EFFECT OF LED LIGHTING AND SILICON SUPPLEMENTATION ON GROWTH AND FLOWERING OF CUT FLOWERS

By

TAYLOR S. MILLS

Bachelor of Science in Plant Science

Southern Arkansas University

Magnolia, Arkansas

2015

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2017

EFFECT OF LED LIGHTING AND SILICON SUPPLEMENTATION ON GROWTH AND FLOWERING OF CUT FLOWERS

Thesis Approved:

Dr. Bruce Dunn

Thesis Adviser

Dr. Niels Maness

Committee Member

Dr. Mark Payton

Committee Member

ACKNOWLEDGEMENTS

First, I believe and give thanks to God. I found much needed grace during this challenging opportunity. Most importantly, I dedicate this thesis to my family, because I am the first to achieve such a great deed and they are so proud. I am and will forever be grateful to my husband who is my biggest supporter ever in life.

I extend many thanks to faculty, friends, and colleagues that I have met at Southern Arkansas University and Oklahoma State University. You all have given me much needed encouragement and advice, which I value so much.

To my committee members Dr. Bruce Dunn, Dr. Niels Maness, and Dr. Mark Payton: thank you all for the support and insight you have provided me regarding this research and thesis work. I feel sincere gratitude towards this experience here at Oklahoma State University.

Name: TAYLOR S. MILLS

Date of Degree: DECEMBER, 2017

Title of Study: EFFECT OF LED LIGHTING AND SILICON SUPPLEMENTATION ON GROWTH AND FLOWERING OF CUT FLOWERS

Major Field: HORTICULTURE

Abstract: Use of light emitting diodes (LED) technology is beginning to replace traditional lighting in greenhouses. This research focused on the effects of LED lighting and GA_3 supplementation on growth and flowering of cut flowers. *Dahlia* spp. (Cav.) 'Karma Serena' and 'Karma Maarten Zwaan', *Liatris spicata* (Gaertn. ex Schreb) 'Kobold', and *Lilium asiatic* (L.) 'Yellow Cocotte' and 'Montreux' were subjected to varying light treatments including LED flowering lamps and halogen lamps. The flowering lamps emitted a combination of red + far-red + white and red + white. Photoperiod was extended by operating all lamps for 7 hours in the night and the experiment ran from late fall to early spring. Results varied within species and cultivars in response to light and GA_3. Light was the most effective on growth and flowering characteristics especially in liatris and both cultivars of dahlia. In liatris, flowering occurred 2 weeks earlier under sole LED lighting than under other light treatments and no supplemental light. Although flowering occurred earliest in both cultivars of dahlias under no light, plants under light treatments had greater height, width, and shoot weight. There were significant effects of GA_3 on growth and flowering characteristics in dahlia cultivars and lily cultivars such as greater height, width, and flower number. A significant interaction of light with GA_3 influenced height, width, mean flower number, flower diameter, days to anthesis, and flowering percentage in several crops. The role of silicon (Si) as a needed supplement in soilless media is gaining interest. This research studied the effects of diatomaceous earth (DE) as a supplemental Si source on growth and flower characteristics, physiology, and nutrient uptake of cut flowers such as *Dahlia* spp. (Cav) 'Dahlinova Montana', *Rudbeckia hirta* (L.) 'Denver Daisy', and *Gerbera jamesonii* (L.) 'Festival Light Eye White Shades'. Nine Si treatments were established, and plants were considered well-watered at 10 centibars or water-stressed at 20 centibars. Silicon treatments included application of DE across the top of the pots (top-dressed) incorporation, and Metro-Mix 360 media with and without Si. For each species, there were six pots per Si rate per irrigation treatment. Significant effects were seen from Si supplementation, irrigation, and interaction in all plants. Growth and flower characteristics, leaf nutrient content, and tolerance to stress were improved by application of DE.

TABLE OF CONTENTS

Chapter Page

I. Silicon Literature Review 1

LIST OF TABLES

Table Page

CHAPTER I

SILICON LITERATURE REVIEW

Uptake, Translocation, and Accumulation of Silicon

Plants take up silicon (Si) via the roots or foliage (Muir et al., 2001) in a soluble form known as silicic acid [$Si(OH)_4$], which becomes deposited in the endoplasmic reticulum, cell walls, and intercellular spaces as amorphous silica or phytoliths (Epstein, 1994). Silicon is distributed in various plant parts including roots, stems, leaves, and flowers with greater amounts being in the foliage (Jones and Handreck, 1967). Silicon also has an association with RNA and DNA, having a series of intracellular sites of action to explain stimulating properties in plant resistance and tolerance (Scarbough, 2007). The process of Si uptake and translocation is energy dependent and the mechanisms involved differ among plant species (Mitani et al., 2005). Transport is both active and passive with active being the most responsible for Si uptake, specifically in maize (*Zea mays* L.) and rice (*Oryza sativa* L.) plants (Liang et al., 2006). The amount of Si in plants typically ranges from 0.1 to 10% of dry weight and varies between species (Epstein, 1994). Currie and Perry (2007) identified plants as high Si accumulators if the levels of the nutrient were greater than 4%, and plants that took up 2 to 4% of Si were considered intermediate accumulators. Ma and Takahashi (2002) identified plants with less than 0.5% of Si as non-accumulators.

Effect of Silicon on Plant Growth and Quality

Silicon plays an important role in plant growth and quality. A series of studies by Kamenidou (2008, 2009, 2010) reported that supplemental Si enhanced the growth and quality of important floricultural crops such as ornamental sunflowers (*Helianthus annuus* L.) 'Ring of Fire', zinnias (*Zinnia elegans* Jacq.) 'Oklahoma Formula Mix' and gerbera (*Gerbera jamesonii* L.) 'Acapella'. Traits that were enhanced in these crops included stem thickness, stem apical and basal diameter, stem strength, flower diameter, and height. Whitted-Haag et al. (2014) applied Si to the foliage of geranium (*Pelargonium* x *hortorum* Bailey) 'Elite Cherry', impatiens (*Impatiens walleriana* Hook.f.) 'Accent White', pansy (*Viola* x *wittrockiana* Hort.) 'Delta Premium Marina', petunia (*Petunia x hybrid* (Hooker) Vilmorin. 'Celebrity White', and snapdragon (*Antirrhinum majus* L.) 'Montego Purple' and found significant effects on plant height, stem diameter, days to flower, and flower diameter of some species. When foliar Si treatment increased from 50 mg·L^{-1} to 200 mg·L^{-1}, height in snapdragon increased and days to flower decreased in impatiens. Only a significant decrease of stem diameter was seen in all plant species as Si treatment increased. Flower diameter increased then decreased in impatiens. Twenty-one different cultivars of floricultural crops grown in pots were supplemented weekly with potassium silicate using the drench method. Silicon content significantly increased in leaves of 11 supplemented cultivars and depending on species, growth parameters such as apical and basal diameter, flower diameter, leaf thickness, fresh and dry weight, and plant height were significantly effected as well

(Mattson et al., 2010). Cucumber (*Cucumis sativas* L.) plants grown in a solution culture with Si grew more, having no abnormal growth compared to cucumbers without Si (Miyaki and Takahashi, 1983). Savvas et al. (2002) reported that Si supplementation of hydroponically-cultured gerbera improved flower quality which was graded as Class I and thickened stems. Agronomic crops such as wheat (*Triticum aestivum* L.), corn (*Zea mays*) 'DK 647 F1', soybean (*Glycine max* L.) 'Zhonghuang 13', and sorghum (*Sorghum bicolor* L.) 'Gadambalia' supplemented with Si had increased dry mass of shoots and roots (Gong et al., 2003; Kaya et al., 2006; Shen et al., 2010; Sonobe et al., 2010).

