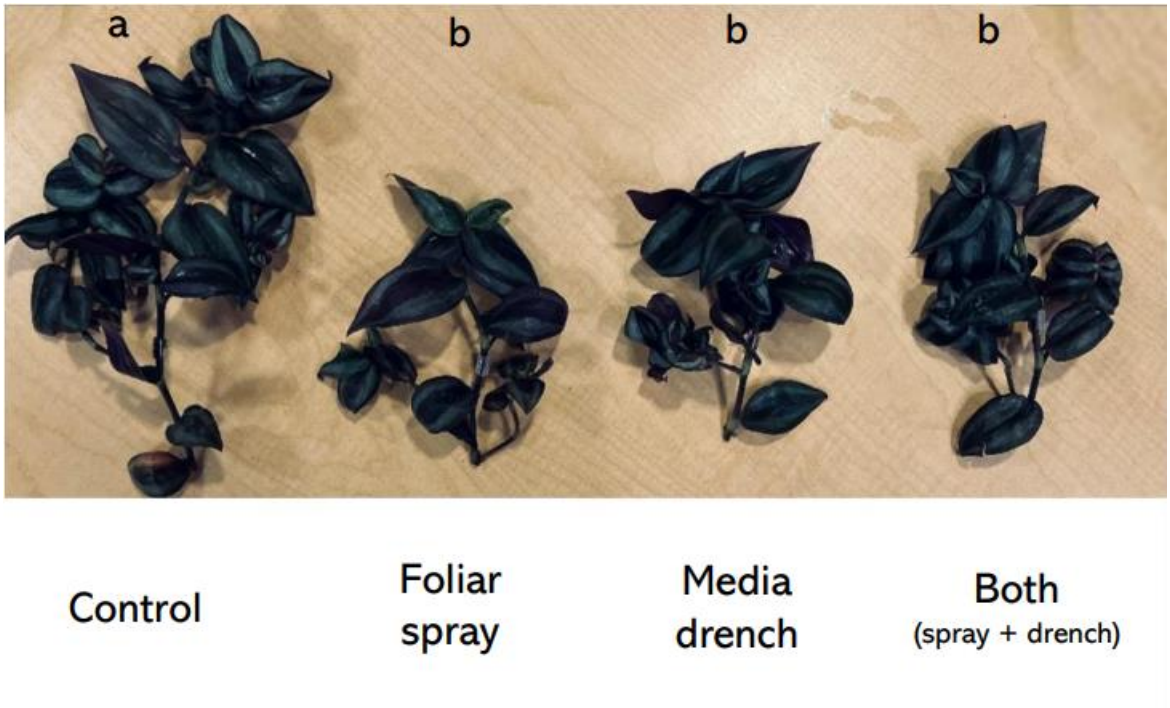


Table 2.1. Change in internode and stem length and monthly stem growth rate across treatments in Experiment 1. Significance levels of the factorial treatment structure are shown for spiderwort selection (zebra plant, zebra plant 'Burgundy', inch plant), chemical application (ancymidol as foliar spray (A), paclobutrazol as foliar spray (P), or paclobutrazol as drench (D); application abbreviated appl'n), chemical concentration (control (C), low (L), medium (M), high (H)), and their interactions. Significant treatments ($\alpha \leq 0.05$) have mean separation values shown.

		Δ Growth (cm)[z]		**Stem growth rate (cm/month)[y]**		
Treatment	**Abbreviation**	**D29-0 Δ internode length**	**D85-0 Δ stem length**	**D0-29 Stem growth rate**	**D29-57 Stem growth rate**	**D57-85 Stem growth rate**
Significance Levels[x]						
Spiderwort selection		***	**	**	**	**
Chemical appl'n		**	NS	NS	NS	NS
Concentration		***	***	***	***	***
Spiderwort x chemical appl'n		NS	NS	NS	NS	NS
Spiderwort x concentration		***	NS	**	**	NS

Chemical appl'n x concentration		**	NS	NS	NS	NS
Spiderwort x chemical appl'n x concentration		NS	NS	NS	NS	NS
Spiderwort selection						
zebra plant		2.27a[w]	13.85b	7.85b	2.48b	2.94b
zebra plant 'Burgundy'		1.95b	13.23b	7.57b	2.58b	2.71b
inch plant		1.75b	17.96a	8.96a	3.85a	4.83a
Chemical application						
ANC foliar spray	A	2.16a	14.98	8.38	2.85	3.43
PBZ foliar spray	S	1.87b	15.63	8.00	3.01	3.58
PBZ media drench	D	1.94ab	14.44	8.01	3.04	3.49
Concentration						
Control	C	2.95a	23.48a	11.41a	4.28a	6.13a
Low rate	L	2.08b	14.93b	7.74b	3.01b	3.26b

Medium rate	M	1.52c	11.82bc	7.36bc	2.71bc	2.34b
High rate	H	1.41c	9.84c	6.00c	1.86c	2.26b
Tradescantia x concentration						
zebra plant	C	3.46a	21.88	11.15ab	3.83abc	4.91
zebra plant	L	2.30b	14.95	7.74bcdef	2.63abc	3.21
zebra plant	M	1.78bcde	9.67	6.49def	2.16bc	1.75
zebra plant	H	1.53cde	8.93	6.00ef	1.29c	1.90
zebra plant ‘Burgundy’	C	3.32a	25.00	12.67a	4.84a	7.12
zebra plant ‘Burgundy’	L	1.83bcde	12.94	7.00def	2.47abc	2.46
zebra plant ‘Burgundy’	M	1.42e	8.11	5.71ef	1.49b	0.86
zebra plant ‘Burgundy’	H	1.23e	6.89	4.92f	1.51b	0.42
inch plant	C	2.08bcd	23.56	10.42abc	4.17ab	6.37

inch plant	L	2.11bc	16.90	8.51bcde	2.63ab	4.11
inch plant	M	1.36e	17.68	9.86abcd	2.16ab	4.40
inch plant	H	1.47de	13.69	7.06cdef	2.77abc	4.46
Chemical appl'n x concentration						
A	C	2.96a	20.73	11.38	3.83	5.01
A	L	2.67a	18.04	8.54	2.93	3.83
A	M	1.54b	11.88	7.57	3.05	2.56
A	H	1.48b	9.26	6.01	1.58	2.31
S	C	2.86a	25.53	11.08	4.41	6.13
S	L	1.67b	13.11	7.60	3.34	3.04
S	M	1.56b	13.47	7.19	2.57	2.99
S	H	1.40b	10.42	6.11	1.82	2.14
D	C	3.04a	24.18	11.80	4.61	7.26
D	L	1.91b	13.63	7.11	2.76	2.89
D	M	1.43b	10.12	7.30	2.52	1.46
D	H	1.35b	9.84	5.87	2.16	2.33

[z] - Change in growth calculated by subtracting internode (day 29) or stem length (day 85) from the initial internode and stem lengths on day 0. 1 cm = 0.3937 inch.

[y] - Change in growth calculated between time intervals by subtracting the length at the larger time by the shorter time, e.g., D0-29 would be the stem length at day 29 of the experiment minus the stem length at day 0.

[x] - NS ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$)

[w] - Mean separation values

Table 2.2. Day (D) zero and D85 stem length and change in stem length over three months for each treatment, Spiderwort selection (zebra plant, zebra plant 'Burgundy', inch plant) x chemical application (ancymidol as a foliar spray, paclobutrazol as a foliar spray, paclobutrazol as a media drench) x concentration, for experiment 1. This three-way interaction was not significant for any of the parameters.

