

Methods for growth regulation of greenhouse produced ornamental pot- and bedding plants – a current review

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ABSTRACT

Chemical plant growth regulators (PGRs) are used in the production of ornamental potted and bedding plants. Growth control is needed for maximizing production per unit area, reducing transportation costs and to obtain a desired visual quality. However, the use of PGRs is associated with toxicity risks to humans and the environment. In many countries the availability of PGRs is restricted as few substances are registered for use. A number of alternative methods have been suggested. The methods include genetic methods (breeding) and crop cultivation practices such as fertigation, temperature and light management. A lot of research into “alternative” growth regulation was performed during the 1980-1990s, revealing several possible ways of using different climatic factors to optimize plant growth with respect to plant height. In recent years, the interest in climatic growth regulation has been resurrected, not least due to the coming phase-out of the plant growth regulator chlormequat chloride (CCC). Today, authorities in many countries are aiming towards reducing the use of agrochemicals. At the same time, there is a strong demand from consumers for products produced without chemicals. This article provides a broad overview of available methods for non-chemical growth control. It is concluded that a combination of plant breeding and management of temperature, fertigation and light management has the potential of replacing chemical growth regulators in the commercial production of ornamental pot- and bedding plants.

Key words: artificial lighting, fertigation, gibberellic acid, ornamental plants, plant breeding

Abbreviations:

CCC – cycocel, DIF – difference, DT – day temperature, EOD – end of day, FL – fluorescent light, FR – far red, GA – gibberellic acid, GMO – genetically modified organism, HPS – high pressure sodium lamp, LDP – long day plant, LED – light emitting diode, MH – metal halide lamp, NT – night temperature, PGR – plant growth regulator, PPF – photosynthetic photon flux, R – red, SL – supplementary light, SDP – short day plant

INTRODUCTION

Growth control is a prerequisite for all production of ornamental pot plants (Davis and Skytt Andersen 1989; Skytt Andersen and Andersen 2000). The introduction of chemical growth retardants in the

1960s laid the foundation for the modern pot plant industry, where plants, which in their wild habitats are bushes or even trees, are made into small plants with a maximum height of around 20 cm. The restriction of root volume which comes with the

very concept of growing plants in containers limits plant growth (Poorter et al. 2012), however, further measures are necessary for obtaining a plant quality which is desirable. In general, retailers and consumers would prefer a plant which is compact without too long internodes, and rich in branching and flowers. The colour of the canopy should be dark green. Apart from satisfying consumer preferences, compact plants have other advantages. When reducing plant size, more plants per m² can be produced, thus increasing the profitability for the grower. A smaller plant will also take less space during transportation, as the distance between the shelves in transportation containers normally restricts plant height to 25 cm (Bañón et al. 2002). A smaller plant will also be less exposed to damage during transportation.

Today, chemical growth retardants such as daminozide, flurprimidol, chlormequat chloride, paclobutrazol, ethephon and ancymidol are generally used in floriculture. Their general mode of action is to inhibit the biosynthesis of gibberellin, which is a growth hormone with the largest influence on plant (cell) elongation. In the present situation, chemical growth regulation is still important for floriculture with advantages such as high efficiency, moderate cost and high controllability. It gives the grower the possibility to really fine-tune his production, and, if applied as sprays, the retardants have the advantage of being “self-regulating”, i.e. a larger plant will collect more spraying fluid and thus be more strongly suppressed. However, the availability of chemical growth retardants is restricted by the authorities in many countries, due to environmental and workers' health aspects. Consumers are also concerned that the plants they bring into their homes have been treated with chemicals. For vegetable transplants, chemical growth control is already not possible in a number of countries. For bedding plants, treatment with chemical growth regulators will slow down plant development at the consumer's end, possibly leading to less satisfied consumers. Municipalities in some Swedish cities are demanding that plants they buy for public plantings should not be treated with chemical growth retardants. Increasing ambient levels of CO₂ in the atmosphere will also lead to a more vigorous growth of greenhouse-grown ornamentals, leading to increased needs for active growth control. Thus, there is a strong demand for alternative methods of controlling plant growth.

The task of controlling growth has occupied horticultural scientists for the last couple of

decades. Technological developments with the introduction of computerized climate controls, more sophisticated shading screens and lighting systems have increased the possibilities for growers to control their plants carefully, but also developments within the biotechnology field have opened up new possibilities for developing the perfect plant. By combining chemical retardants with other ways of controlling growth, good results can be obtained with limited ecological impact.

This paper is reviewing the current methods of controlling growth in potted greenhouse crops.

THE SIGNIFICANCE OF PLANT GROWTH REGULATION

Chemical growth regulation has been and still is a crucial factor for the floricultural industry. Skytt Andersen and Andersen (2000) state that growth regulation is a “necessary prerequisite for the introduction of new plants”. Broadly introduced in the 1960s, the chemical plant growth regulators (PGRs) started a revolution in new potted ornamental crops, and a shift in production from mainly cut flowers to mainly potted flowers in many European countries. Although important to the floriculture industry, growth regulation chemicals only account for around 3–4% of the turnover of agrochemical companies. It is also a non-growing market, thus reducing the incentives for devoting a great deal of research and development into this group of agrochemicals (Rademacher and Bucci 2002, Rademacher 2015). The substances used today are often simple molecules introduced into the market already 40–50 years ago, like, for example, chlormequat chloride (CCC) (Rademacher and Bucci 2002), and not much research on chemical plant growth regulators designed for ornamental plants is ongoing. For ornamental crops, new active substances might be introduced by minor-use registration of PGRs used in major agricultural crops (Rademacher 2015). Davis and Skytt Andersen (1989) claim that chemical growth retardants are a temporary solution and that genetic engineering of plants would be the ultimate solution to controlling plant size.

GENETIC MATERIAL AND PLANT MANAGEMENT

Selection and breeding for more compact cultivars has been one of the main scopes of ornamental plant breeding for the past decades. Long-time running breeding programmes led by multinational

breeding companies have been most successful in creating ever new varieties with new flower colours and better shelf-life. However, when it comes to breeding for compactness, development has been slower. Bhattacharya et al. (2010) suggest that the limited gene pool and the fact that competition in nature has favoured strong-growing clones are making traditional breeding for compact varieties troublesome. Also Schum (2003) names the limited availability of genes as a major obstacle to mutation breeding. However, the introduction of biotechnology has improved the possibilities of creating new varieties that match the desired properties to a large extent. Genetic modification of *Kalanchoë* to reduce internode length was suggested by Lütken et al. (2010) and by Teixeira da Silva (2004) to alter the morphogenesis in *Chrysanthemum*. Islam et al. (2013) inserted a “short internode gene” from *Arabidopsis* into Poinsettia using *Agrobacterium*, which resulted in a reduction in shoot length by up to 50%. Genetic modification using biotechnology seems to have great potential; however, the resistance from consumers and authorities against GMO crops is a problem, especially in Europe, even if it may be a little less difficult to gain acceptance for using this technology in non-edible crops (Bhattacharya et al. 2010). Another drawback in using weakly growing cultivars is that once such a cultivar is chosen, the grower has reduced his options for controlling growth, and might end up with too small end products.