Silicon Relieving Abiotic and Biotic Stress

Silicon plays an important role in combating various biotic and abiotic stresses in horticultural crops by acting as a physical and chemical barrier and improving plant tolerance and resistance. There has been an increased interest in the use of Si to reduce effects of abiotic and biotic plant stress in several horticultural crops. These studies have shown that beneficial effects of Si on plants are more apparent under stressful conditions. Addition of Si in small concentrations enhanced salt tolerance in several crops such as rice, mesquite (*Prosopis julifora* DC.), wheat, barley (*Hordeum vulgare* L.), cucumber, and tomato (*Lycopersicon esculentum* Mill.) (Ahmad et al., 1992; Bradbury and Ahmad, 1990; Al-Aghabary et al., 2004; Liang et., 1996; Matoh et al., 1986; Zhu et al., 2004). The possible mechanism for salinity tolerance involves reducing membrane permeability and improving structure and stability (Liang et al., 2007). A combination of internal and external mechanisms is involved in the effect of Si alleviating metal toxicity (Ma, 2004). Alleviation from Si on Manganese (Mn) and aluminum (Al) toxicity has been observed in rice (*Oryza sativa* L.), bean (*Phaseolus vulgaris* L.), and pumpkin (*Cucurbita moschata* Duch ez Poir.) (Horst and Marscher, 1978; Horiguchi, 1988; Iwasaki and Matsumura, 1999; Rogalla and Romheld, 2002). Silicon deposited beneath the cuticle of leaves decreased transpiration, alleviating stress from water deficiency or drought stress, (Gunes et al., 2008; Ma et al., 2004; Saud et al., 2014). When supplemented with Si, the roots of cucumbers infected by *Pythium* spp. (Pringsh.) formed rigid barriers and lignin in plants (Cherif et al., 1994). High concentrations of Si suppressed powdery mildew on leaves of strawberry (*Fragaria ananassa* Duch.) and grapes (*Vitis vinifera* L.) (Bowen et al. 1992; Kanto et al., 2002; Menzies et al., 1992; Miyake and Takahasi, 1983). In addition, Si suppressed insect damage (Savant et al., 1996).

Effect of Silicon on Plant Physiology

The effects of Si on plant physiology has not been fully understood (Agarie et al., 1998; Lewin and Reimann, 1962). However, most studies highlight the effect of Si on osmosis, photosynthesis, and transpiration. These physiological phenomena occur in cell membranes. When abiotic and biotic stress disrupts the plants physiologically, cell membranes are damaged. Silicon, however, plays an important role in cell membrane integrity. Maize (c.v. 704) suffering from salinity had photosynthetic rates increased when Si was supplemented (Rohanipoor et al., 2013). Nasseri et al. (2012) found that supplementary Si at 0.2 mM ameliorated the negative effects of salinity on plant dry matter and chlorophyll content of fenugreek (*Trigonella foenum- graceum* L.). Results indicated that Si increased the tolerance to salt stress, in which the leaf relative water content and chlorophylls a and b were maintained in higher levels. Kaya et al. (2006) found that maize under water-stressed conditions had reduced total dry matter (DM), chlorophyll content, and relative water content (RWC), as well as increased proline accumulation and electrolyte leakage. Silicon treatments improved these parameters by increasing DM, chlorophyll content, and RWC, while reducing proline accumulation and electrolyte leakage. In rice, the rate of transpiration was reduced by application of silica (Agarie et al., 1998). Floricultural crops such as zinnia grown under optimal greenhouse conditions had increased leaf resistance in recently mature leaves when 100 $mg \cdot L^{-1}$ of $NaSiO_3$ was applied as a weekly foliar spray (Kamenidou et al., 2009).

Effect of Silicon on Nutrient Uptake and Availability

Silicon has plays a role in the uptake, translocation, and availability of other nutrients. Kaya et. al (2006) found that the addition of Si increased both leaf and root calcium (Ca), which partially restores the membrane integrity in water-stressed plants and maintains membrane stability and permeability. Gerbera grown in a hydroponic system had increased Ca in leaf tissue (Savvas et al., 2002). Potassium (K) also increased when Si is available. Potassium is involved in osmotic adjustment and the cell membranes and the process itself are maintained with the presence of both Si and K, respectively (Ashraf et al., 2001; Iannucci et al., 2002; Liang, 1999). Nitrogen (N) is another essential element that is increased in the presence of Si. Pati et al. (2016) found that higher concentrations of soluble Si enhanced the uptake and concentration of N. Others have noted that Si has the potential to raise available N and N-use efficiency in plants (Savant et al., 1996; Singh, 2005). Accessibility of phosphorous (P) can be increased indirectly by decreasing the availability of iron (Fe) and Mn in plants (Ma, 2004). In addition, Si application can increase root growth allowing more efficient uptake of P (Subramanian and Gopalswamy, 1990). Aluminum, Fe, and Mn have an antagonistic relationship with Si. Toxicity effects from these metals can be alleviatd when Si is present (Mills and Jones, 1996). In cotton, maize, soybean, and barley, increased levels of Si decrease Al toxicity (Epstein, 1994; Hodson and Evans, 1995). In return, aluminum oxides can reduce availability of Si for plant uptake (Jones and Handreck, 1965; Exley 1998; Perry and Keeling-Tucker, 1998). Plants deficient in Si will uptake excess Mn and Fe. However, Si supplementation can releive both toxicities (El-Jaoual and Cox, 1998). Ma and Yamaji (2006) suggested that deposition of Si in roots result in the decreased uptake of toxic metals.

Sources of Silicon

Silicon is available from natural resources, fertilizers (organic and inorganic), and industrial by-products. Considerations such as solubility, availability, suitability, physical properties, and contaminants-free must be considered before choosing a source (Gascho, 2001). Bodies of water and soils, depending on geology, can have low or high concentrations of Si (Imaizumi and Yoshida, 1958; Kobayashi, 1961). By-products include sodium silicate, potassium silicate, calcium silicate (slag), magnesium silicate, basalt dust, dolomite, and rock phosphate, which are known to help with plant disease in fruit tree production (Mitre et al., 2010) as well as improve horticultural traits in zinnia, ornamental sunflowers, and gerbera (Kamenidou, 2008, 2009, 2010). Rice hulls are from plant residues and have sufficient Si concentration (Tubana, 2016). Rice hulls help alleviate effects of anthracnose disease and improve some growth and fruit parameters of capsicum grown in a hydroponics system (Ishibashi, 1956; Jayawardaba et al., 2016). Diatoms, a group of algae, accumulate amorphous silica when fossilized. When extracted and processed, the fossilized diatoms turn into a powdery-soft-siliceous sedimentary rock known as diatomaceous earth (DE). In agriculture, fresh-watered DE is often used as an insecticide or dewormer for livestock (Fernandez, 1998). Diatomaceous earth can also be used as an additive in hydroponic systems and potted plant production for seedlings and plugs (Yildiz, 2008). Diatomaceous earth helps to retain water and nutrients as well high oxygen circulation within the growing medium or solution. Meerow and Broschat (1996) and Wehtje (2003) showed that DE increased plant growth and quality ratings in bermudagrass (*Cynodon dactylon* L.) and hibiscus (*Hibiscus rosasinensis* L.), respectively. A field experiment conducted during a rainy season by Pati et al., (2016) studied the effect of DE as a Si fertilizer on growth, yield, and nutrient uptake of rice. Results showed application increased yield as well as attributing parameters such as plant height, number of tillers, number of panicles, and weight. In addition, uptake of Si, N, P, and K were also increased.