					Stem growth (cm)		**Stem growth rate[z] (cm/month)**		
Spiderwort selection	**Chemical**	**Treatment**	**Rate ($mg \cdot L^{-1}$)[y]**	**D0 Stem length**	**D85 Stem length**	**D85-0[x] Stem length**	**D0-29 Growth rate**	**D29-57 Growth rate**	**D57-85 Growth rate**
zebra plant	Control	Spray	0	15.5	37.1	21.5	10.3	2.6	4.0
	Ancymidol	Spray	25[w]	16.0	31.2	15.2	6.6	3.1	2.7
			100	15.2	27.2	12.1	8.6	3.0	2.8
			200	15.7	28.4	12.7	7.7	2.3	4.7
	Paclobutrazol	Spray	20[v]	16.6	29.0	12.4	8.0	2.3	3.0
			80	16.0	23.5	7.5	5.13	1.4	1.4
			160	15.1	22.4	7.3	4.8	0.9	1.3

	Control	Drench	0	15.2	36.4	21.2	12.6	5.8	6.2
	Paclobutrazol	Drench	1	14.7	29.5	14.8	7.5	2.5	3.4
			4	15.3	25.4	10.1	7.4	3.0	1.4
			8	14.8	22.7	7.8	5.5	1.3	1.1
zebra plant ‘Burgundy’	Control	Spray	0	13.7	26.8	13.1	11.3	5.1	6.1
	Ancymidol	Spray	25[w]	13.5	36.1	22.7	10.48	4.2	5.6
			100	13.3	20.3	7.4	5.8	1.2	1.0
			200	13.6	20.3	6.7	5.24	1.3	0.6
	Paclobutrazol	Spray	20[v]	11.8	19.5	7.8	5.2	1.8	0.2
			80	13.7	22.6	8.9	6.2	2.2	0.7
			160	12.9	18.8	5.9	4.7	1.6	0.4
	Control	Drench	0	13.4	41.3	27.8	13.9	5.6	9.8
	Paclobutrazol	Drench	1	14.8	24.5	9.7	6.4	2.5	1.6

			4	13.3	20.8	7.4	5.7	2.2	0.5
			8	12.3	18.8	6.5	4.5	1.6	0.4
inch plant	Control	Spray	0	16.6	41.3	24.7	11.1	4.2	6.3
	Ancymidol	Spray	25[w]	17.7	34.2	16.5	8.0	2.0	3.5
			100	16.8	32.4	15.6	9.8	5.7	4.6
			200	17.1	25.4	8.3	6.1	1.8	2.8
	Paclobutrazol	Spray	20[v]	15.6	34.2	18.6	10.7	7.4	7.2
			80	17.8	41.5	23.7	10.2	4.3	6.1
			160	16.4	33.9	17.5	8.5	3.4	5.5
	Control	Drench	0	16.7	39.5	22.8	10.1	3.1	7.9
	Paclobutrazol	Drench	1	16.6	35.1	18.5	7.9	3.6	3.0
			4	15.2	28.2	13.1	10.5	4.0	2.1
			8	16.2	30.5	14.3	7.0	3.8	6.8
Prob > F				ns	ns	ns	ns	ns	ns

[z] – Change in growth calculated between time intervals by subtracting the length at the larger time by the shorter time, e.g., D0-29 would be the stem length at day 29 of the experiment minus the stem length at day 0.

[y] – 1 mg•L^{-1}= 1 ppm

[x] - Change in growth calculated by subtracting stem length (day 85) from the initial stem lengths on day 0. 1 cm = 0.3937 inch.

[w] - recommendation from commercially available PGR information (Whipker, 2021)

[v] - recommendation from commercial growers (Green Circle Growers, Oberlin, OH)

Table 2.3. Day (D) zero and D84 stem length and change in stem length over three months for zebra plant (*Tradescantia zebrina*) 'Burgundy' for each paclobutrazol treatment in experiment 2.

			Stem growth (cm)			Stem growth rate (cm/month)[z]		
Cultivar	**Treatment**	**Rate of paclobutrazol**	**D0 Stem length**	**D84 Stem length**	**D84-0[y] Stem length**	**D0-28 Growth rate**	**D28-56 Growth rate**	**D56-84 Growth rate**
zebra plant 'Burgundy'	Control	0 mg•L^{-1} [x]	22.59a[w]	32.32a	10.24a	5.57a	2.91a	1.76a
	Subirrigation	1 mg•L^{-1} x 4 applications	22.39a	27.10b	4.71b	3.10b	1.40b	0.52b
	Spray	80 mg•L^{-1}	22.08a	25.72b	3.13b	2.70b	1.11b	0.50b
	Subirrigation + Spray	1 mg•L^{-1} x 4 applications & 80 mg•L^{-1}	21.18a	25.8b	4.62b	2.15b	0.72b	0.27b

[z] – Change in growth calculated between time intervals by subtracting the length at the larger time by the shorter time, e.g., D0-29 would be the stem length at day 29 of the experiment minus the stem length at day 0.

[y] – Change in growth calculated by subtracting stem length (day 84) from the stem lengths on day 0. 1 cm = 0.3937 inch.

[x] - 1 ppm = $mg \cdot L^{-1}$

[w] – Mean separation values were calculated with Tukey's HSD ($\alpha \leq 0.05$).

Table 2.4. Chemical costs per pot for each treatment used in experiments 1 and 2 based on chemical costs in July 2022

Chemical	Ancymidol Spray[z]			Paclobutrazol Drench[y]				Paclobutrazol Mix	Paclobutrazol Spray		
mg•L^{-1} [x]	25	100	200	1	1 x 4 appl'n	4	8	80 + 1 x 4 appl'n	20	80	160
$ / pot	0.096	0.383	0.766	0.001	0.004	0.003	0.005	0.018	0.003	0.014	0.029

[z] - A-Rest (SePRO Corp., Carmel, IN)

[y] – Pac-O (OHP Inc., Bluffton, SC)

[x] - 1 mg•L^{-1} = 1 ppm

Chapter 3 - Treatment of Pothos and Philodendron with Paclobutrazol Does Not Affect Leaf Darkening or Stem Elongation Across Light Levels in an Interior Green Wall

Introduction

Interiorscape plantings are becoming more common in workplaces around the world. Companies are beginning to recognize the benefits of having plants displayed and they are commonly used as focal points in these locations (DelPrince 2013). As plants become more prevalent in workplaces, studies have documented the popularity of certain species commonly used in interiorscapes. Chatakul and Janpathopong (2022) found that pothos (*Epipremnum aureum)* and other vining aroid species like *Philodendron* and *Monstera* were popular. Species in each of these genera come in a variety of leaf patterns and colors, especially *Epipremnum* and *Philodendron*. Pothos and heartleaf philodendron (*Philodendron scandens*) are also common species used in vertical green walls. However, these plants are not without their drawbacks. One issue with using chartreuse or variegated varieties of philodendron and pothos in interior environments is the darkening of green foliage and loss of leaf variegation over time. Under low light conditions, variegated and neon plants tend to lose their vibrant variegation and neon color to cope with low light levels (McConnell et al. 2021). To maintain the aesthetic design elements, professional interiorscapers must replace the plants, leading to increased maintenance costs. Another issue with vining species is that they must be periodically pruned to maintain the aesthetic, which can be a time-consuming and costly task, as green walls typically cover a large area (Fediw 2015).

Several species of trailing aroids are used commonly in interiorscapes, including pothos and heartleaf philodendron. In commercial production, each of these species is grown under light conditions ranging from 220 to 440 μmol•m^{-2}•s^{-1} (Griffith 1998). They are generally grown as hanging baskets, though potted production ranging in container size from 3 to 6 in. is common (Griffith 1998). In interiorscapes, pothos and heartleaf philodendron will tolerate light levels of 7 to 11 μmol•m^{-2}•s^{-1}, though new leaves will be smaller and loose variegation and leaf color, so levels of at least 22 μmol•m^{-2}•s^{-1} are preferred (McConnell et al. 2018, McConnell et al. 2021). Plants should be maintained at 15.5 to 29.4˚C and the media should be allowed to dry between waterings (Griffith 1998).

Anti-gibberellins are a group of plant growth regulators (PGRs) that block plant's ability to synthesize the hormone gibberellic acid (GA). Many types of anti-gibberellin PGRs are used during commercial production of aroid species, but limited research has been published on their use with pothos and heartleaf philodendron. Whipker (2021) recommends a spray application of ancymidol of 25-132 mg•L^{-1}, a daminozide foliar spray of 2500-7500 mg•L^{-1}, or a 4-6 mg•L^{-1} media drench of paclobutrazol to control growth of pothos. For heartleaf philodendron, it is recommended that ancymidol be applied as a foliar spray at 25-132 mg•L^{-1} and as a media drench at 2-4 mg•L^{-1}, chloromequat chloride foliar spray at 3000 mg•L^{-1}, and daminozide foliar spray at 2500-7500 mg•L^{-1}. Frank and Donnan (1975) recommend applications of ancymidol at a rate of 0.625 mg/ft^2 for pothos and a rate of 1.25 mg/ft^2 for heartleaf philodendron.