Breeding for compact cultivars might be the way to go when it comes to pot plants for indoor use; however, for bedding plants intended for outdoor use significant growth after transplanting by the end consumer is preferable, making too compact growing cultivars troublesome, as their growth at the end consumer will be limited. Plants genetically prone to compact growth will have lower “garden performance” at the consumer’s end.

TEMPERATURE MANAGEMENT

Regulation of temperature has always been one of the most central measures in greenhouse horticulture. One of the first to systematically analyse the impact of temperature on growth and development of horticultural crops was Went (1944). He found that not only does the average daily temperature affect growth, but fluctuations between day temperature (DT) and night temperature (NT) have a great impact on plant growth, and, therefore, he coined the term “Thermoperiodicity”. He also concluded that

fluctuating temperatures were beneficial for plant growth, and that a positive DIF (day temperature higher than night temperature) would increase stem elongation. One of the first to acknowledge the usefulness of negative DIF (night temperature higher than day temperature) for horticultural purposes was Tangerås (1979), who showed that a negative DIF (DIF being the difference between NT and DT) reduced stem elongation in *Fuchsia × hybrida*. From there on, a great deal of work was done on negative DIF in various greenhouse crops. Moe (1990) demonstrated a reduction in stem length in *Campanula isophylla* by up to 50% when changing from DIF +10 to DIF -10, and established a quantitative relationship between DIF and stem elongation. Also Jensen et al. (1996) were able to reduce stem length in *Campanula* by applying a negative DIF. Moe et al. (1995) as well as Myster et al. (1997) found that stem elongation in *Begonia* was reduced by a negative DIF. Jacobsen and Amsen (1990) as well as Bertram (1992), and Cuijpers and Vogelezang (1992) made similar observations for *Chrysanthemum*. For Poinsettia, the usefulness of negative DIF was suggested by Cockshull et al. (1995) and Cuijpers and Vogelezang (1992). For cucumber, a reduction in stem length by up to 27% was observed under negative DIF compared with positive DIF (Grindal Patil and Moe 2009). Also in lilies, *Lilium longifolium*, Miller et al. (1993) found that negative DIF greatly reduced not only stem length but also leaf dry weight compared with positive DIF, and without delaying anthesis. However, for *Kalanchoe* a negative DIF was not recommended (Kresten Jensen 1994).

The plant physiological responses to DIF are suggested to be related to gibberellin synthesis (Jensen et al. 1996, Grindal et al. 1998). Transformation of the active form GA_1 to the inactive form GA_8 via 2 β -hydroxylation, which in turn is regulated via the phytochrome system, is a major factor (Grindal et al. 1998).

However, despite the numerous publications on the effects of negative DIF, the concept of negative DIF is not without controversy. Carvalho et al. (2002) suggest that DIF effects are merely a result of the day and night temperatures as such, rather than the actual difference. Langton and Cockshull (1997) call the negative DIF concept an “artefact” lacking biological significance. Using negative DIF is also connected with practical implications such as problems of obtaining low temperatures during daytime in summer. As increased nighttime temperatures are used as part of the concept,

negative DIF will increase energy consumption, thus the use of DIF will also have a negative environmental impact. Generally, increasing the greenhouse temperature set point by 1°C will increase energy consumption by 10% (Tantau 1998). These factors have prevented the negative DIF concept from winning wide-spread acceptance among growers.

Another way of controlling elongation by temperature which is related to negative DIF is by using temperature-drop. This concept involves a fast reduction in temperature for a few hours around the shift from scotoperiod (dark) to photoperiod (light) (Moe et al. 1992). Also the term “pulse-DIF” is used for this practice (Kresten Jensen 1994). It is normally assumed that stem elongation reaches its maximum around daybreak (Bertram 1992), so probably the drop concept simply acts by slowing the cell division process when it is at its highest, thereby reducing elongation. Grindal and Moe (1994) found that a drop in temperature from 18°C to 12°C for two hours just before daybreak reduced stem length, plant height and peduncle length in *Begonia*. They also concluded that temperature drop has greatest effect in short-day plants (SDP). Moe et al. (1992) showed that a 2-hour drop from 19°C to 13°C just before or after the beginning of the photoperiod reduced stem length in Poinsettia by 25% without reducing plant width or bract size, but with a 3.5 days delay in plant development. However, applying the same drop in the middle of the scotoperiod did not have any significant effects, supporting the theory that the drop needs to occur close to daybreak. Moe et al. (1995) demonstrated a reduction in plant height in *Campanula* using temperature drop, with the effect being more pronounced with increased duration of the drop. They also reported a somewhat delayed crop development as a result of temperature drop treatments, as did Moe et al. (1992). Also Cockshull et al. (1995) proved temperature drop useful in controlling stem elongation in *Chrysanthemum* and Poinsettia. Ihlebakk et al. (1994) demonstrated reductions in stem length by up to 29% when applying temperature drop in *Campanula*, indicating the involvement of GA in the mode of action for temperature drop.

The use of morning temperature drops seems like a more feasible solution than negative DIF, as it can be combined with temperature integration strategies and dynamic climate control, as suggested by Tantau (1998) and Ottosen et al. (2004). Dynamic climate control allows higher temperatures during

daytime (when the sun is heating the greenhouse) and compensates by lower temperatures during night-time, which reduces energy consumption. By applying the lower night temperature as a drop at the end of the night, a reduction in elongation can be obtained at the same time as energy consumption is reduced compared with conventional heating strategies (Möller-Nielsen, pers. comm. 2014).