Silicon Measurements and Analysis Methods

Total, extractable, and soluble are the different forms of Si in soils and amendments, with soluble Si being the most agronomical important (Berthelsen et al., 2003). Therefore, testing of Si content in plants, soil, and fertilizers is recommended (Savant et al., 1996). Leaf tissue sampling is the most common method for analyzing Si in plants. X-ray fluorescence is another method used on oven dried plant matter. Auto-clave induced digestion procedure is a well-established method and is the most reliable when outputting results (Elliot and Snyder, 1991). For soil analysis of Si, extraction methods are used. Muir et al. (2001) suggested that there is importance when choosing a method, because extraction processes may solubilize more Si compounds in the soil than usually available to plants. The weakest extractants are water and calcium chloride (Berthelsen et al., 2003), while acetates/acetic acids are known to be too strong but are the most successful (Nonaka and Takahashi, 1990). Various studies have used different methods. Mattson et al. (2010) determined leaf tissue Si in several floricultural crops using autoclave digestion and silicomolybdous acid colorimetric method of Elliott and Snyder (1991). Silicon content in rice straw was determined by using Ma et al. (2006) method in which powdered plant samples are digested in varying acids (e.g. boric acid, hydrochloric acid, and tartaric acid) as well as hydrogen peroxide, ammonium molybdate, and a reducing agent (Pati et al., 2016). In both studies conducted by Agarie et al. (1998), Si in leaves of rice plants was determined by gravimetric procedures and a colorimetric method with molybdenum blue (Yoshida et al., 1976).

Literature Cited

Agarie, S., H. Uchida, W. Agata, F. Kubota, and P.B. Kaufman. 1998. Effects of silicon on transpiration and leaf conductance in rice plants (*Oryza sativa* L.). Plant Prod. Sci. 1(2):89-95.

Agarie, S., H. Uchida, W. Agata, F. Kubota, and P.B. Kaufman. 1998. Effects of silicon on tolerance to water deficit and heat stress in rice plants (*Oryza sativa* L.), monitored by electrolyte leakage. Plant Prod. Sci. 1(2):96-103.

Ahmad, R., S.H. Zaheer, and S. Ismail. 1992. Role of silicon in salt tolerance of wheat (*Tritium aestivum* L.). Plant Sci. 85:43-50.

Al-Aghabary, K., Z.J. Zhu, and Q.H. Shi. 2004. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence, and antioxidative enzyme activities in tomato plants under salt stress. J. Plant Nutr. 27:2101-2115.

Ashraf, M., A. Ahmad, and T. McNeilly. 2001. Growth and photosynthetic characteristics in pearl millet under water stress and different potassium supply. Photosynthetica 39:389-394.

Belanger, R.R., P.A. Bowen, D.L. Ehret, and J.G. Menzies. 1995. Soluble silicon: its role in crop and disease management of greenhouse crops. Plant Dis. 79:329-336.

Berthelsen, S., A.D. Noble, G. Kingston, A. Hurney, A. Rudd, and A. Garside. 2003. Improving yield and ccs in sugarcane through the application of silicon based amendments. Final report on SRDC Project CLW009. http://elibrary.sugarresearch.com.au. Accessed 9 October 2017.

Bloodnick,E. 2017. Role of Silicon in plant culture. http://www.pthorticulture.com/en/training-center/role-of-silicon-in-plant-culture/. Accessed 9 October 2017.

Bowen, P., J. Menzies, D. Ehret, L. Samuels, and A.D. Glass. 1992. Soluble silicon sprays inhibit powdery mildew development on grape leaves. J. Amer. Soc. Hort. Sci. 117(6):906-912.

Bradbury, M. and R. Ahmad. 1990. The effect of silicon on the growth of *Prosopis julifora* growing in saline soil. Plant Soil 125:71-74.

Buechel, T. 2017. Role of Nickel in Plant Culture. http://www.pthorticulture.com/en/training-center/role-of-nickel-in-plant-culture/. Accessed 9 October 2017.

Carvalho-Zanao, M.P., J. LAZ, J.G. Barbosa, J.A.S. Grossi, and V.T. Ávila. 2012. Yield and shelf life of *Chrysanthemum* in response to the silicon application. Hort. Brasileira 30:403-408.

Chérif, M., A. Asselin, and R.R. Bélanger. 1994. Defense responses induced by soluble silicon in cucumber roots infected by *Pythium* spp. Phytopathology 84(3):236-242.

Currie, H.A. and C.C. Perry. 2007. Silica in plants: biological, biochemical, and chemical studies. Ann. Bot. 100:1383-1389.

De Kreij, C. W. Voogt, and R. Baas. 1999. Nutrient solutions and water quality for soilless cultures. Research Station for Floriculture and Glasshouse Vegetables Brochure, Naaldwijk, The Netherlands.

Ehret, D.L., J.G. Menzies, and T. Helmer. 2005. Production and quality of greenhouse roses in recirculating nutrient systems. Sci. Hort. 106:103-113.

Elliott, C.L. and G.H. Snyder. 1991. Autoclave-induced digestion for the colorimetric determination of silicon in rice straw. J. Agr. Food Chem. 39(6):1118-1119.

El-Jaoual, T. and D.A. Cox. 1998. Manganese toxicity in plants. J. Plant Nutr. 21:353-386.

Epstein, E. 1994. The anomaly of silicon in plant biology. Proc. Natl. Acad. Sci. USA. 91:11-7.

Epstein, E. 2009. Silicon: its manifold roles in plants. Ann. Appl. Biol. 155:155-160.

Exley, C. 1998 Silicon in life: A bioinorganic solution to bioorganic essentiality. J. Inorg. Biochem. 69:139-144.

Fernandez, M., B. Woodward, and B. Stromberg. 1998. Effect of diatomaceous earth as an anthelmintic treatment on internal parasites and feedlot performance of beef steers. Anim. Sci. 66(3):635-641.

Fisher, R.A. 1929. A preliminary note on the effect of sodium silicate in increasing the yield of barley. J. Agric. Sci. 19:132-139.

Friedman, H., N. Bernstein, M. Bruner, I. Rot, Z. Ben-Noon, A. Zuriel, R. Zuriel, S. Finklestein, N. Umiel, and A. Hagiladi. 2007. Application of secondary-treated effluents for cultivation of sunflower (*Helianthus annus* L.) and celosia (*Celosia argentea* L.) as cut flowers. Sci. Hort. 115:62-69.

Gascho, G.J. 2001. Silicon sources for agriculture. Stud. Plant Sci. 8:197-207.

Gong, H.K., G. Chen, S. Wang, and C. Zhang. 2003. Effects of silicon on growth of wheat under drought. J. Plant Nutr. 26:1055-1063.