Paclobutrazol is a PGR that blocks the conversion of ent-kaurene to ent-kaurenoic acid in the GA synthesis pathway (Hedden and Graebe 1985). A primary reason growers apply anti-gibberellins to a crop is to achieve a more compact size when shipped. This happens as anti-gibberellins mitigate the effects of gibberellins, which promote cells to elongate after division

occurs. Thus, anti-gibberellins do not stop cell division; they reduce the elongation of newly formed cells, which reduces overall stem length (Desta and Amare 2021). Paclobutrazol (PBZ) is used on many ornamental crops to achieve desired compactness for sale, including cut flower *Dianthus* (Bañon et al. 2002) and potted *Zinnia* (Rossini Pinto et al. 2005).

Another side effect of paclobutrazol application is the increased production of phytyl, a component of chlorophyll (Desta and Amare 2021). Whipker (2021) states that blocking the production of ent-kaurenoic acid is like "damming a river." The extra phytyl created by this blockage is a precursor in the production of chlorophyll, leading to greener leaves in the plant. Another hypothesis for the increases in plant "greenness" in the plants is similar to the growth limiting effects of paclobutrazol. Treated plants produce similar amounts of chlorophyll compared to their untreated counterparts, but the inhibition of cell elongation results in the same amount of chlorophyll in a smaller area, leading to plants that appear greener (Khalil and Rahman 1995).

Several formulations of PBZ are commercially available, including Pac-O (OHP Inc., Bluffton, SC) and Bonzi (Syngenta, Basel, Switzerland). These chemicals contain 0.04% active ingredient; however, according to the label, only Bonzi can be applied in interiorscapes, provided the proper PPE is worn by the applicator and no layperson comes in contact with the active ingredient until after the 12-hour re-entry interval is met. Pac-O does not support application in interiorscapes. That said, PGRs can be applied by growers or wholesalers prior to shipment and/or installation into an interiorscape and the growth limiting and chlorophyll concentrating side effects of PBZ will be in the pot and plant upon installation into a site.

Our objective was to determine whether the anti-gibberellin PBZ could be used to slow the stem elongation of pothos and heartleaf philodendron. Secondly, we sought to determine

whether use of PBZ would slow the rate of neon coloration in chartreuse leaves of ‘Neon’ and ‘Lemon Lime’ cultivars of these aroid species.

Materials and Methods

We conducted two experiments with *Epipremnum aureum* and one experiment with *Philodendron scandens* using the interior modular living wall system (Versa Wall, GSky, Delray Beach, FL) in a common area of Throckmorton Plant Sciences Center at Kansas State University (KSU), Manhattan, KS, USA. Our first experiment (Expt. 1) occurred from 11 Apr to 4 July 2022 using only ‘Neon’ pothos (*E. aureum* ‘Neon’), and our second experiment (Expt. 2) occurred from 15 Aug to 7 Nov 2022 using ‘Neon’ pothos and ‘Marble Queen’ pothos (*E. aureum* ‘Marble Queen’) and ‘Lemon Lime’ philodendron (*P. scandens* ‘Lemon Lime’).

Plant material. For Expt. 1, ‘Neon’ pothos plants were purchased from The Plant Factory, LLC (Greenwood, MO, USA) on 5 Apr 2022. In Expt. 2, we took cuttings of ‘Neon’ pothos, ‘Marble Queen’ pothos and ‘Lemon Lime’ philodendron, taken from plants in the KSU Horticulture Foliage Plant Collection, on 13 and 27 May 2022. Cuttings were stuck into BX General Purpose Growing Media (Premier Horticulture Inc.; Quackerton, PA, USA) filled 4-in terracotta-colored, 375 mL plastic pots (Pöppelman Plastics USA LLC, Claremont, NC, USA). Four cuttings were placed in each pot in Expt. 2. The cuttings were rooted and subsequently grown under 52% white shade cloth (PAK Unlimited, Inc., Cornelia, GA) in a glass greenhouse at Kansas State University. Average light levels under production were 158 μmol•m^{-2}•sec^{-1} and temperature setpoints for the greenhouse were 25°C D: 22°C N.

During production, we overhead irrigated plants with 200 mg•L^{-1} N from 20N-4.3P-16.6K (Compass Minerals, Overland Park, KS, USA). Before installation, we applied 4 g of controlled release fertilizer (15N-3.87P-9.96K; OsmocotePLUS, Scotts MiracleGro, Marysville,

OH, USA) to each pot and then watered in the controlled release fertilizer with municipal water to bring all plants to the same water status prior to installation. All plants were distributed in the interior green wall, with 36 plants per row and 14 rows, installed by Ambius (Wyomissing, PA, USA) in 2015.

Experiment 1. We applied PBZ to 'Neon' pothos plants. We established four treatments of a 0 mg•L^{-1} control, a subirrigation treatment of 1 mg•L^{-1} PBZ applied at each irrigation event (days 0, 23, 51, and 78 after installation), a foliar spray of 80 mg•L^{-1} PBZ applied before plant installation into the wall, and a combination of a 1 mg•L^{-1} PBZ subirrigation treatment during irrigation events, and an 80 mg•L^{-1} PBZ foliar spray. To simulate green wall irrigation with a PGR without affecting other treatments, we removed plants in the subirrigation treatment from the green wall and placed them in a flat with 2000 mL of the treatment PGR solution, allowed the plants to absorb for 1 hr, and replaced them in the green wall every time the wall was irrigated. In the foliar spray treatment, 17 mL of the treatment solution was applied to each plant two days prior to installation in the green wall. Control plants had 17 mL of RO water applied via foliar spray. Experimental plants were placed in the wall in randomized complete block design with light intensity as the primary blocking factor. Plants were separated into eight blocks based on differences in light intensity and irrigation. Each of the eight blocks had four pots (1 species x 4 PGR treatments) for a total of four plants per block and 32 experimental plants.

Experiment 2. We used PBZ on *E. aureum* 'Neon' and 'Marble Queen' and *P. scandens* 'Lemon Lime'. We assessed four chemical treatments including a 0 mg•L^{-1} control, and three media drenches at 4 mg•L^{-1} PBZ, 12 mg•L^{-1} PBZ, and 24 mg•L^{-1} PBZ. For chemical applications, plants were drenched with 60 mL of the assigned concentration of PBZ. Control plants were drenched with 60 mL of reverse osmosis (RO) water.

As well as PGR treatment, light intensity was a treatment factor in Expt. 2. Prior to the onset of the experiment, a light meter (LI-250 Light Meter, LI-COR; Lincoln, NE, USA) was used to measure the light intensity at each pot location in the green wall (Figure 3-1A). From this data, twelve regions with low variance in light levels were selected (Figure 3-1B). From these, three light levels were designated: low (3.46- 4.95 $\mu mol \bullet m^{-2} \bullet s^{-1}$), medium (7.13-9.80 $\mu mol \bullet m^{-2} \bullet s^{-1}$), and high (15.50-19.32 $\mu mol \bullet m^{-2} \bullet sec^{-1}$). Four blocks of each light level were established in the wall. We used a split-plot design with light as the main plot and subplots were randomized as cultivar and PGR treatments. We established four blocks in each of three light level treatments based on differences in irrigation. Each of the four blocks within a light treatment had one of each treatment (3 species x 4 PGR treatments) for a total of 12 plants per block and 144 plants total. Remaining plants in the green wall were filled with a mix of the same plant species.

Green wall light, temperature, and irrigation. HOBO Pendant MX Temperature/ Light Data Logger MX2202s (Onset Computer Corp.; Bourne, MA, USA) were used to measure temperature and light intensity of the green wall at 15-minute intervals for the duration of the experiment. We determined irrigation timing using eight randomly selected sentinel pots in various locations throughout the wall. The weight of each pot at container capacity was recorded and averaged with the other sentinel plants. When the average weight of the sentinel pots reached 70% (+/- 5%) of the container capacity, the irrigation system was turned on for 1 hr using a Hunter X-Core Irrigation Controller (Hunter Industries; San Marcos, CA, USA). After the irrigation system had finished running for 30 min, we remeasured weights of the same eight sentinel pots. We ran the green wall irrigation system on days 0, 23, 51, and 78 after installation (DAI) in Expt. 1 and on days 11, 30, 53, and 72 DAI in Expt. 2.