MECHANICAL GROWTH REGULATION

Mimicking the wind’s sweeping of plants as a way of keeping them compact is probably one of the oldest known methods for growth control. Two different processes are involved in the concept of mechanical stress in plants: seismic and thigmic stress. Seismic stress is referring generally to the shaking of plants, whereas thigmic stress more specifically refers to the bending of shoots (Latimer and Mitchell 1988). Mechanical stress might reduce stem length, but also growth in terms of leaf area and shoot fresh and dry weight (Latimer and Mitchell 1988). The use of seismomorphogenetic stress as a means of controlling growth in horticultural plants has been investigated by several authors. Autio et al. (1994) used brushing with burlap and found significant reduction in plant height of *Aster* and *Petunia* when plants were brushed daily for 60-180 minutes. Garner et al. (1996) demonstrated a reduction in shoot length in transplants of *Pelargonium*, *Impatiens*, *Petunia* and *Viola* when plants were agitated every 10 minutes. However, leaf damage occurred. Garner and Björkman (1996) obtained a reduction in stem length with up to 30% without a reduction in biomass when tomato seedlings were brushed daily 30 times.

Mechanical growth control seems to be feasible for young plants, and can easily be automatized using ramps travelling over the crop for brushing. This method will, however, like other growth regulation methods connected with the greenhouse climate, have its limitations if more than one species or cultivar is cultivated in the same greenhouse compartment. The risk of leaf damage also limits the use of mechanical growth control in the production of potted ornamental crops.

FERTIGATION MANAGEMENT

Restriction of water and nutrient availability by using a limited volume of root mass is one of the basic principles of pot plant production. Poorter et al. (2012) used meta-analysis to establish

a relationship between pot size and plant size, where restriction in water and nutrient availability is the reason for the restriction of plant growth. However, irrigation management will have great influence on plant growth. Keeping plants “on the dry side” is commonly used by growers as a standard means of restricting elongation. However, decisions on irrigation are in practice often taken subjectively, by weighing a pot in the hand in what has sometimes been referred to as “the golden grip” (Alsanius et al. 2009). Here, the growers’ skills are important factors. Technical limitations of irrigation systems, such as limited capacity and long cycles, might also contribute to the growers’ decision on irrigation. The decision on the initiation of an irrigation cycle might also be taken based on technical measurements with irradiation meters (Löfkvist et al. 2009), dendrometers (Miralles-Crespo et al. 2010) or sensors measuring soil moisture (Caron et al. 2002). If the decision on irrigation is taken strictly on the basis of measured physical parameters, modifications of the irrigation strategy are easier to undertake.

Álvarez et al. (2009) demonstrated that reducing water supply to potted carnations significantly reduced plant height and that it was possible to obtain a reduction in plant height without affecting the number of flowers. Cameron et al. (2002) found similar results for potted woody ornamentals. For geraniums, deficit irrigation inhibited plant height and width, without affecting flower colour (Sánchez-Blanco et al. 2009).

Restriction of nutrient availability is advantageously oriented towards those nutrients where deficiency symptoms do not decrease the ornamental value of the plant. For ornamental plants, a high supply of potassium (K) is generally recommended (Neto et al. 2015). As a general basic nutrient composition, N-P-K 20-10-24 has been recommended (Nelson 1998). Restricting nitrogen availability would reduce growth and was suggested by Starkey and Andersson (2000). Nitrogen deficiency also causes pale leaf colour and possibly leaf senescence, causing a significant reduction in ornamental value. However, a “dynamic” supply of nitrogen has been suggested as a way of overcoming this problem (Hansen et al. 2003). Restriction of phosphorus seems a more feasible solution for growth control, as phosphorus deficiency causes stunting of plants, but with maintaining a dark green colour of leaves (Benton Jones 1998). The use of controlled phosphorus deficiency for controlling growth of ornamental

plants was also suggested by Baas et al. (1993). Hansen and Nielsen (2001) demonstrated growth regulating effects in *Euphorbia pulcherrima*, *Aster Novi-belgii*, *Argyranthemum frutescens* and *Pentas lanceolata* when the P-supply was reduced to 5% of the normally recommended dosage. However, there is a significant challenge in supplying accurate levels of phosphorus to obtain the desired effects. Using phosphorus buffers in the growing medium, as suggested by Hansen and Nielsen (2001) might be a feasible way.

LIGHT MANAGEMENT

Light is the most important factor for plant growth and the quality and quantity of light will greatly affect plant growth. In the early days of greenhouse horticulture, light was not controlled to any great extent. The only method available to the grower of the early 1900’s was whitewashing of the glass, to some extent reducing excessive radiation and heat. Around 1930 the use of supplementary lighting was introduced. Incandescent tubes, neon tubes or mercury vapour lamps were used to support growth during winter months. Later photoperiodic lighting, commonly using incandescent bulbs, was introduced for controlling flowering in short- and long-day plants. Automatically operated shading screens were also introduced as a way of saving the labour costs of whitewashing, and to be able to control the light influx a little more precisely. In the 1950’s, short-day plants such as *Chrysanthemum* were introduced into large-scale production featuring flowering control with black plastic, normally manually operated, used for controlling photoperiod and inducing flowering. Light is an important tool in the grower’s tool box for controlling the growth of his plants (Folta and Childers 2008, van Ieperen 2012). In modern greenhouses of today, the grower can manipulate light with respect to 1). Intensity (increasing by artificial lighting or decreasing using shading curtains), 2). Photoperiod (extending by using artificial light or shortening by using blackout screens), and 3). Quality (complement the natural light with artificial light of a certain quality, or filter the natural light to reduce the occurrence of certain wavelengths). All these measures will affect plant growth and morphology.

Photoperiod controls flower induction in many common floricultural plant species like Kalanchoe, Poinsettia, and *Campanula*. The role of photoperiodic control in the flowering regulation of poinsettia was described by Parker et al. (1950),

ultimately leading to the commercial introduction of poinsettia, and other short-day plants, in horticulture in the 1950s and onwards. For flower induction of long-day plants, light from incandescent bulbs has traditionally been used at low intensities. Attempts have been made to replace the incandescent bulbs with fluorescent lights. However, due to the low emission of far red light from this lamp type, such a replacement might delay flowering, but also, for some species, reduce elongation (Runkle et al. 2012). Using LED-based light makes it possible to design a “flowering-control spectrum”, resembling the spectrum of an incandescent lamp, but with lower energy consumption and a longer life span.