Gunes, A., D.J. Pilbeam, A. Inal, and S. Coban. 2008. Influence of silicon on sunflower cultivars under drought stress. I: growth, antioxidant mechanisms, and lipid peroxidation. Commun. Soil Sci. Plant Anal. 39:1885-1903.

Hammond, K.E., D.E. Evans, and M.J. Hodson. 1995. Aluminum/silicon interactions in barley (*Hordeum vulgare* L.) seedlings. Plant Soil 173:89-95.

Horiguchi, T. 1988. Mechanism of manganese toxicity and tolerance of plants: IV. Effects of silicon on alleviation of manganese toxicity of rice plants. Soil Sci. Plant Nutr. 34(1):65-73.

Horst, W.J. and H. Marschner. 1978. Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil 50(1-3):287-303.

Hwang, S.J., H.M. Park, and B.R. Jeong. 2005. Effects of potassium silicate on the growth of miniature rose Pinnochio grown on rockwool and its cut flower quality. J. Jpn. Soc. Hort. Sci. 74:242-247.

Iannucci, A., M. Russo, L. Arena, N. Di Fonzo, and P. Martiniello. 2002.Water deficit effects on osmotic adjustment and solute accumulation in leaves of annual clovers. Eur. J. Agron. 16:111-122.

Imaizumi, K. and S. Yoshida. 1958. Edophological studies on silicon supplying power of paddy fields. Bulletin Natl. Inst. Agr. Sci. series B. No.8:261-304.

Ishibashi, H. 1956. Influence of silica on the growth of rice plant. Jpn. J. Soil Sci. Plant Nutr. 10:244-256.

Iwasaki, K. and A. Matsumura. 1999. Effect of silicon on alleviation of manganese toxicity in pumpkin (*Cucurbita moschata* Duch cv. Shintosa). Soil Sci. Plant Nutr. 45(4):909-920.

Jana, S. and B.R. Jeong. 2014. Silicon: the most under-appreciated element in horticultural crops. Trends Hort. Res. 4:1-19.

Jawardana, R.K., D. Weerahewa, and J. Saparamadu. 2016. The effect of rice hull as a silicon source on anthracnose disease resistance and some growth and fruit parameters of capsicum grown in simplified hydroponics. Intl. J. Recycling Organic Waste Agr. 5(1): 9-15.

Jones, L.H.P. and K.A. Handreck. 1965. Studies of silica in the oat plant. III-Uptake of silica from soils by the plant. Plant Soil 23:79-96.

Jones, L.H.P. and K.A. Handreck. 1967. Silica in soils, plants, and animals. Adv. Agron. 19:107-149.

Kalra, Y. 1998. *Handbook of reference methods for plant analysis*. Boston, MA: CRC Press.

Kamenidou, S., T.J. Cavins, and S. Marek. 2008. Silicon supplements affect horticultural traits of greenhouse-produced ornamental sunflowers. HortScience 43(1):236-239.

Kamenidou, S., T.J. Cavins, and S. Marek. 2009. Evaluation of silicon as a nutritional supplement for greenhouse zinnia production. Sci. Hort. 119(3):297-301.

Kamenidou, S., T.J. Cavins, and S. Marek. 2010. Silicon supplements affect floricultural quality traits and elemental nutrient concentrations of greenhouse produced gerbera. Sci. Hort. 123(3):390-394.

Kanto, T., A. Miyoshi, T. Ogawa, K. Maekawa, and M. Aino. 2006. Suppressive effect of liquid potassium silicate on powdery mildew of strawberry in soil. J. Gen. Plant Pathol. 72(3):137-142.

Kaya, C., L. Tuna, and D. Higgs. 2006. Effect of silicon on plant growth and mineral nutrition of maize grown under water-stress conditions. J. Plant Nutr. 29:1469-1480.

King, P.A. and S. Reddy, inventors; SunGro Horticulture, Inc., assignee. US patent 6074988. Jun 13, 2000.

Kobayashi, J. 1961. A chemical study on the average quality and characteristics of river waters of Jpn. Nogaku-kenkyu 48:63-106.

Kovda, V.A. 1973. The bases of learning about soils. Moscow: Nayka.

Lewin, J. and B.E.F. Reimann. 1962. Silicon and plant growth. Ann. Rev. Plant Physiol. 20:289-304.

Liang, Y.C., Q.R. Shen, Z.G. Shen, and T.S. Ma. 1996. Effects of silicon on salinity tolerance of two barley cultivars. J. Plant Nutr. 19:173-183.

Liang, Y. 1999. Effects of silicon on enzyme activity and sodium, potassium and calcium concentration in barley under salt stress. Plant Soil 209:217-224.

Liang, Y., W. Sun, Y.G. Zhu, and P. Christie. 2006. Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. Environ. Pollut. 147:422-428.

Lim, M.Y., E.J. Lee, S. Jana, I. Sivanesan, and B.R. Jeong. 2012. Effect of potassium silicate on growth and leaf epidermal characteristics of Begonia and Pansy grown *in vitro*. Korean J. Hort. Sci. Technol. 30:579-585.

Lindsay, W.L. 1979. Chemical equilibria in soil. John Wiley & Sons, New York.

Ma, J.F. and E. Takahashi. 1993. Interaction between calcium and silicon in water-cultured rice plants. Plant Soil. 148:107-113.

Ma, J. F. and E. Takahashi. 2002. *Soil, fertilizer, and plant silicon research in Japan*. Amsterdam, The Netherlands: Elsevier.

Ma, J.F. 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Sci. Plant Nutr. 50(1):11-18.

Ma, J.F. and N. Yamaji. 2006. Silicon uptake and accumulation in higher plants. Trends Plant Sci. 11(8):392-397.

Mali, M. and N.C. Avery. 2008. Influence of silicon on growth, relative water contents and uptake of silicon, calcium and potassium in wheat grown in nutrient solution. J. Plant Nutr. 31:1867-1876.

Matoh, T., P. Kairusmee, and E. Takahashi. 1986. Salt-induced damage to rice plants and alleviation effect of silicate. Soil Sci. Plant Nutr. 32:295-304.

Mattson, N.S. and W.R. Leatherwood. 2010. Potassium silicate drenches increase leaf silicon content and affect morphological traits of several floriculture crops grown in a peat-based substrate. HortScience 45(1):43-47.

Meerow, A.W. and T.K. Broschat. 1996. Growth of *Hibiscus* in media amended with a ceramic diatomaceous earth granule and treated with a kelp extract. HortTechnology 6(1):70-73.

Menzies, J.G., P.A. Bowen, D.L. Ehret, and A.D.M. Glass. 1992. Foliar applications of potassium silicate reduce severity of powdery mildew of cucumber, muskmelon, and zucchini squash. J. Amer. Soc. Hort. Sci. 117:902-905.

Mills, H.A. and B.J. Jones. 1996. *Plant analysis handbook II*. Athens, GA: MicroMacro Publishing Inc.

Mitani, N, J.F. Ma, and T. Iwashita. 2005. Identification of the silicon form in xylem sap of rice (*Oryza sativa* L.). Plant Cell Physiol. 46:279-283.

Mitre, V., I. Mitre, A.F. Sestras, and R.E. Sestras. 2010. New products against apple scab and powdery mildew attack in organic apple production. Not. Bot. Hort. Agrobot. Cluj. 38(3):234-238.

Miyake, Y. and E. Takahashi. 1983. Effect of silicon on the growth of solution-cultured cucumber plant. Soil Sci. Plant Nutr. 29(1):71-83.