Data collected. Selected leaf Soil Plant Analysis Development (SPAD) measures (Expt. 1 and 2) and total stem length (Expt. 2) were measured on 0, 14, 28, 42, 56, 70, and 84 DAI for both experiments. We marked individual leaves and stems with silicone tomato grafting clips (Hydro-Gardens, Colorado Springs, CO, USA) for repeated measures. We selected the first fully expanded leaves from two stems in each pot for measurement. These leaves were marked for repeated measures on each data collection. SPAD measurements were taken with a SPAD-502 meter (Spectrum Technologies, Inc., Aurora, IL, USA) on three leaf regions; left and right of the midvein at the base of the leaf and at the leaf tip (Figure 3-2). These three measurements were averaged to obtain average SPAD reading for each leaf. SPAD measurements were taken on both 'Neon' pothos and 'Lemon Lime' philodendron. Total stem lengths were measured on two stems in each pot from the edge of the pot to leaf tip, and we marked selected stems for data recollection. Stem measurements were obtained from all three cultivars.

Statistical analyses. We assessed variance of the factorial treatment structure for each experiment using JMP Pro ver. 16.0.0 (SAS Institute Inc., Cary, NC). We used one-way analysis of variance to quantify differences between control and treated plants in Expt. 1. Differences between cultivar SPAD measurements were determined with a Student's t-test. All other analyses were conducted with Tukey's HSD. We conducted all analysis at the 0.05 significance level.

Results and Discussion

Experiment 1. Treated plant SPAD measurements were different from the control at the D84-0 SPAD measurement and month 1 SPAD change rate (Table 3-1). Each of the PGR treatments were not significantly different, showing there was no compounding effect of the 80 $mg•L^{-1}$ foliar spray + 1 $mg•L^{-1}$ subirrigation PGR treatment from the 80 $mg•L^{-1}$ foliar spray and 1

mg•L^{-1} subirrigation treatment (Table 3-1). When comparing control to treated plants, there was a significance in the blocking effect (P=0.02) for the change in SPAD readings (D84-0), leading us to believe that light was a factor in the variable effects of SPAD green up. This led us to make light level a treatment factor in Expt 2.

Experiment 2. SPAD measurements varied for each treatment (Table 3-2), with the Royal Horticultural Society (RHS) Colour Chart color codes corresponding to each range of leaf colors (Figure 3-3). Both cultivars reacted to the combination of PGR treatments and light treatments differently, though no interaction between PGR and light was observed. At the end of the experiment, pothos plants were greener than philodendron at the D84-0 time period (Table 3-3). Chlorophyll concentration per month was also greater in pothos plants than philodendron, but especially in months two and three (Table 3-3). In 2-wk time periods, changes in SPAD were different between both cultivars at the D28-42 and D42-56 intervals (Figure 3-4), with pothos leaves having a greater change in SPAD that philodendron.

Our medium PBZ application rate (12 mg•L^{-1}) resulted in greater SPAD measurements between D84-0 SPAD measurements than from control (0 mg•L^{-1}) and the low-application rates (4 mg•L^{-1}). At D0-28, low application rates (4 mg•L^{-1}) provided a significant difference in SPAD measurements than the high application rates (24 mg•L^{-1}) (Table 3-3). Though not significant, our 4 mg•L^{-1} PBZ application rate resulted in slower green up in these cultivars.

Light treatments were only effective in the first month, where SPAD measurements at low and medium light treatments were significantly lower than SPAD measurements in high light treatments (Table 3-3). Though not significant, low light treatments generally resulted in d lower rates of leaf darkening. Light is necessary for chlorophyll biosynthesis, so the lowest light treatment may not have been bright enough to induce a chlorophyll production response (Liu et

al. 2017). Although we denoted our light treatments as low, medium, and high, the highest light levels were still below the lowest recommendations for pothos and philodendrons in interiorscapes (McConnell et al. 2018, McConnell et al. 2021).

In the first two weeks (D0-14), *E. aureum* 'Neon' stems grew more than *E. aureum* 'Marble Queen' and *P. scandens* 'Lemon Lime' stems. We did not observe differences in biweekly growth for days 14-70. At the 70-84 time interval, however, *E. aureum* 'Marble Queen' stems grew longer than *P. scandens* 'Lemon Lime' stems (Table 3-4, Table 3-5, Figure 3-5). PGR concentration did not significantly affect stem length at any time interval (Table 3-5). Even at three and six times the recommended rate for growth control, there were no significant differences in chemical treatment for controlling stem elongation. In the day 70-84 time interval, plant stems in high light treatments were longer than those in the low light treatments (Table 3-5), which was unexpected. For all three cultivars, McConnell et al. (2018, 2021) recommends light levels between 220 to 440 $\mu mol \bullet m^{-2} \bullet s^{-1}$ to produce high quality plants.

There was a significant interaction between cultivar and light in D84-0 growth (Table 3-5). 'Marble Queen' plants in the medium light treatment group were significantly longer than 'Marble Queen' plants exposed to low light treatment (Figure 3-6, Figure 3-7). These differences were likely due to differences in variegation, with the medium light treated plants being slightly less variegated than their low-light treated counterparts. Under lower light conditions, new leaves tend to grow with lower levels of variegation, whereas those grown in higher light levels have more variegation (McConnell et al. 2021). Plants with less chlorophyll and more variegation, tend to grow faster than those with more chlorophyll and less variegation.

For the control of chlorophyll concentration in chartreuse aroid species, the use of a 4 $mg \bullet L^{-1}$ media drench of paclobutrazol or maintaining light levels between 3.5-5.0 $\mu mol \bullet m^{-2} \bullet sec^{-1}$

can be used to slow greening, but not differently from other PGR application or lighting conditions. A combination of these two factors may not be as effective, as there were no significant interactions between these treatments. Chemical application did not control stem growth differently than the control, however, plants held at light levels between 3.46- 4.95 $\mu mol \bullet m^{-2} \bullet sec^{-1}$ tended to be shorter than those in other light regiments.

Though our results were not significant, there are other methodologies that could control growth of aroids. Application of different qualities of light at night, outside of hours of operation, could be a way to control stem elongation in green walls. Application of a higher blue light fraction has been seen to decrease shoot fresh weight in lettuce (Meng and Runkle 2023), therefore limiting the growth capacity of these plants.

Other active ingredients of plant growth regulators could also be explored. Chemicals containing uniconazole (Concise, Sumagic) could be used to control growth, but there is a concern for phytotoxicity. Other PGRs, such as chlormequat chloride or daminozide, can be tested. The drawback of these ingredients is that they tend to be less effective than other ingredients, however, there is less likelihood of phytotoxicity occurring (Whipker 2021).

Figure 3.1. (A) Light readings for each pot location in the green wall (µmol•m^2•s), measured with a calibrated light meter. Outlines denote blocks of minimal variance we used as a treatment in experiment 2. (B) Locations of research plants in experiment 2, determined by regions of similar light levels.