Reduced photoperiod is also known to reduce elongation. This was suggested to be either due to the restriction of assimilates (Warrington and Norton 1991), or to the fact that gibberellin production is light dependent (Yamaguchi 2008). Beel et al. (1997) demonstrated a correlation between photoperiod and stem elongation in *Ficus*, as did Moe et al. (1995) for *Petunia*. Schüssler and Kosiba (2006), and Schüssler and Bergstrand (2012) developed the concept for several bedding plants, including *Calibrachoa*, *Pelargonium*, *Petunia* and *Scaevola*. A strong reduction in shoot elongation was obtained in *Calibrachoa*, *Scaevola* and *Petunia* when a two-week period with a short photoperiod (6 or 8 h) was applied in the middle or at the end of crop cultivation. Even if flower buds were initiated already at the onset of the short-day treatment, as plants are LDP, flowering was somewhat delayed due to the short-day treatment. For the daylength-neutral *Pelargonium*, responses to short photoperiods were less apparent but significant. In addition to the fact that gibberellin production is dependent on photoperiod rather than the amount of light (Yamaguchi 2008), the exclusion of the far-red rich evening light by blackout screens is probably also part of the explanation. Also diffusing the light, using a covering material with a haze factor, might improve plant quality parameters such as leaf area, the number of lateral shoots and fresh weight (Markvart et al. 2010). For plant types with a determinate growth pattern, early flower initiation (using photoperiodic control) will act as growth regulation.

It has been known for a long time that the red:far red (R:FR) ratio of light is important for controlling the growth via its direct impact on the phytochrome system, in turn regulating the gibberellic acid synthesis. The phytochrome photostationary state can be calculated for each light spectrum as

described by Sager et al. (1988). Stem elongation is inversely proportional to $\phi (P_{fr}:P_{total})$ (Morgan and Smith 1976, Morgan and Smith 1979). Sunlight has an R:FR ratio of around 1. The R:FR responses of plants have an important ecological role in controlling shade-avoidance reactions (elongation). Therefore, modification of the natural daylight using spectral filters has attracted a lot of interest. Filters can be either fluid (e.g. $CuSO_4$ filters) or solid (plastic screens) (Rajapakse and Kelly 1995). The filter might be an integrated part of the greenhouse cladding material, or mounted inside the greenhouse as an extra screen. Van Haeringen et al. (1998) reduced plant height and internodal length of *Chrysanthemum* and *Antirrhinum* using solid filters that reduced the FR portion of the light. However, flowering was delayed, which was probably attributable to the fact that flowering is controlled by the far-red light. Khatkhatk et al. (2004) similarly demonstrated a 19% reduction in the plant height of *Chrysanthemum* using filters increasing the R:FR ratio. Similar results were demonstrated by Tatineni et al. (2000). Mata and Botto (2009) were able to reduce plant height in *Poinsettia* up to 17% using FR-reducing films, and stated that the effect was within the same range as that obtained after applying PGRs. McMahon and Kelly (1990) used $CuSO_4$ filters and were able to reduce plant height of potted roses by 25-35%, and at the same time got a higher chlorophyll content of the leaves. Mortensen and Strømme (1987) also used fluid filters and obtained significant reductions in stem elongation of tomato, stating alterations of R:FR ratio as a plausible explanation. Runkle and Heins (2001) used FR reducing films to reduce stem extension in *Campanula*, *Coreopsis*, *Lobelia* and *Pisum*. Cerny et al. (2003) presented similar results for *Zinnia*, *Cosmos*, *Chrysanthemum*, *Antirrhinum* and *Petunia*. *Rosa*, however, was found to be less sensitive to the manipulated R:FR ratio. In cucumber, stem length was reduced up to 52% when using FR-selective filters (Grindal Patil and Moe 2009). Li et al. (2003) used FR-absorbing filters in *Chrysanthemum* and found reductions in plant height up to 18%. However, the development was slowed and also the amount and size of flowers was reduced, which was speculated to be connected with a lower total light integral. Clifford et al. (2004) demonstrate that filters reducing FR are almost as affective as two treatments with CCC in controlling the height of *Poinsettia*, but also that the time to anthesis is prolonged by 6 days due to a lower total light integral. In contrast, Mortensen

Table 1. Spectral properties of different lamp types, measured using JAZ spectrometer, Ocean Optics inc., Dunedin, FL USA

Lamp type	Spectral distribution (%)				
	Blue (400-500 nm)	Green/yellow (500-600 nm)	Red (600-700 nm)	Other (UV, FR)	Red:Far red ratio ²
HPS (400 W, Philips)	4.0	55.1	34.1	6.8	12.8:1
FL (Sylvania, 58W)	10.9	46.2	40.4	2.5	20.1:1
MH (Solljus, 150 W)	10.3	45.0	36.4	8.3	5.6:1
LED (Valoya B150) ¹	7.6	30.2	58.5	3.7	16.3:1

¹Spectrum AP673²Defined as (600-700 nm)/(700-800 nm)

and Strømme (1987) were not able to affect the plant height of Poinsettia by using blue, green, yellow or red spectra. Clifford et al. (2004) suggest movable screens, applied only in the morning and afternoon when the R:FR ratio of the natural light is at its lowest.

Filters creating a blue-biased light are also of interest. Already in 1965 Evans et al. demonstrated the hypocotyl length-reducing effect of blue filters. Increasing the B:R-ratio from 0.98 to 85.5 using spectral filters was proven to strongly reduce stem elongation of *Chrysanthemum* (Oyaert et al. 1995). Also Lykas et al. (2008) used filters increasing B:R ratio to decrease plant height in *Gardenia*. However, it is also stated that increasing the proportion of blue light is only effective if FR is present (Casal and Smith 1989). Khattak and Pearson (2006) found reduced plant height and internodal length in *Chrysanthemum* when applying blue filters, especially during low light conditions. Cummings et al. (2008) found reduced stem length in *Pisum* when grown under blue nets, and drew the conclusion that a Cryptochrome-dependent reaction is responsible for this phenomenon.

Using spectral filters, for example integrated as a dye in greenhouse cladding materials, seems like a feasible solution in many cases. It might be feasible especially if the greenhouse is situated in an area with high levels of radiation, where the loss in light transmission due to the filter might be less significant. For cultivation at higher latitudes (> 50°N), natural daylight irradiation is normally suboptimal during 5-7 months per year (Mortensen 2014). At the same time, there is often a demand for heating the greenhouse due to low outside temperatures. Applying spectral filters would possibly lead to an increased demand for heating, and also reduce the light influx. Therefore, manipulating the spectral environment by amending narrow-band light (NBL) to the natural sunlight is

an interesting solution. Supplementary lighting is a prerequisite for producing high-quality plants during winter months in the north (Mortensen 2014). All commercially available technologies for supplementary lighting emit a spectrum deviating from that of the sun, thus affecting the spectral quality of the light supplied to the plants (Table 1).