Muhammad, A., A. Shafaqat., R. Muhammad, Z.R. Muhammad, I. Muhammad, A. Farhat, F. Mujahid, F.Q. Muhammad, and K.I. Muhammad. 2015. Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: a review. Ecotoxicol. Environ. Saf. 119:186-197.

Muir, S. 2001. Plant-available silicon (Si) as a protectant against fungal diseases in soil-less potting media. https://www.ngia.com.au/Story?Action=View&Story_id=1782. Accessed 9 October 2017.

Nasseri, M., H. Arouiee, M. Kafi, and H. Neamati. 2012. Effect of silicon on growth and physiological parameters in fenugreek (*Trigonellafoenum-graceum* L.) under salt stress. Int. J. Agr. Crop Sci. 21:1554-1558.

Nonanka, K. and K. Takahashi. 1990. A method for assessing the need of silicate fertilisers in paddy soils. Soil Sci. 4:513-514.

Pati, S., B. Pal, S. Badole, G.C. Hazra, and B. Mandal. 2016. Effect of silicon fertilization on growth, yield, and nutrient uptake of rice. Commun. Soil Sci. Plant Anal. 47(3):284-290.

Perry, C.C. and T. Keeling-Tucker. 1998. Crystalline silica prepared at room temperature from aqueous solution in the presence of intrasilica bioextracts. Chem. Commun. 23:2587-2588.

Reezi, S., M. Babalar, and S. Kalantari. 2009. Silicon alleviates salt stress, decreases malondialdehyde content and affects petal color of salt stressed cut rose (*Rosa xhybrida* L.) Hot Lady. Afr. J. Biotechnol. 8:1502-1508.

Rogalla, H and V. Romheld. 2002. Role of leaf apoplast in silicon-mediated manganese tolerance of *Cucumis sativus* L. Plant, Cell Environ. 25:549-555.

Rohanipoor, A., M. Norouzi, A. Moezzi, and P. Hassibi. 2013. Effect of silicon on some physiological properties of maize (*Zea mays*) under salt stress. J. Biol. Environ. Sci. 7(20):71-79.

Saud, S., X. Li, Y. Chen, L. Zhang, S. Fahad, S. Hussain, A. Sadiq, and Y. Chen. 2014. Silicon application increases drought tolerance of Kentucky bluegrass by improving plant water relations and morphophysiological function. Sci. World J. 23(17):17647-17655.

Savant, N.K., Snyder, G.H., and L.E. Datnoff. 1996. Silicon management and sustainable rice production. Adv. Agron. 58:151-199.

Savvas, D., G. Manos, A. Kotsiras, and S. Souvaliotis. 2002. Effects of silicon and nutrient-induced salinity on yield, flower quality and nutrient uptake of gerbera grown in a closed hydroponic system. J. Appl. Bot. 76(5-6):153-158.

Scarbrough, S. 2007. Silica in plant nutrition. http://www.firt.org/sites/default/files/Scarbrough_Silica_in_Plant_Nutrition_presentation.pdf. Accessed 9 October 2017.

Shen, X., Y. Zhou, L. Duan, Z. Li, A.E. Eneji, and J. Li. 2010. Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. J. Plant Phys. 167:1248-1252.

Singh, A.K., R. Singh, and K. Singh. 2005. Growth, yield, and economics of rice (*Oryza sativa*) as influenced by level and time of silicon application. Ind. J. Agron. 50:190-93.

Sivanesan, I., M.S. Son, J.P. Lee, and B.R. Jeong. 2010. Effects of silicon growth of *Tagetes patula* L. Boy orange and Yellow boy seedlings cultured in an environment controlled chamber. Propag. Ornam. Plants 10:136-140.

Sivanesan, I. and S.W. Park. 2014. The role of silicon in plant tissue culture. Front. Plant Sci. 5:1-4.

Sonobe, K., T. Hattorri, P. An, W. Tsuji, A.E. Eneji, S. Kobayashi, Y. Kawamura, K. Tanaka, and S. Inanaga. 2010. Effect of silicon application on sorghum root responses to water stress. J. Plant Nutr. 34:71-82.

Subramanian, S. and A. Gopalswamy. 1990. Effect of moisture, organic matter, phosphate, and silicate on availability of silicon and phosphorus in rice soils. J. Indian Soc. Soil Sci. 39:99-103.

Taiz, L. and E. Zeiger. 2002. *Plant physiology, Third Edition*. Sunderland, MA: Sinauer Associates.

Trenholm, L.E., L.E. Datnoff, and R.T. Nagata. 2004. Influence of silicon on drought and shade tolerance of St. Augustinegrass. HortTechnology. 14(4):487-490.

Tubana, B.S., B. Tapasya, and L.E. Datnoff. 2016. Review of silicon in soils and plants and its role in US agriculture: History and future perspectives. Soil Sci. 181:393-411.

Voogt, W. and C. Sonneveld. 2001. *Silicon in agriculture*. Amsterdam, The Netherlands: Elsevier.

Wehtje, G.R., J.N. Shaw, R.H. Walker, and W. Williams. 2003. Bermudagrass growth in soil supplemented with inorganic amendments. HortScience 38(4):613-617.

Whitted-Haag, B., D.E. Kopsell, D.A. Kopsell, and R.L. Rhykerd. 2014. Foliar silicon and titanium applications influence growth and quality characteristics of annual bedding plants. Open Hort. J. 7:6-15.

Yildiz, N. 2008. Diatomite: A new substrate for hydroponics. International Meeting on Soil Fertility Land Management and Agroclimatology, Special Issue, 527-536.

Yoshida, S., Y. Ohnishi, and K. Kitagishi. 1962. Chemical forms, mobility and deposition of silicon in rice plant. Soil Sci. Plant Nutr. 8(3):15-21.

Yoshida, S., D.A. Forno, J.H. Cock, and K.A. Gomez. 1976. Laboratory manual for physiological studies of rice. IRRI Press, Manila. 61-66.

Zhu, Z.J., G.Q. Wei, J. Li, Q.Q. Qian, and J.P. Yu. 2004. Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (*Cucumis sativus* L.). Plant Sci. 167:527-533.

CHAPTER II

LED LITERATURE REVIEW

Photoperiodic Lighting

Photoperiodic lighting is used to create a long day and inhibits or promotes flowering in short day plants (SDP) and long day plants (LDP), respectively. This manipulation can lower production time and costs, while improving overall plant quality (Runkle and Heins, 2006). Light intensity requirements for photoperiodic lighting is low (Whitman et al., 1998). Day-extension (DE), night-interruption (NI), or cyclic lighting (CL) are the different types of photoperiodic lighting. Day-extension lighting operates before or at sunset and continues until the desired day length is achieved during the night. This is usually implemented when the natural photoperiod is short. Night-interruption lighting interrupts the dark period in the middle of the night and traditionally has a 4-hour duration period. Cyclic lighting is delivered to plants intermittently (but not constantly) during the night. Shillo et al. (1981) grew gladiolus (*Gladiolus grandiflorus* L.) under long day and cyclic lighting regimes. The long day treatment promoted flowering percentage and enhanced flower quality features like length of stem and spike, and number of florets per spike. Lighting for 1 hour at midnight was effective, but the greatest effect was observed by lighting throughout the night. Most of the promotive effects were obtained by lighting for 4 hours as day extension or as night break, and this treatment was recommended for commercial use. Cyclic lighting of 5 minutes of light and 10 minutes of dark was as effective as continuous light for 4 hours (Blanchard and

Runkle, 2010). A 16-hour photoperiod encouraged high flowering percentages in two cultivars of Canterbury bells plants ‘Champion Blue’ and ‘Champion Pink (*Campanula medium* L.) as well as reduced days to anthesis (Cavins and Dole, 2001). Also, flowering in rice (*Oryza sativa* L.) occurred much faster when plants were under a NI illuminated by lamps emitting red (Ishikawa et al., 2009).