A

1.3	1.7	3.4	5.0	7.5	8.1	10.2	12.3	12.0	9.3	7.1	6.1	5.7	6.1	9.0	9.1	12.4	15.4	19.3	17.5	15.7	16.0	15.5	15.0	12.5	10.0	6.8	4.9	3.4	2.4	2.0	1.7	1.5	1.4	1.4	1.5
1.9	2.9	4.1	5.4	7.1	7.4	9.4	13.8	16.4	15.5	12.3	11.3	10.4	10.6	8.9	8.1	7.2	7.8	11.7	16.6	16.4	16.9	15.7	16.1	15.6	13.2	10.6	7.8	5.5	3.6	2.4	2.0	1.8	1.7	2.0	3.3
3.0	4.8	4.4	4.7	4.5	9.1	13.0	15.6	17.9	18.2	18.9	17.0	15.3	14.3	11.1	8.4	6.0	6.2	8.5	12.5	14.1	15.9	14.8	16.9	16.8	15.5	13.8	11.8	7.9	5.1	3.5	2.7	2.3	2.3	3.4	4.7
4.3	6.1	5.7	8.0	8.6	9.6	12.6	16.4	17.7	19.6	21.3	20.5	18.2	15.7	12.8	9.3	6.5	5.2	5.6	9.8	9.3	14.2	15.8	16.9	17.3	16.8	15.4	13.7	11.0	7.3	5.2	4.0	3.4	3.5	4.4	5.1
5.6	7.9	9.0	10.7	9.2	10.8	14.0	16.1	18.0	19.7	21.9	21.0	19.6	15.8	13.1	9.6	7.0	5.3	4.6	6.1	8.0	10.5	12.9	14.8	16.2	16.2	15.9	15.8	13.5	9.3	7.1	5.3	4.6	4.3	4.8	4.8
7.3	9.0	9.8	10.4	10.9	11.4	13.8	14.6	17.1	17.8	20.2	20.5	17.8	15.7	11.9	9.6	6.6	5.1	4.6	4.8	6.1	8.9	10.9	13.4	15.5	15.4	16.1	15.9	13.6	11.1	8.7	7.3	5.5	4.6	4.0	4.4
8.1	9.6	10.0	11.0	10.1	11.7	13.7	13.6	13.9	16.6	17.5	17.6	16.0	14.3	11.5	9.2	6.1	4.8	4.4	4.4	4.6	7.4	9.2	12.7	13.5	14.1	15.4	15.3	13.5	11.7	9.3	7.7	6.1	4.5	4.3	3.7
8.2	8.9	9.8	10.1	10.5	10.4	9.9	10.2	13.0	13.1	14.2	14.4	13.1	12.4	10.3	7.8	5.7	4.7	3.7	4.2	4.2	5.5	7.4	10.5	12.8	13.9	10.6	9.2	12.1	11.2	9.1	7.2	6.0	4.7	3.5	4.2
7.1	8.7	9.0	9.8	9.3	9.2	8.4	9.4	8.2	6.9	10.4	10.5	10.6	9.0	7.9	6.7	4.9	4.0	3.8	3.8	3.9	4.9	6.5	7.6	8.8	9.0	12.7	8.1	12.0	10.2	9.1	7.6	6.2	4.8	4.5	3.1
7.0	7.8	7.9	8.0	8.3	7.8	8.6	8.0	6.1	5.1	8.0	7.7	7.7	7.3	6.3	5.2	4.3	3.7	3.5	3.4	2.8	4.8	6.3	6.0	6.8	6.6	7.5	6.9	10.2	8.8	7.9	7.0	5.4	4.4	3.9	3.1
5.6	6.6	7.0	7.1	7.6	7.1	6.9	6.6	5.0	5.8	6.0	5.9	5.9	5.3	5.0	4.5	3.8	3.7	3.3	3.6	3.3	4.7	5.5	7.1	7.6	7.8	8.9	8.3	7.6	7.6	7.6	6.0	5.2	4.2	3.2	3.0
5.4	5.8	6.4	6.7	5.9	6.5	6.2	5.6	5.2	4.9	5.1	4.2	4.5	4.3	4.9	3.8	3.4	3.5	3.2	3.3	4.1	4.4	5.1	5.4	6.6	6.9	7.6	7.2	6.6	6.5	6.0	5.1	4.3	3.6	3.7	3.0
4.9	5.3	5.1	5.7	5.7	5.7	5.5	4.9	4.4	4.3	4.3	4.2	3.9	3.8	3.7	3.8	3.4	3.7	3.3	3.3	3.0	4.0	4.5	4.9	3.6	4.0	6.1	5.5	6.7	5.6	4.7	4.2	3.8	4.1	2.8	3.2
4.5	4.3	4.9	5.1	5.5	4.9	4.7	3.8	4.0	3.7	3.7	3.5	3.2	3.3	3.3	2.9	3.0	3.2	3.4	3.8	4.1	3.3	3.3	4.4	5.2	5.3	5.5	5.7	5.6	5.6	5.4	4.9	4.5	4.0	3.9	3.2

B

Figure 3.2. *E. aureum* ‘Neon’ leaf showing where SPAD measurements were taken at each data collection date. Red regions denote areas where we took one SPAD measurement. We averaged each of the three SPAD readings to obtain the measurement on each leaf.

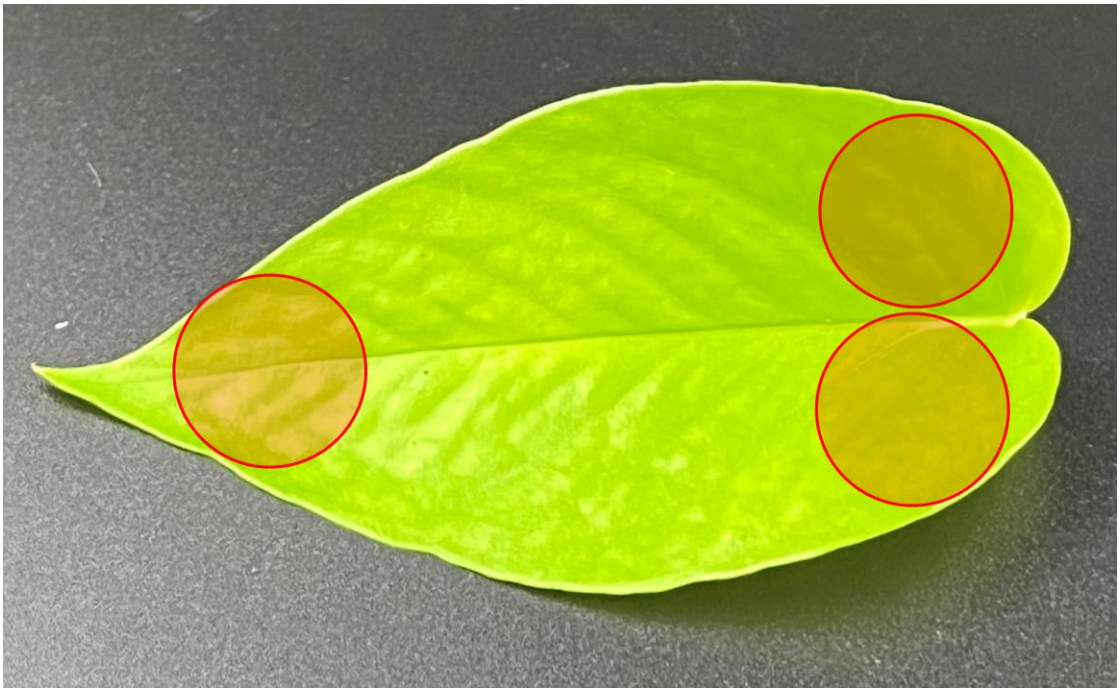


Figure 3.3. *Epipremnum aureum* ‘Neon’ (A) leaves and *Philodendron scandens* ‘Lemon Lime’ (B) leaves at ascending SPAD measurement ranges (upper value), with the adjoining RHS Colour Chart color codes (lower value) to match the leaf color.