With the introduction of LED-technology, new possibilities for actively controlling the spectral distribution of light have opened up (Morrow 2008). Adjusting the amount of red and blue light in the spectrum, as well as the red:far red ratio, are interesting possibilities for modulating stem elongation. Currey and Lopez (2013) stated that enriching the natural light with narrow-band light would not affect plant growth much. However, Islam et al. (2012) were able to demonstrate shorter internodes in Poinsettia grown under red and blue LEDs as supplementary lights, compared with conventional HPS-light. Also Bergstrand et al. (2016) were able to obtain a reduction in elongation of Poinsettia by applying solely 660 nm light at low PPF (30 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for 8 h day⁻¹) in combination with natural sunlight.

Applying End-of-day (EOD) treatments with red light is one method where a low input of light can have a great influence on plant elongation. According to Decoteau and Friend (1991), shoot length of tomato can be reduced by applying a 15 min. period of red light (peak wavelength 640 nm) at the end of the photoperiod. Hatt Graham and Decoteau (1995) demonstrated similar effects in bell pepper by applying a 1 h EOD-treatment with white fluorescent light. Hatt Graham and Decoteau (1995) also stated that different species differ in their response to EOD treatments, with pepper being more sensitive than tomato. Also Islam et al. (2012) obtained a reduction in internode length in Poinsettia when a 30 minute period of red EOD-light at 5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was applied. However, Islam

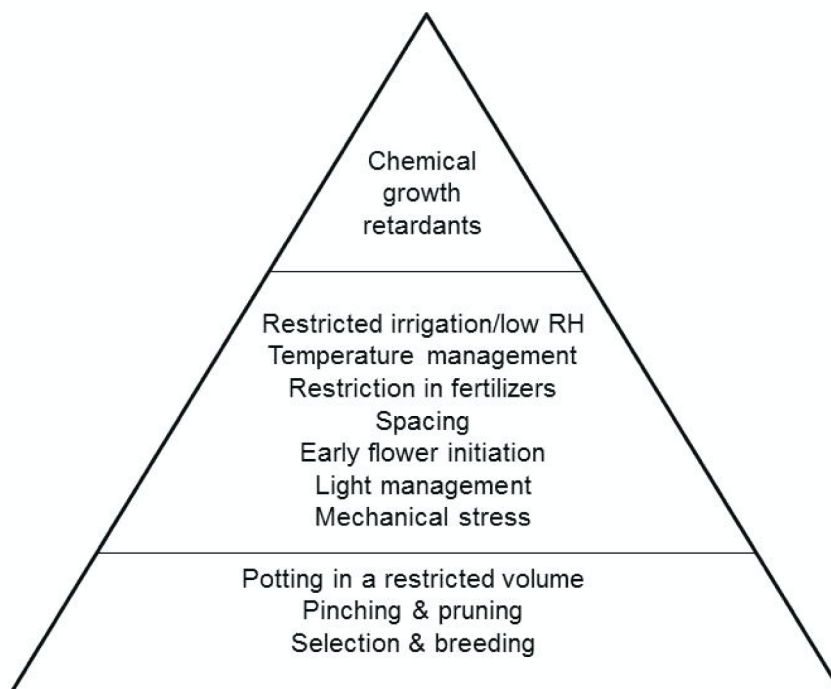


Figure 1. The growth regulation pyramid describes the order in which different growth restricting measures are taken in the production of potted ornamentals

et al. (2012) also found that the response to EOD-treatments was dependent on light quality during the main photoperiod, i.e., when using a “main” light rich in blue, the effect of red EOD-light was reduced. Also Vince-Prue (1977) and Xiong *et al.* (2002) found that EOD-treatments with red light reduced internode length in *Fuchsia* and cucumber, respectively. Yang *et al.* (2012) suggested the use of EOD-treatments with far-red light as a means of increasing the length of the hypocotyl in plants designated for grafting.

Using LED-technology with pure narrow-band light and low energy consumption in combination with the use of blackout screens to exclude the twilight from the greenhouse seems a promising method for growth regulation using light. The most efficient quality and quantity of the light used for EOD-treatments, and the response of different plant species to EOD-treatments, still needs further investigation.

OTHER METHODS

Reduced humidity or salt stress induced, for example, with potassium sulphate, are growth control measures that are related to water stress (Hendriks and Ueber 1995). Pinching will reduce apical elongation and result in bushier plants with a lower total plant height. It might be labour

intensive but is a common cultural practice used in commercial nurseries (Norcini *et al.* 1996). Use of compounds not registered as agrochemicals is another option. Ethanol treatments to induce compact growth in *Kalanchoë* was suggested by Mibus *et al.* (2014). Plant extracts are also suggested for growth regulation purposes (Alexenizer and Dorn 2007).

CONCLUSIONS

The transformation of wild plants into relatively small indoor ornamental plants involves many different practices, which can be symbolized with a “growth regulation pyramid”, Figure 1. Chemical growth regulators should be used as a last resort, but have been, and still are, an important production factor in the floriculture industry. However, in many countries we are facing a phase-out of chemical growth regulators due to decisions by authorities and to consumer preferences. Technological development, both in greenhouses and biotechnology, improves the possibilities of a chemical-free ornamental crop production. Breeding and biotechnology have the potential to solve growth control issues for most indoor ornamentals. However, authority regulations regarding genetically modified crops are restricting the development in this field. Traditional breeding

has also been successful in creating compact-growing cultivars within a longer timeframe.

For bedding plants, weakly-growing cultivars are undesirable. Here, different climatic measures during plant production will continue to be the major method of controlling growth. Better climate control with new types of sensors and improved computer programs will improve the possibilities for successfully steering crop development using parameters such as irrigation, temperature and humidity. In addition, light management using photoperiodic control and semi-conductor based light sources providing narrow-band light seems very promising. It seems reasonable to expect that successful production of both ornamental pot- and bedding plants without chemical growth regulators will be possible within a few years.