Light Quantity

The number of light particles or photons able to perform photosynthesis is light quantity (LQ). Expression of LQ include radiant flux, radiant emittance, irradiance, lumen, foot-candle, illumination intensity, lux, and quantum flux density (Nelson, 2012). The most appropriate way to measure and report light levels with respect to plant growth and development. Quantum flux density is an actual measure of the number of photons available within the photosynthetic active radiation (PAR) to drive photosynthesis and to control photomorphogenic responses (Bodley and Newman, 2009). Light quantity varies from both sunlight and electric light sources by latitude, season, elevation, cloud cover, greenhouse structure and layout, glazing material, shading, and time of day (Both, 2000). Plant response to light quantity for flowering greatly varies, although increased light levels usually have positive effects (Marcelis et al., 2006).

Measuring Light

Studies using LED no longer refer to lumens, lux, and foot-candles for determining light requirements for plants. Photosynthetic active radiation, photosynthetic photon flux (PPF), and photosynthetic photon flux density (PPFD) are light units often used. The type of light needed to support photosynthesis in plants is known as PAR and is determined by PPF. The PPF is a measurement of the total light (photons) emitted by a light source each second and is measured in micromoles per second. Another measurement, expressed in micromoles per square meter per second is PPFD which measures the amount of light reaching a target or surface each second. Daily light integral (DLI) is a cumulative measurement of total light reaching a target or surface over a 24-hour period each day and is expressed as number of moles per square meter per day ($mol \cdot m^2 \cdot d$). The requirements for these parameters depends on crop type and geographic location of the greenhouse facility. To measure, quantum sensors, spectroradiometers, and light meters are used.

Light Quality

Light quality relates to wavelength, which can be expressed in units such as micron (μ), micrometer (μm), nanometer (nm), and angstrom (Å). Wavelengths of 400 to 700 nm are referred to as PAR and are optimum for plant photosynthesis (Bjorn, 2002). Blue (460-480 nm) and red (650-700 nm) light are strongly absorbed by chlorophylls while green light is reflected (McDonald, 2003). Depending on type, LEDs can emit wavelengths between 250 nm (ultraviolet) and 1,000 nm (infrared) or more. However, 440 (B), 660 (R), and 730 (far-red) nm are greatly optimized by most plants (Nelson, 2012). There are three main groups of photoreceptors that are important for light absorption. These proteins are categorized into families which are phytochromes (phy), cryptochromes (cry), and phototropins. These photoreceptors, when absorbing their respective light, initiate specific responses in plants at all stages. Phytochromes are the primary photoreceptors that regulate flowering of photoperiodic crops (McDonald, 2003). These pigments exist as either P_R (red light-absorbing phy) or P_{FR} (far-red light-absorbing phy). Upon light absorption of red (660 nm), P_R is transformed to P_{FR} which is the physiologically active form. In addition, light absorption of far-red light (700 to 800 nm) converts P_{FR} into P_R. Cryptochromes absorb B and ultraviolet-A and B light between 320 and 400 nm. There are two members of this family which are cry 1 and cry 2 identified in *Arabidopsis* (Casal, 2000). However, some studies have shown that along with phytochromes, cryptochromes also regulate flowering (Lin et al., 2008; Devlin and Kay, 2000). Phototropins are B-light receptors that control a range of responses such as phototropism, light-induced stomatal opening, and chloroplast movements in response to changes in light intensity.

Plant Responses to Red and Far-Red Light

Red and FR are phytochrome-mediated responses that can be reversed to regulate flowering. Red light triggers a response by converting phytochromes into their biologically active form, F_R. Exposure to FR light can counteract the response and P_{FR} reverts to inactive P_R. Proportions of P_{FR} and P_R depend on the R:FR, which mediates extension growth and flowering responses in plants (Sager et al., 1988). Different mechanisms and pathways of flowering exist in SDPs and LDPs in response to the R and FR. Therefore, studying the use of LEDs that emit R and/or FR light can increase the understanding of how these light spectra in photoperiodic lighting regulate flowering.

Potato (*Solanum tuberosum* L.) plantlets grown under LEDs emitting red and far-red had increased shoot length (Miyashita et al.,1995). In addition, dry weight, leaf area, growth, morphology, and photosynthesis were significantly affected. In long-day plants such as bellflower (*Campanula carpatica* Jacq.) ‘Blue Clips’ and English pea (*Pisum* *sativum* L.) ‘Utrillo’, red light increased plant height and far-red inhibited flowering in pansy (*Viola* x*wittrockiana* Gams.) ‘Crystal Bowl Yellow’ (Heins and Runkle, 2001). Total leaf area, height, and dry shoot weight of impatiens (*Impatiens walleriana* J. Hooker) ‘SuperElfin XP Red’, salvia (*Salvia splendens* J.A. Schultes*)* ‘Vista Red’, tomato (*Solanum lycopersicum* L.) ‘Early Girl’, and petunia (*Petunia* x*hybrida* (Hooker) Vilmorin ‘Wave Pink’ increased when grown under R LEDs (Wollaeger and Runkle, 2015). Dianthus (*Dianthus* L.) ‘Floral Lace Purple’ and ‘Super Parfait Strawberry’ grew taller with LED or incandescent lamps during a night-interruption study (Kohyama et al., 2014). Inhibition or promotion of stem elongation and plant height occurs when red:far-red ratios are either high or low. For petunia ‘Suncatcher Midnight Blue’ cuttings grown under a R:FR ratio, stem elongation was greater (Currey and Lopez, 2013). A low R:FR ratio (0.8) promoted stem elongation of tussock bellflower when grown under INC lamps (Kristiansen, 1988). Plant height in Easter lily (*Lilium longiflorum* Thunb.) ‘Nellie White’ was inhibited when R:FR ratios were high.

In night-interruption studies, flowering of short day plants such as cocklebur (*Xanthium strumarium* L.), chrysanthemum (*Chrysanthemum indicum* L.), and soybean (*Glycine max* L. Merr.) was inhibited when R:FR ratios were either high or low (Borthwick et al., 1952; Cathey and Borthwick, 1957; Downs, 1958). The effect on flowering by either high or low R:FR ratios is species specific. Craig and Runkle (2013) found that in chrysanthemum ‘Adiva Purple’, a R:FR of 0.66 or above reduced flowering percentage and in African marigold (*Tagetes erecta* L.) ‘American Antigua Yellow’, flowering was greater under NI with only FR. For all species, including dahlia (*Dahlia x hortensis* Syn.) ‘Dahlinova Figaro Mix’, stem length increased as the R:FR of the NI increased, reaching a maximum of 0.66. It was concluded that a moderate to high R:FR (0.66 or greater) is most effective at interrupting the long night.