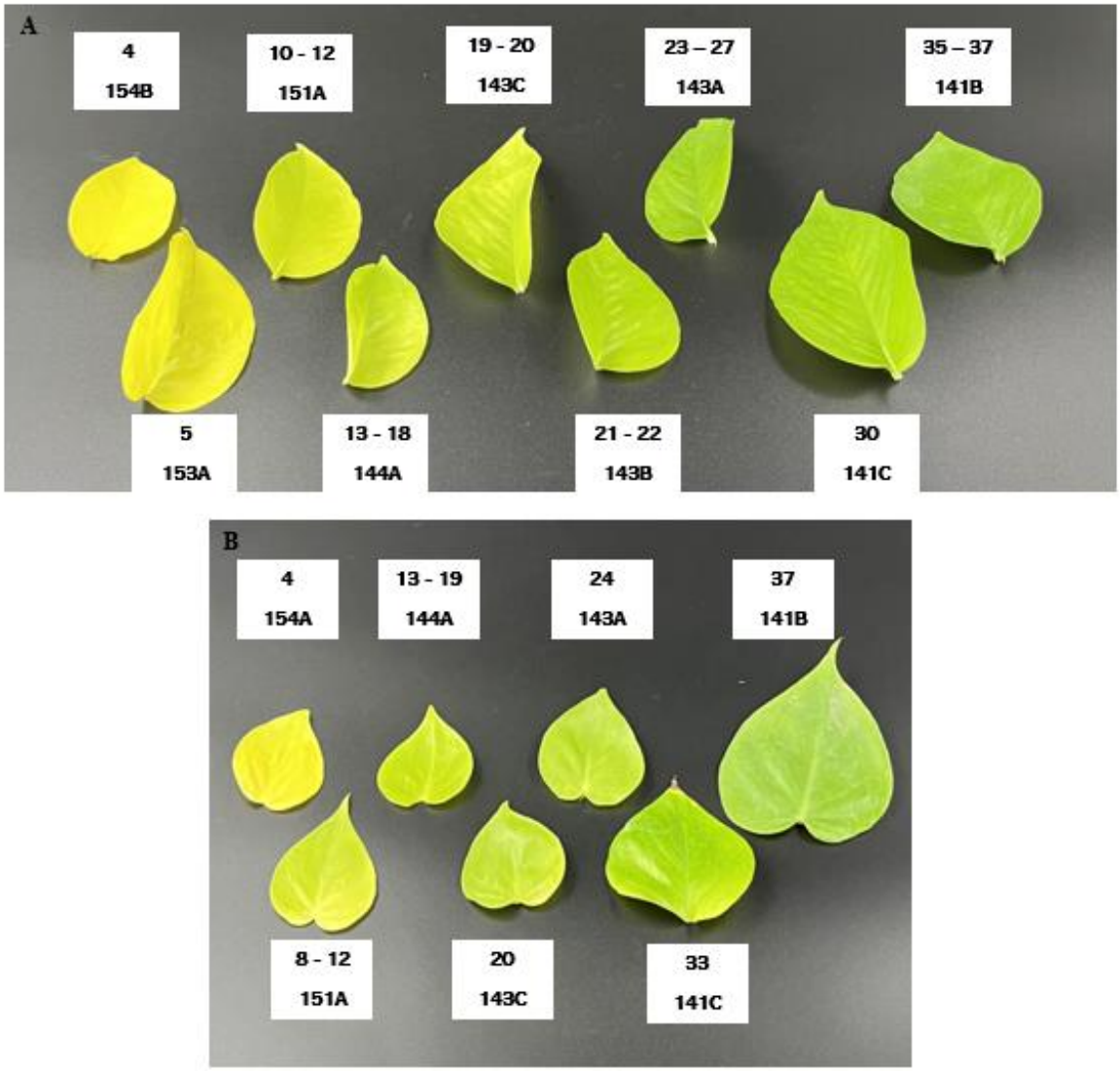


Figure 3.4. Species and cultivar differences in green-up over time. Two-week SPAD green up measurements are shown. Values shown are the amount each cultivar greened up in 14 days. Datapoint at day 28 is the difference between the SPAD measurement at day 28 and the SPAD measurement at day 14. Significance levels based on Student's t-test at $\alpha \leq 0.05$. Datapoints circled in red were significant at the $\alpha \leq 0.01$ level (**). All values not circled were not different from one another ($\alpha \geq 0.05$).

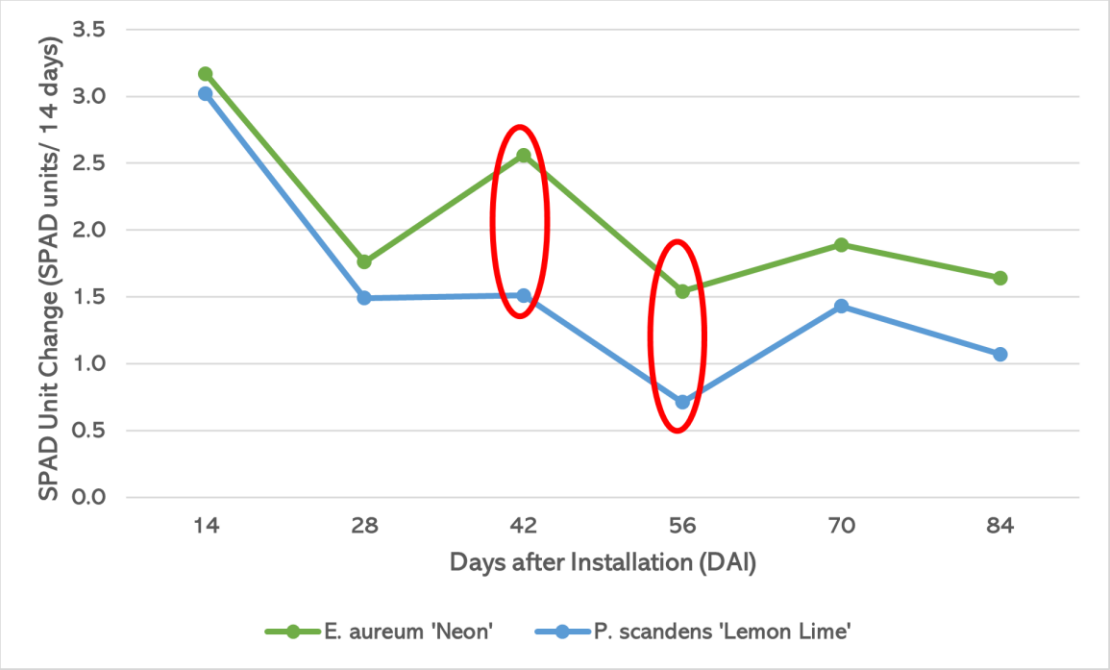
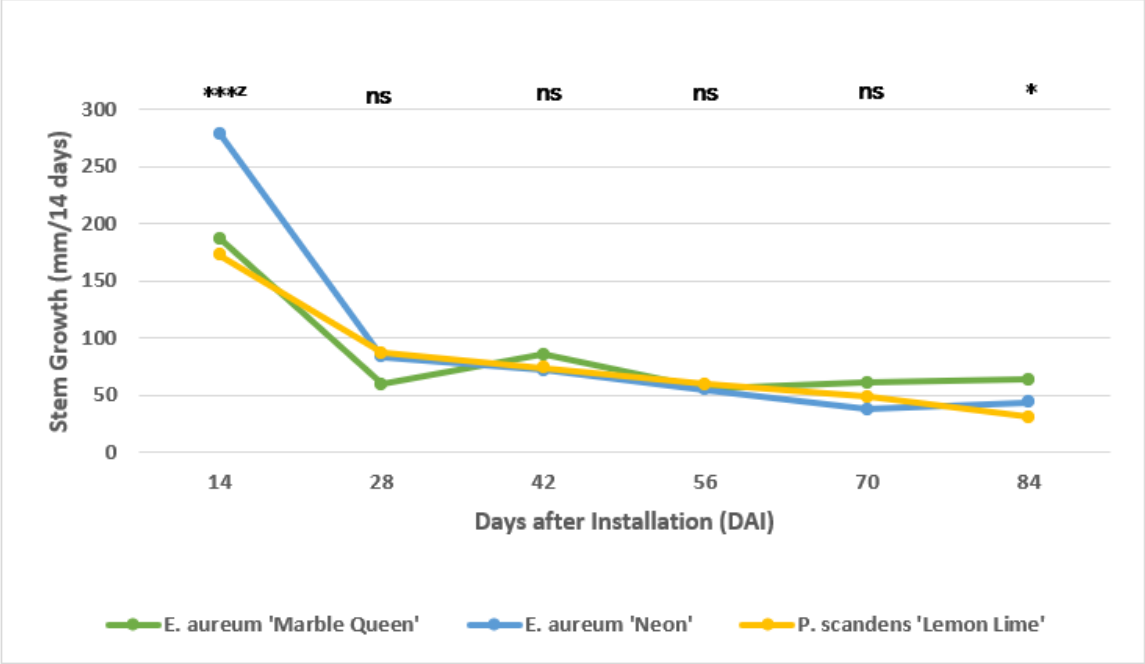


Figure 3.5. Stem length differences between cultivars at two-week intervals. Values shown are the amount each cultivar grew in 14 days. Datapoint at day 28 is the difference between the stem length at day 28 and the stem length at day 14 in mm. Significance levels at Tukey HSD $\alpha \leq 0.05$.



z - ns ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$)

Figure 3.6. Two-way interaction of chemical and light on *Epipremnum aureum* 'Neon' (A), *E. aureum* 'Marble Queen' (B), and *Philodendron scandens* 'Lemon Lime' (C) stem length at day 84 after installation. Columns of stems denote light treatment differences and rows denote PBZ treatment differences.