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CONFLICT OF INTEREST

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REFERENCES

- ALEXENIZER M., DORN A., 2007. Screening of medicinal and ornamental plants for insecticidal and growth regulating activity. *J. Pest Sci.* 80: 205-215.
- ALSANIUS B.W., LÖFKVIST K., KRITZ G., RATKIC A., 2009. Reflection on reflection in action: a case study of growers conception of irrigation strategies in pot plant production. *AI & Soc.* 23: 545-558.
- ÁLVAREZ S., NAVARRO A., BAÑÓN S., SÁNCHEZ-BLANCO M.J., 2009. Regulated deficit irrigation in potted *Dianthus* plants: Effects of severe and moderate water stress on growth and physiological responses. *Sci. Hortic.* 122: 579-585.
- AUTIO J., VOIPIO I., KOIVUNEN T., 1994. Responses of aster, dusty miller, and petunia seedlings to daily exposure to mechanical stress. *HortScience* 29: 1449-1452.
- BAAS R., BRANDTS A., STRAVER N., 1993. Growth regulation of bedding plants and poinsettia using low phosphorus fertilization and ebb-and flow irrigation. *Acta Hort.* 378: 129-138.
- BAÑÓN S., GONZÁLEZ A., CANO E.A., FRANCO J.A., FERNÁNDEZ J.A., 2002. Growth, development and colour response of potted *Dianthus caryophyllus* cv. Mondriaan to paclobutrazol treatment. *Sci. Hortic.* 94(3): 371-377
- BEEL E., DE BRUYN P., FREDERICK F., LEMEUR R., 1997. Effects of different lighting strategies on the growth and development of *Ficus benjamina*. *Acta Hort.* 418: 37-44.
- BENTON JONES J., 1998. *Plant Nutrition Manual*. CRC Press, Boca Raton, USA.
- BERGSTRAND K.-J., ASP H., SCHÜSSLER H.K., 2016. Growth control of ornamental and bedding plants by manipulation of photoperiod and light quality. *Acta Hort.* 1134: 33-40.
- BERTRAM L., 1992. Stem elongation of *Dendranthema* and tomato plants in relation to day and night temperatures. *Acta Hort.* 327: 61-70.
- BHATTACHARYA A., KOURMPETLI S., DAVEY M.R., 2010. Practical applications of manipulating plant architecture by regulating gibberellin metabolism. *J. Plant Growth Regul.* 29: 249-256.
- CAMERON R., WILKINSON S., DAVIES W., HARRISON-MURRAY R., DUNSTAN D., BURGESS C., 2002. Regulation of plant growth in container-grown ornamentals through the use of controlled irrigation. *Acta Hort.* 630: 305-312.
- CARON J., RIVIÈRE L.-M., CHARPENTIER S., RENAULT P., MICHEL J.-C., 2002. Using TDR to estimate hydraulic conductivity and air entry in growing media and sand. *Soil Sci. Soc. Am. J.* 66: 373-383.
- CARVALHO S., HEUVELINK E., CASCAIS R., VAN KOOTEN O., 2002. Effect of day and night temperature on internode and stem length in chrysanthemum: is everything explained by DIF? *Ann. Bot.* 90: 111-118.
- CASAL J., SMITH H., 1989. The function, action and adaptive significance of phytochrome in light-grown plants. *Plant Cell Environ.* 12: 855-862.
- CERNY T.A., FAUST J.E., LAYNE D.R., RAJAPAKSE N.C., 2003. Influence of photoselective films and growing season on stem growth and flowering of six plant species. *J. Amer. Soc. Hort. Sci.* 128: 486-491.
- CLIFFORD S.C., RUNKLE E.S., LANGTON F.A., MEAD A., FOSTER S.A., PEARSON S., HEINS R.D., 2004. Height control of poinsettia using photoselective filters. *HortScience* 39: 383-387.
- COCKSHULL K.E., LANGTON F.A., CAVE C.R.J., 1995. Differential effects of different DIF treatments on *Chrysanthemum* and poinsettia. *Acta Hort.* 378: 15-25.
- CUIJPERS L.H.M., VOGELZANG J.V.M., 1992. DIF and temperature drop for short-day pot plants. *Acta Hort.* 327: 25-32.
- CUMMINGS I.G., FOO E., WELLER J.L., REID J.B., KOUTOULIS A., 2008. Blue and red photoselective shade cloths modify pea height through altered blue irradiance perceived by the cryl photoreceptor. *J. Hort. Sci. Biotechnol.* 83: 663-667.
- CURREY C.J., LOPEZ R.G., 2013. Cuttings of *Impatiens*, *Pelargonium*, and *Petunia* propagated under light-emitting diodes and high-pressure sodium lamps