Traditional Lighting Sources

Traditionally, growers have used incandescent (INC), fluorescent (FL), and high-pressure sodium (HID) lamps (Bula et al., 1991). Incandescent are the least efficient lamp and have low intensity, short life span, and release infrared heat. For supplemental lighting in greenhouses, these lamps are not suitable to produce effective lighting for photosynthesis. However, for day-length extension studies, which require relatively low light levels for photoperiodic lighting, incandescent is recommended. In addition, these lamps emit high amounts of FR photons, which promote flowering in LDP, inhibits flowering in short-day plants (SDPs), and promotes elongated stems, which can sometimes be an undesirable trait. Although not commonly used in greenhouses, FL are more efficient in light output and energy consumption than INC (Nelson, 2012). Blue (B) and green (G) light are mostly emitted from FL. For adequate voltage, FL require ballasts which adds to costs and dead load of a structure. High intensity discharge lamps are commonly used for supplemental lighting, which increases total quantity of photosynthetic light during the day (Lopez, 2013). Metal halide (MH) and high-pressure sodium lamps (HPS) are most commonly used in the greenhouse for supplemental lighting (Nelson, 2014). Proportions of B are mostly emitted by MH (Fisher and Donnelly, 2001) and HPS emit light that is in the orange (O), red (R), and yellow (Y) spectrum. Higher photosynthetically active radiation (PAR) intensity, quantum flux density, and heat are emitted from these HID lamps and spacing from plants is very important because plant tissue can be damaged if placed too close (Boodley and

Newman, 2009). Many governments around the world have passed laws to reduce electricity consumption by phasing out INC bulbs and replacing them with energy-efficient alternatives, such as compact FL lamps or light-emitting diodes (LEDs) (Bullough et al., 2011).

Light-Emitting Diodes (Grow Lights)

Light emitting diodes are fourth generation lighting sources and are the emerging technology in horticulture. These devices have proven to be more efficient when compared to the traditional lighting sources (Nelson and Bugbee, 2014). LEDs are solid-state semiconductors and when turned on or off, the action is instant. As for life expectancy, LEDs can operate between 20,000 and 50,000 hours (Morrow, 2008). Single diodes or lamps do not need to be replaced constantly because LEDs do not burn out and factors such as design, materials used, and heat release affect life expectancy (Fisher, 2001). Another important feature of LEDs is that heat does not escape from the surface but instead through a heat sink, which allows for proximity between plants and LEDs. As for consumption of energy, LEDs are more efficient and use less energy than any other traditional greenhouse lights (Nelson, 2012). Operating costs and carbon emissions are lowered when using LEDs (Bullough, 2011). Another feature regarding color emission from LEDs is that the composition can be created or adjusted (color tuning) for specific plant responses (Yano and Fujiwara, 2012). LED grow lights include toplights, inter-lights, tubular LEDs (TLEDs), and flowering lamps. Toplights, inter-lights, and TLEDs are considered module lighting systems, which are for multilayer production systems such as city (vertical) farming, tissue culture, and indoor research facilities such as grow rooms and growth chambers. Toplights have high lighting outputs and low heat emission and are used specifically for high wire and leafy vegetables (Philips, 2017). Interlights allow plants to receive light horizontally and vertically and are used for plants that rise such as cucumbers and tomatoes. TLEDs are replacement lamps for traditional fluorescent tubes used in tissue culture and offer more uniformed lighting and produce less heat (Philips, 2017). The latest are flowering lamps that emit FR, R + white (W), and R + W + FR light for photoperiodic applications on a wide range of photoperiodic plants. Using LEDs reduces energy usage by up to 90% and offers big energy savings versus traditional light sources (Philips, 2017). In addition, custom light recipes enhance quality, consistency, and flowering (Kohyama et al., 2014; Rantanen et al., 2014; Meng and Runkle, 2014). Sole or supplementary lighting from LEDs have been successful in culturing a range of horticultural crops. African marigold (*Targetes erecta* L.) ‘Orange Boy’ grown under R LEDs had higher dry weight (Heo et al., 2002). A 4-hour NI study using R and white LEDs increased flowering time of chrysanthemum (Ho et al., 2012). Also for chrysanthemums, stem length was increased when subjected to a subsequent 30-min DE provided by R and FR LEDs (Lund et al., 2007). Poinsettias supplemented with LED lighting below the canopy had greater dry weight and increased plant width (Bergstrand et al., 2015). Flowering time and blooming period for *Fressia* hybrid (Eckl. ex Klatt) ‘Yvonne’ was accelerated under green and red LED lighting, respectively (Lee and Hwang, 2014). These studies and so many others focus on a range of applications in which LED technology can be used in horticulture. However, the use of LEDs seems to be restricted and are mostly used in research settings compared to commercial production. This is because the initial costs of LEDs are high. However, Kim et al. (2007) noted that the efficiency of LEDs can compensate for their expense. In addition, more research with LEDs needs to be conducted on a broader range of crops to fulfill the needs of growers wanting to switch over to this new and promising technology.

Gibberellic Acid and Light

Gibberellic acid (also called Gibberellin A_3, GA, and GA_3) is a hormone found in plants. Its chemical formula is $C_{19}H_{22}O_6$ and when purified, it is a white to pale-yellow solid. Plants produce low amounts of GA_3, therefore this hormone is available commercially. Gibberellic acid is a very influential hormone by controlling plant development, promoting growth, and elongating cells (Gupta, 2013). This hormone produces bigger leaves and longer stems, establishes robust root systems, enhances photosynthesis, stimulates seed germination, and triggers transitions from the vegetative to the flowering stage (Gupta, 2013). Applications of very low concentrations can have a profound effect, while too much will have the opposite effect (Riley, 1987). Gibberellic acid was first identified in Japan in 1926, as a by-product of the plant pathogen *Gibberella fujikuroi*, which infects rice plants. The pathogen causes plants to develop or grow much taller than normal, which is referred to as bakanae or foolish seedling disease. The role of GA influencing flowering is complex but plausible. Lang (1956) initially discounted the idea of GA being a universal flowering stimulus. Only in certain species, GA acts as a mobile signal transmitting photoperiodic flowering stimulus (Kobayashi and Weigel, 2007; Simpson and Dean, 2002). However, the role of GA_3 in flower development is considered universal and essential (Griffiths et al., 2006; Hu et al., 2008; Singh et al., 2002; Chhun et al., 2007). For flower induction, soaking bulbs, rhizomes, corms. or spraying the foliage with a GA_3 solution are common applications (Dennis et al., 1993; Delvadia et al., 2009; Ranwala et al., 2002). The effect of various GA_3 levels was studied on flowering in gerbera (*Gerbera jamesonni* Hooker f.) ‘Alcochete’. Results revealed that foliar application of 100 ppm performed greater for flowering parameters such as days to anthesis and number of ray florets per flower (Chauhan et al., 2014). Pobudkiewicz and Nowak (1992) also found that flowering parameters of gerbera such as flower size were enhanced when GA_3 was applied at 200 ppm and for Singh et al. (2009) flower size in chrysanthemum was maximized at 200 ppm as well. Early flowering was seen in damask rose (*Rosa x damascene* Mill.) when applied with GA_3 at 200 ppm (Porwal et al., 2002). In philodendron (*Philodendron* Schott) ‘Black Cardinal’, a single foliar spray of GA_3 at concentrations of 125, 250, 500, or 1,000 $mg \cdot L^{-1}$ induced flowering in 170 days and mean flower number increased as GA_3 concentrations increased (Chen et al., 2003). Double spraying with GA_3 accelerated bud development of ajania (*Ajania pacifica* K. Bremer & Humphries) ‘Bea’ (Zalewska and Antkowiak, 2013). Kaaz and Karaguzel (2010) found that goldenrod (*Solidago* x *hybrida* Mill.) ‘Tara’ sprayed once or twice with GA had the best flowering characteristics such as accelerated days to anthesis and higher number of secondary inflorescences. There are statistically valid interactions between light and GA_3 and both factors are known to have synergistic effects mainly on germination. In certain species, growth and flower initiation are also affected (Lona and Bocchi, 1956; Lockhart, 1956). Dissanayake et al. (2010) studied the effects of light quality (e.g. red, far-red, blue, yellow, green, and blue) and endogenous GA on germination of guayule (*Parthenium argentatum* A. Gray). This research found that a higher ratio of red to far-red radiation stimulated GA production, which increased germination. Toyomasue et al. (1993) also found similar results in lettuce seed. Yamaguchi and Kamiya (2001) emphasized that light stimulates GA biosynthesis in lettuce as well as Arabidopsis (*Arabidopsis thaliana* L.) seed. As for stem elongation, Vince (1967) saw an increase in garden peas ‘Alaska’ and ‘Duke of Albany’ when exposed to far-red light and saturated with GA_3. Reid et al. (2002) and Foo et al. (2006) reported that phytochrome A-mediated FR light responses regulate GA synthesis in plants, and therefore, affect stem elongation. Floral induction of sorghum (*Sorghum bicolor* L.) ‘Moench’ was hastened by 30 days when supplemented with GA_3 and exposed to far-red light (Williams and Morgan, 1979). Similar results were seen in a previous study (Williams and Morgan, 1977) suggesting that the conversion of FR to R at the beginning of the dark period significantly increases effectiveness of GA_3 in promoting floral initiation of sorghum. However, this observation needs to be furthered tested in other plant species to fully assess the regulation of flowering by light and GA_3.