Figure 3.7. D84-0 stem lengths based on cultivar x light interactions. Cultivars are shown on the y-axis, with low light treatments shown by green bars, medium light treatments by blue bars, and high light treatments by yellow bars. Mean separation are shown at Tukey's HSD $\alpha \leq 0.05$.

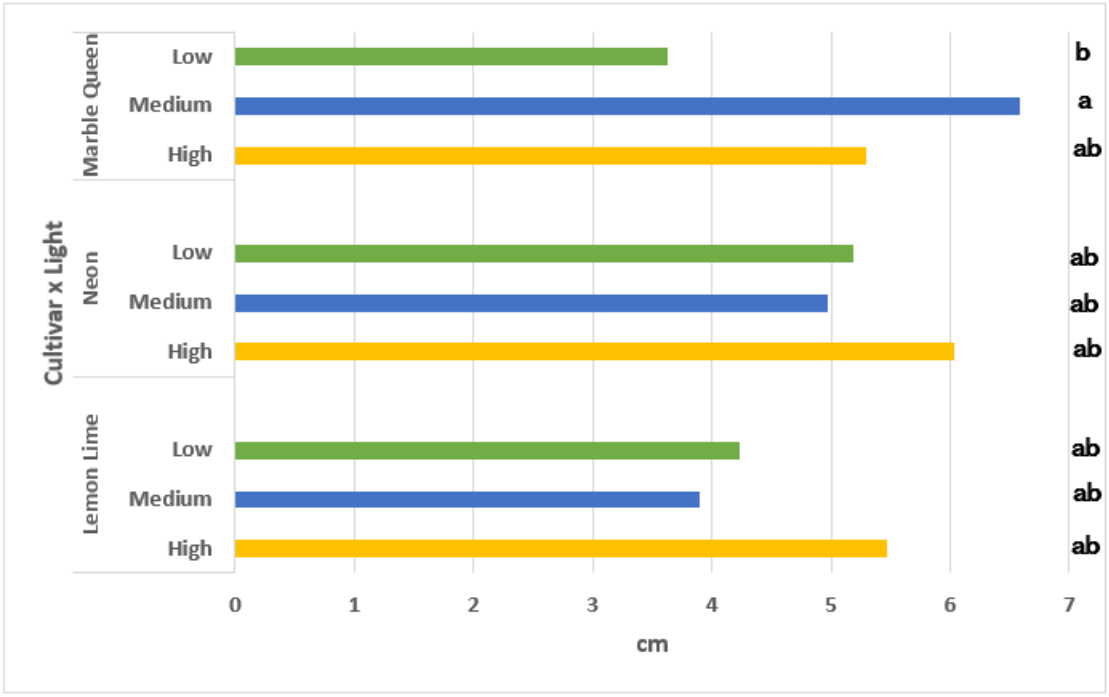


Table 3.1. SPAD measurement results for each treatment in Experiment 1 (n=14, two readings per e.u.). ANOVA was performed on each parameter separately at the $\alpha \leq 0.05$ significance level.

			SPAD readings (SPAD units)		Δ SPAD by month (SPAD units/month)[z]			
Cultivar	**Treatment**	**Rate (mg•L^{-1} [y] PBZ)**	**D0 SPAD**	**D84 SPAD**	**D84-0[x] Δ SPAD**	**D0-28 Δ SPAD**	**D28-56 Δ SPAD**	**D56-84 Δ SPAD**
'Neon' pothos	Control	0	5.3	9.8	4.5	1.0	0.5	0.7
	Control vs. Treated		ns[w]	ns	*	**	ns	ns
	Spray	80	6.7	13.9	7.2	1.3	0.5	0.4
	Drench	1	5.9	12.2	6.3	1.0	0.4	0.5
	Drench + Spray Mix	80+1	5.5	9.1	3.7	1.4	0.6	0.5
			ns	ns	ns	ns	ns	ns

[z] – Change in SPAD between the two days given, e.g., D0-28 is the change in SPAD from day 0 of the experiment to day 28.

[y] – 1 $mg \bullet L^{-1} = 1$ ppm

[x] – D84-0 Δ SPAD = Change in SPAD, measurement from day 84 of the experiment minus day 0 of the experiment

[w] – ns ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$)

Table 3.2. Day (D) zero, D14, D28, D42, D56, D70, and D84 SPAD measurements for each treatment to show green up in neon aroid species in experiment 2. Significance levels of the factorial treatment structure for chartreuse aroid cultivars ('Neon' pothos, 'Lemon Lime' philodendron), chemical application (control (C), low (L), medium (M), high (H)) and light (low (L), medium (M), high (H), application abbreviated to appl'n), and their interactions. See Figure 3 for adjoining RHS Colour Chart color codes.

				SPAD measurements (SPAD Units)[z]						
Cultivar	**Treatment**	**Rate (mg•L^{-1} PBZ)** [y]	**Light treatment**	**D0**	**D14**	**D28**	**D42**	**D56**	**D70**	**D84**
Significance Levels[x]										
Cultivar				***	***	***	***	***	***	***
Chemical application				ns	ns	ns	**	**	ns	ns
Light				ns	ns	*	**	ns	ns	ns

Cultivar x chemical appl'n				ns	ns	ns	ns	ns	ns	ns
Cultivar x light				ns	ns	ns	ns	ns	ns	ns
Chemical appl'n x light				ns	*	ns	ns	ns	ns	ns
Cultivar x chemical appl'n x light				ns	ns	*	ns	ns	ns	ns
'Neon' pothos	Control	0	L	10.3	11.4	13.6	15.1	16.7	18.1	20.4
			M	9.1	12.2	13.0	14.6	16.0	20.0	20.3
			H	8.0	11.2	12.6	15.5	16.5	17.4	19.7
	Drench	4	L	9.6	11.1	11.2	13.6	13.8	14.7	16.8
			M	9.6	12.8	14.0	15.2	16.3	18.2	18.6
			H	9.2	11.8	14.4	17.5	18.0	20.6	22.7
		12	L	11.2	14.1	14.9	17.2	21.4	23.4	24.7

			M	8.8	12.8	14.1	16.9	19.1	22.5	24.3
			H	7.2	11.8	14.2	17.5	18.1	20.2	22.01
		24	L	8.6	10.4	13.6	15.6	17.6	18.2	20.0
			M	8.6	11.6	13.9	17.0	19.0	19.8	21.7
			H	11.9	19.0	21.7	26.5	28.0	30.3	30.7
‘Lemon Lime’ philodendron	Control	0	L	9.3	10.9	12.1	13.2	13.7	15.5	16.5
			M	8.3	10.0	11.6	12.7	14.0	15.9	17.0
			H	6.8	10.8	12.3	14.1	14.9	16.0	17.0
	Drench	4	L	8.7	11.2	12.5	14.0	15.6	16.8	17.1
			M	8.2	10.7	10.9	12.3	12.3	15.8	17.3
			H	7.2	10.1	12.3	13.9	14.4	15	15.6
		12	L	8.7	11.1	11.8	14.2	14.4	15.7	19.3
			M	6.4	9.7	12.2	13.0	14.3	16.3	17.0
			H	7.2	11.9	13.9	15.4	15.8	16.8	18.3
		24	L	7.7	10.1	12.4	13.5	14.6	15.6	16.0

M	8.3	10.8	11.9	13.9	14.1	14.7	16.2
H	5.8	11.2	12.7	14.5	15.2	16.1	16.9

[z] – SPAD measurements are an average for each treatment on the day listed.

[y] - 1 mg•L^{-1}= 1 ppm

[x] - ns ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$)

Table 3.3. Change in SPAD readings and monthly change in SPAD across treatments in experiment 2. Significance levels of the factorial treatment structure are shown for cultivar, chemical application (abbreviated to appl'n), light levels, and their interactions.