- have comparable growth, morphology, gas exchange, and post-transplant performance. *HortScience* 48: 428-434.
- DAVIS T.D., SKYTT ANDERSEN A., 1989. Growth retardants as aids in adapting new floricultural crops to pot culture. *Acta Hort.* 252: 77-85.
- DECOTEAU D.R., FRIEND H.H., 1991. Growth and subsequent yield of tomatoes following end-of-day light treatment of transplants. *HortScience* 26: 1528-1530.
- EVANS L.T., HENDRICKS S.B., BORTHWICK H.A., 1965. The role of light in suppressing hypocotyl elongation in lettuce and *Petunia*. *Planta* 64: 201-218.
- FOLTA K.M., CHILDERS K.S., 2008. Light as a growth regulator: controlling plant biology with narrow-bandwidth solid-state lighting systems. *HortScience* 43: 1957-1964.
- GARNER L., ALLEN LANGTON F., BJÖRKMAN T., 1996. Commercial adaptations of mechanical stimulation for the control of transplant growth. *Acta Hort* 435: 219-230.
- GARNER L.C., BJÖRKMAN T., 1996. Mechanical conditioning for controlling excessive elongation in tomato transplants: sensitivity to dose, frequency, and timing of brushing. *J. Amer. Soc. Hort. Sci.* 121: 894-900.
- GRINDAL G., MOE R., 1994. Effects of temperature-drop and a short dark interruption on stem elongation and flowering in *Begonia hiemalis* Fotsch. *Sci. Hortic.* 57: 123-132.
- GRINDAL G., MOE R., JUNTILLA O., 1998. The role of gibberellin and phytochrome in DIF-mediated stem elongation. *Acta Hort.* 514: 205-212.
- GRINDAL PATIL G., MOE R., 2009. Involvement of phytochrome B in DIF mediated growth in cucumber. *Sci. Hortic.* 122: 164-170.
- HANSEN C., NIELSEN K., 2001. Reduced phosphorus availability as a method to reduce chemical growth regulation and to improve plant quality. *Plant Nutrition*. Springer, pp. 314-315.
- HANSEN C.W., PETERSEN K.K., LARSEN A.K., 2003. Effects of reduced nutrient and water availability on plant growth and post-production quality of *Hibiscus rosa-sinensis*. *Acta Hort.* 669: 269-274.
- HATT GRAHAM H.A., DECOTEAU D.R., 1995. Regulation of bell pepper seedling growth with end-of-day supplemental fluorescent light. *HortScience* 30: 487-489.
- HENDRIKS L., UEBER E., 1995. Alternative methods of regulating the elongation growth of ornamental plants: a current assessment. *Acta Hort.* 378: 159-167.
- IHLEBEKK H., EILERTSEN S., JUNTILLA S., GRINDAL G., MOE R., 1994. Control of plant height in *Campanula isophylla* by temperature alternations; involvement of GAs. *Acta Hort.* 394: 347-355.
- ISLAM M.A., 2013. Genetic engineering and light quality as tools to control shoot elongation in poinsettia (*Euphorbia pulcherrima* Willd ex Klotsch). Diss, Norwegian University of Life Sciences, Ås, Norway.
- ISLAM M.A., KUWAR G., CLARKE J.L., BLYSTAD D.R., GISLERØD H.R., OLSEN J.E., TORRE S., 2012. Artificial light from light emitting diodes (LEDs) with a high portion of blue light results in shorter poinsettias compared to high pressure sodium lamps. *Sci. Hortic.* 147: 136-143.
- JACOBSEN L.H., AMSSEN M.G., 1990. The effect of temperature and light quality on stem elongation of chrysanthemum. *Acta Hort.* 305: 45-50.
- JENSEN E., EILERTSEN S., ERNSTEN A., JUNTILLA O., MOE R., 1996. Thermoperiodic control of stem elongation and endogenous gibberellins in *Campanula isophylla*. *J. Plant Growth Regul.* 15: 167-171.
- KHATTAK A.M., PEARSON S., 2006. Spectral filters and temperature effects on the growth and development of chrysanthemums under low light integral. *Plant Growth Regul.* 49: 61-68.
- KHATTAK A.M., PEARSON S., JOHNSON C.B., 2004. The effects of far red spectral filters and plant density on the growth and development of chrysanthemums. *Sci. Hortic.* 102: 335-341.
- KRESTEN JENSEN H.E., 1994. Effects of duration and degree of pulse-DIF temperatures on plant height and flowering of *Kalanchoe blossfeldiana* v. Poelln. *Sci. Hortic.* 59: 45-54.
- LANGTON F.A., COCKSHULL K.E., 1997. Is stem extension determined by DIF or by absolute day and night temperatures? *Sci. Hortic.* 69: 229-237.
- LATIMER J.G., MITCHELL C.A., 1988. Effects of mechanical stress or abscisic acid on growth, water status and leaf abscisic acid content of eggplant seedlings. *Sci. Hortic.* 36: 37-46.
- LI S., RAJAPAKSE N.C., YOUNG R.E., 2003. Far-red light absorbing photosensitive plastic films affect growth and flowering of *Chrysanthemum* cultivars. *HortScience* 38: 284-287.
- LYKAS C., KITTAS C., KATSOULAS N., 2008. *Gardenia jasminoides* height control using a photosensitive polyethylene film. *HortScience* 43: 2027-2033.
- LÜTKEN H., SANDER JENSEN L., HOVBYE TOPP S., MIBUS H., MÜLLER R., RASMUSSEN S.K., 2010. Production of compact plants by overexpression of *AtSHI* in the ornamental *Kalanchoë*. *Plant Biotechnol. J.* 8: 211-222.
- LÖFKVIST K., LARSEN R., ENGLUND J.-E., ALSANIUS B., 2009. Light integral as an indicator of water use in commercial greenhouse nurseries. *Acta Agric. Scand., Sect. B* 59: 326-334.
- MARKVART J., ROSENQVIST E., AASLYNG J.M., OTTOSEN C.-O., 2010. How is canopy photosynthesis and growth of *Chrysanthemum* affected by diffuse and direct light? *Europ. J. Hort. Sci* 75(6): 253-258
- MATA D.A., BOTTO J.F., 2009. Manipulation of light environment to produce high-quality Poinsettia plants. *HortScience* 44: 702-706.

- McMAHON M.J., KELLY J.W., 1990. Influence of spectral filters on height, leaf chlorophyll, and flowering of *Rosa x hybrida* 'Meirutral'. *J. Environ. Hort.* 8: 209-211.
- MIBUS H., HOFF K., SEREK M., 2014. Ethanol treatment induces compact growth in *Kalanchoë*. *Sci. Hortic.* 168: 234-239.
- MILLER W.B., HAMMER P.A., KIRK T.I., 1993. Reversed greenhouse temperatures alter carbohydrate status in *Lilium longiflorum* Thunb. 'Nellie White'. *J. Amer. Soc. Hort. Sci.* 118: 736-740.
- MIRALLES-CRESPO J., SÁNCHEZ-BLANCO M.J., NAVARRO G.A., MARTÍNEZ-SÁNCHEZ J.J., FRANCO L.J.A., BAÑÓN A.S., 2010. Comparison of stem diameter variations in three small ornamental shrubs under water stress. *HortScience* 45(11):1681-1689.
- MOE R., 1990. Effect of day and night temperature alternations and of plant growth regulators on stem elongation and flowering of the long-day plant *Campanula isophylla* Moretti. *Sci. Hortic.* 43: 291-305.
- MOE R., GLOMSRUD N., BRATBERG I., VALSØ S., 1992. Control of plant height in Poinsettia by temperature drop and graphical tracking. *Acta Hort.* 327: 41-48.
- MOE R., WILLUMSEN K., IHLEBEKK I.H., STUPA A.I., GLOMSRUD N.M., MORTENSEN L.M., 1995. DIF and temperature drop responses in SDP and LDP, a comparison. *Acta Hort.* 378: 27-33.
- MORGAN D., SMITH H., 1979. A systematic relationship between phytochrome-controlled development and species habitat, for plants grown in simulated natural radiation. *Planta* 145: 253-258.
- MORGAN D.C., SMITH H., 1976. Linear relationship between phytochrome photoequilibrium and growth in plants under simulated natural radiation. *Nature* 262: 210-212.
- MORROW R.C., 2008. LED Lighting in Horticulture. *HortScience* 43: 1947-1950.
- MORTENSEN L.M., 2014. The effect of photon flux density and lighting period on growth, flowering, powdery mildew and water relations of miniature roses. *Amer. J. Plant Sci.* 5: 1813-1818.
- MORTENSEN L.M., STRØMME E., 1987. Effects of light quality on some greenhouse crops. *Sci. Hortic.* 33: 27-36.
- MYSTER J., JUNTILA O., LINDGAARD B., MOE R., 1997. Temperature alternations and the influence of gibberellins and indoleacetic acid on elongation growth and flowering of *Begonia x hiemalis* Fotsch. *Plant Growth Regul.* 21: 135-144.
- NELSON P.V., 1998. Greenhouse operation and management. Prentice Hall, Upper Saddle River, USA.
- NETO A.E.F., BOLDRIN K.V.F., MATTSON N.S., 2015. Nutrition and quality in ornamental plants. *Ornamental Horticulture* 21(2): 139-150
- NORCINI J.G., HUDSON W.G., GARBER M.P., JONES R.K., CHASE A.R., BONDARI K., 1996. Pest management in the US greenhouse and nursery industry: III. *Plant Growth Regul. HortTechnology* 6: 207-210.
- OTTOSEN C.-O., ROSENQVIST E., AASLYNG J.M., JAKOBSEN L., 2004. Dynamic climate control in combination with average temperature control saves energy in ornamentals. *Acta Hort.* 691: 133-140.
- OYAERT E., VOLCKAERT E., DEBERGH P.C., 1995. Growth of *Chrysanthemum* under coloured plastic films with different light qualities and quantities. *Sci. Hortic.* 79: 105-205.
- PARKER M.W., BORTHWICK H.A., RAPPLEYE L.E. 1950. Photoperiodic responses of poinsettia. *Florist's Exchange*, 115(20):11, 49-50.
- POORTER H., BÜHLER J., VAN DUSSCHOTEN D., CLIMENT J., POSTMA J.A., 2012. Pot size matters: a meta-analysis of the effects of rooting volume on plant growth. *Functional Plant Biology* 39: 839-850.
- RADEMACHER W., 2015. Plant growth regulators: Backgrounds and uses in plant production. *J. Plant Growth Regul.* 34: 845-872
- RADEMACHER W., BUCCI T., 2002. New plant growth regulators: High risk investment? *HortTechnology* 12: 64-67.
- RAJAPAKSE N.C., KELLY J.W., 1995. Spectral filters and growing season influence growth and carbohydrate status of *Chrysanthemum*. *J. Amer. Soc. Hort. Sci.* 120: 78-83.
- RUNKLE E.S., HEINS R.D., 2001. Specific functions of red, far red, and blue light in flowering and stem extension of long-day plants. *J. Amer. Soc. Hort. Sci.* 126: 275-282.
- RUNKLE E.S., PADHYE S.R., OH W., GETTER K. 2012. Replacing incandescent lamps with compact fluorescent lamps may delay flowering. *Sci. Hortic.* 143:56-61.
- SAGER J., SMITH H., EDWARDS J., CYR K. 1988. Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. *Trans. ASABE (Am. Soc. Agric. Biol. Eng.)* 31: 1882-1889.
- SÁNCHEZ-BLANCO M.J., ÁLVAREZ S., NAVARRO A., BAÑÓN S., 2009. Changes in leaf water relations, gas exchange, growth and flowering in potted geranium plants irrigated with different water regimes. *J. Plant. Physiol.* 166:467-476.
- SCHUM A., 2003. Mutation breeding in ornamentals: an efficient breeding method? *Acta Hort.* 612: 47-60.
- SCHÜSSLER H.K., BERGSTRAND K.J., 2012. Control of the shoot elongation in bedding plants using extreme short day treatments. *Acta Hort.* 956: 409-415.
- SCHÜSSLER H.K., KOSIBA A., 2006. Effects of extreme short-day treatment (ESD) on the development and appearance of *Calibrachoa hybr.* Cerv. and *Scaevola saligna* G. Forst. *Acta Hort.* 711: 297-300.
- SKYTT ANDERSEN A., ANDERSEN L., 2000. Growth regulation as a necessary prerequisite for introduction of new plants. *Acta Hort.* 541: 183-192.

- STARKEY K.R., ANDERSSON N.E., 2000. Effects of light and nitrogen supply on the allocation of dry matter and calcium in poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch). *J. Hortic. Sci. Biotech.* 75: 251-258.
- TANGERAS H., 1979. Modifying effects of ancymidol and gibberellins on temperature induced elongation in *Fuchsia* × *hybrida*. *Acta Hort.* 91: 411-417.
- TANTAU H.-J., 1998. Energy saving potential of greenhouse climate control. *Mathematics and Computers in Simulation* 48: 93-101.
- TATINENI A., RAJAPAKSE N.C., FERNANDEZ T., RIECK J.R., 2000. Effectiveness of plant growth regulators under photoselective greenhouse covers. *J. Amer. Soc. Hort. Sci.* 125: 673-678.
- TEIXEIRA DA SILVA J.A., 2004. Ornamental chrysanthemums: improvement by biotechnology. *Plant Cell Tissue Organ Cult.* 79: 1-18.
- VAN HAERINGEN C.J., WEST J.S., DAVIS F.J., GILBERT A., HADLEY P., PEARSON S., WHELDON A.E., HENBEST R.G.C., 1998. The development of solid spectral filters for the regulation of plant growth. *Photochem. Photobiol.* 67: 407-413.
- VAN IEPEREN W., 2012. Plant morphological and developmental responses to light quality in a horticultural context. *Acta Hort.* 956: 131-139.
- VINCE-PRUE D., 1977. Photocontrol of stem elongation in light-grown plants of *Fuchsia hybrida*. *Planta* 133: 149-156.
- WARRINGTON I., NORTON R., 1991. An evaluation of plant growth and development under various daily quantum integrals. *J. Americ. Soc. Hort. Sci.* 116: 544-551.
- WENT F.W., 1944. Plant growth under controlled conditions. II. Thermoperiodicity in Growth and Fruiting of the Tomato. *Am. J. Bot.* 31(3): 135-150.
- XIONG J., GRINDAL PATIL G., MOE R., 2002. Effects of DIF and end-of-day light quality on stem elongation in *Cucumis sativus*. *Sci. Hortic.* 94: 219-229.
- YAMAGUCHI S., 2008. Gibberellin metabolism and its regulation. *Annu. Rev. Plant Biol.* 59: 225-251.
- YANG Z.-C., KUBOTA C., CHIA P.-L., KACIRA M., 2012. Effect of end-of-day far red light from a movable LED fixture on squash rootstock hypocotyl elongation. *Sci. Hortic.* 136: 81-86.

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