Treatment	**D84-0 Δ SPAD[z] (SPAD units)**	**D0-28 Δ SPAD[y]**	**D28-56 Δ SPAD**	**D56-84 Δ SPAD**
Significance Levels[x]				
Cultivar	***	ns	***	**
Chemical application	**	**	ns	ns
Light	ns	***	ns	ns
Cultivar x chemical appl'n	ns	ns	ns	ns
Cultivar x light	ns	ns	ns	ns
Chemical appl'n x light	ns	ns	ns	ns
Cultivar x chemical appl'n x light	ns	ns	ns	ns
Cultivar				
'Neon' pothos	12.5a	4.9	4.1a	3.5a
'Lemon Lime' philodendron	9.5b	4.5	2.2b	2.6b

Chemical				
Control	9.9b	3.9ab	2.8	3.8
Low	9.4b	3.8b	2.5	3.0
Medium	13.0a	5.3ab	3.7	3.6
High	11.9ab	5.9a	3.7	2.2
Light				
Low	9.7	3.5b	3.2	2.7
Medium	10.8	4.3b	2.9	3.5
High	12.5	6.4a	3.4	2.8

[z] - D84-0 Δ SPAD = Change in SPAD, measurement from day 84 of the experiment minus day 0 of the experiment.

[y] - Change in SPAD between the two days given, e.g., D0-28 is the change in SPAD from day 0 of the experiment to day 28.

[x] - ns ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$)

Table 3.4. Day (D) zero and D84 stem length and change in stem length over three months for each treatment, cultivar x chemical application x light treatment, for experiment 2. This three-way interaction was not significant for any of the parameters.

				Stem length (cm)			Stem growth rate (cm/month)[z]		
Cultivar	**Treatment**	**Rate (mg•L^{-1} [y] PBZ)**	**Light treatment**	**D0**	**D84**	**D84-0[x]**	**D0-28**	**D28-56**	**D56-84**
'Marble Queen' pothos	Control	0	L	17.4	21.7	4.3	2.4	0.9	1.0
			M	19.7	25.1	5.4	2.3	2.0	1.2
			H	18.8	27.7	8.6	3.7	2.7	2.3
	Drench	4	L	17.0	20.4	3.4	1.6	1.3	0.5
			M	20.1	26.2	6.1	3.0	1.6	1.5
			H	17.5	21.4	4.0	2.0	1.3	0.6
		12	L	18.9	22.8	3.9	2.5	0.9	0.6
			M	19.0	28.3	9.3	3.7	1.4	4.3
			H	16.6	20.2	3.6	1.9	1.1	0.6
		24	L	17.1	20.0	2.9	1.8	0.7	0.5

			M	19.4	24.9	5.5	2.9	1.7	0.9
			H	21.6	26.5	5.0	2.0	1.6	1.4
				ns[w]	ns	ns	ns	ns	ns
‘Neon’ pothos	Control	0	L	20.1	24.7	4.7	2.7	1.1	0.9
			M	23.4	28.6	4.7	3.7	0.9	0.7
			H	26.6	32.1	5.3	2.5	1.7	1.3
	Drench	4	L	21.2	26.1	5.6	2.9	1.4	0.6
			M	20.6	27.3	4.9	5.0	1.0	0.8
			H	22.7	28.7	6.7	3.6	1.2	1.2
		12	L	22.3	27.0	6.0	3.2	0.9	0.7
			M	22.2	25.9	4.7	2.4	0.9	0.5
			H	22.0	28.8	3.8	3.3	1.8	1.7
		24	L	18.2	24.7	6.8	5.3	0.8	0.4
			M	23.3	27.4	6.5	2.3	1.4	0.5
			H	24.1	29.9	4.1	3.0	2.1	0.8
				ns	ns	ns	ns	ns	ns

‘Lemon Lime’ philodendron	Control	0	L	14.4	19.3	2.5	1.9	1.8	0.2
			M	15.6	18.4	2.8	1.9	0.8	0.2
			H	21.3	27.5	6.2	3.3	1.7	1.2
	Drench	4	L	15.3	20.3	5.7	2.5	1.1	1.8
			M	17.8	21.2	3.4	2.9	1.1	1.1
			H	17.4	22.9	5.5	3.1	1.5	1.0
		12	L	15.1	21.5	4.9	1.9	1.1	0.4
			M	15.7	21.8	6.1	4.3	1.1	0.7
			H	18.9	25.7	6.8	3.6	2.5	0.7
		24	L	15.8	19.7	3.9	1.9	1.7	0.4
			M	14.6	17.9	3.3	1.7	1.1	0.5
			H	16.2	19.5	3.3	2.2	0.7	0.5
				ns	ns	ns	ns	ns	ns

[z] – Growth rate calculated by subtracting the stem length at the smaller date by the larger date, e.g. D28-56 growth rate would be the length at day 56 minus the length at day 28. 1 cm= 0.3937 in.

[y] – 1 ppm = $mg \bullet L^{-1}$

[x] – D84-0 stem length is calculated by taking the stem length at day 84 minus the stem length at day 0.

[w] - ns ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$)

Table 3.5. Change in stem length and biweekly stem growth rate across treatments in experiment 2. Significance levels of the factorial treatment structure are shown for cultivar ('Marble Queen' pothos (*E. aureum* 'Marble Queen'), 'Neon' pothos (*E. aureum* 'Neon', 'Lemon Lime' philodendron (*P. scandens* 'Lemon Lime'), chemical application (control (C), low (L), medium (M), high (H), abbreviated appl'n) light levels (low (L), medium (M) high (H)), and their interactions. Significance levels based on Tukey's HSD ($\alpha \leq 0.05$).

Treatment	**Abbreviation**	**D84-0[z] Δ Stem length (cm)**	**D0-14[y] Stem growth**	**D14-28 Stem growth**	**D28-42 Stem growth**	**D42-56 Stem growth**	**D56-70 Stem growth**	**D70-84 Stem growth**
Significance Levels[x]								
Cultivar		ns	***	ns	ns	ns	ns	**
Chemical application		ns	ns	ns	ns	ns	ns	ns
Light		ns	ns	ns	ns	ns	ns	*
Cultivar x chemical appl'n		ns	ns	ns	ns	ns	ns	ns
Cultivar x light		**	ns	ns	ns	ns	ns	ns
Chemical appl'n x light		ns	ns	ns	ns	ns	ns	ns

Cultivar x chemical appl'n x light		ns	ns	ns	ns	ns	ns	ns
Cultivar								
'Marble Queen' pothos		5.2	1.9a[w]	0.6	0.9	0.6	0.6	0.7a
'Neon' pothos		5.4	2.8b	0.8	0.7	0.6	0.4	0.4ab
'Lemon Lime' philodendron		4.6	1.7a	0.9	0.7	0.6	0.5	0.3b
Light								
Low	L	4.4	2.0	0.5	0.6	0.6	0.4	0.3b
Medium	M	5.2	2.3	1.0	0.8	0.4	0.6	0.5ab
High	H	5.6	2.1	0.8	0.9	0.7	0.5	0.6a
Cultivar x Light								
'Marble Queen' pothos	L	3.6b	1.6	0.5	0.5	0.6	0.2	0.4
'Marble Queen' pothos	M	6.6a	2.2	0.8	1.0	0.6	1.1	0.9

‘Marble Queen’ pothos	H	5.3ab	1.8	0.6	1.1	0.6	0.5	0.7
‘Neon’ pothos	L	5.2ab	3.1	0.4	0.5	0.6	0.4	0.3
‘Neon’ pothos	M	5.0ab	2.8	1.4	0.7	0.4	0.2	0.4
‘Neon’ pothos	H	6.0ab	2.4	0.7	1.0	0.7	0.6	0.7
‘Lemon Lime’ philodendron	L	4.2ab	1.4	0.6	0.8	0.6	0.5	0.2
‘Lemon Lime’ philodendron	M	3.9ab	1.8	0.9	0.7	0.3	0.5	0.3
‘Lemon Lime’ philodendron	H	5.5ab	2.0	1.0	0.7	0.9	0.5	0.4

[z] - D84-0 Δ Stem length calculated by subtracting stem length at day 84 from the initial stem length. 1 cm= 0.3937 inch.

[y] – Biweekly growth rate calculated by subtracted the stem length by the larger day from the more recent day, e.g. D0-14 would be the stem length at day 14 subtracted from the stem length at day 0.

[x] - ns ($\alpha \geq 0.05$), * ($\alpha \leq 0.05$), ** ($\alpha \leq 0.01$), *** ($\alpha \leq 0.001$).

[w] – Mean separation values were calculated with Tukey’s HSD ($\alpha \leq 0.05$)

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