Literature Cited

Bergmann, B.A., J.M. Dole, and I. McCall. 2016. Gibberellic acid shows promise for promoting flower stem length in four field-grown cut flowers. HortTechnology 26(3):287-292.

Bergstrand, K.J., H. Asp, E.H. Larsson-Jonsson, and H.K. Schussler. 2015. Plant developmental consequences of lighting from above or below in the production of poinsettia. Europ. J. Hort. Sci. 80(2):51-55.

Bessho, M. and K. Shimizu. 2012. Latest trends in LED lighting. Electronics and Comm. Jpn. 95(1):315-320.

Bieleski, R., J. Elgar, J. Heyes, and A. Woolf. 2000. Flower opening in Asiatic lily is a rapid process controlled by dark-light cycling. Ann. Bot. 86:1169-1174.

Bjorn, L.F 2002. *Photobiology: the science of light and life*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Blanchard, M.G. and E.S. Runkle. 2010. Influence of NIR-reflecting shading paint on greenhouse environment, plant temperature, and growth and flowering of bedding plants. Trans. ASABE. 53(3):939-944.

Boodley, J. and S.E. Newman. 2009. *The commercial greenhouse, 3rd edition*. Clifton Park, NY: Delmar Cengage Learning.

Borthwick, H.A., S.B. Hendricks, and M.W. Parker. 1952. The reaction controlling floral initiation. Proc. Natl. Acad. Sci. USA 38:929-934.

Briggs, W.R. and J.M. Christie. 2002. Phototropin 1 and phototropin 2: Two versatile plant blue-light receptors. Trends Plant Sci. 7:204-209.

Bula, R.J., R.C. Morrow, T.W. Tibbitts, D.J. Barta, R.W. Ignatius, and T.S. Martin. 1991. Light-emitting diodes as a radiation source for plants. HortScience 26:203-205.

Bullough, J.D., Y. Zhu, and N. Narendran. 2011. Characteristics of light-emitting diodes sources: Relevance for visual signal detection. http://www.nfpa.org/~/media/files/news-and-research/resources/research-foundation/foundation-proceedings/2012-supdet/13bullough-presentation.pdf?la=en. Accessed 9 October 2017.

Bultynck, L. and H. Lambers. 2004. Effects of applied gibberellic acid and paclobbutraol on leaf expansion and biomass allocation in two *Aegilops* species with contrasting leaf elongation rates. Physiol. Plantarum 122:143-151.

Bulyalert, O. 1988. Effect of gibberellic acid on growth and flowering of liatris corm (*Liatris spicata*) c.v. "Florist violet" propagated from seed (Abstract). http://agris.fao.org/agris-search/search.do?recordID=TH9220028. Accessed 9 October 2017.

Casal J.J. 2000. Phytochromes, cryptochromes, phototropin: Photoreceptor interactions in plants. Photochem Photobiol. 71:1-11.

Cathey, H.M. and H.A. Borthwick. 1957. Photoreversibility of floral initiation in *Chrysanthemum*. Bot. Gaz. 119:71-76.

Cavins T.J. and J.M. Dole. 2001. Photoperiod, juvenility and high intensity lighting affect flowering and cut stem qualities of *Campanula* and *Lupinus*. HortScience 36:1192-1196.

Chauhan, R.V., K.P. Kava, V.J. Babariya, P.B. Pansuria, and A.B. Savaliya. 2014. Effect of gibberellic acid on flowering and cut flower yield in gerbera under protected condition. Asian J. Hort. 9(2):404-407.

Chen, R.J. Henny, D.B. McConnell, and R.D. Caldwell. 2003. Gibberellic acid affects growth and flowering of *Philodendron* ‘Black Cardinal’. J. Plant Growth Regul. 41:1-6.

Chhun, T., K. Aya, K. Asano, E. Yamamoto, Y. Morinaka, M. Watanabe, H. Kitano, M. Ashikari, M. Matsuoka, and M. Ueguchi-Tanaka. 2007. Gibberellin regulates pollen viability and pollen tube growth in rice. Plant Cell 19:3876-3888.

Craig, D.S. and E.S. Runkle. 2013. A moderate to high red to far-red light ratio from light-emitting diodes controls flowering of short-day plants. J. Amer. Soc. Hort. Sci. 138:167-172.

Currey C.J. and R.G. Lopez. 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(4):428-434.

Delvadia, D.V., T.R. Ahlawat, and B.J. Meena. 2009. Effect of different GA_3 concentration and frequency on growth, flowering and yield in Gaillardia (*Gaillardia pulchella* Foug.) cv. Lorenziana. J. Hort. Sci. 4(1):81-84.

Dennis, D.J., J. Doreen, and T. Ohteki. 1994. Effect of gibberellic acid ‘quick-dip’ and storage on the yield and quality of blooms from hybrid *Zantedeschia* tubers. Sci. Hort. 57:133-142.

Devesh, S., C. Basu, M. Meinhardt-Wollweber, and B. Roth. 2014. LEDs for energy efficient greenhouse lighting. https://arxiv.org/abs/1406.3016. Accessed 9 October 2017.

Devlin, P.F. and S.A. Kay. 2000. Cryptochromes are required for phytochrome signaling to the circadian clock but not for rhythmicity. Plant Cell. 12:2499-2510.

Dissanayake, P., D.L. George, and M.L. Gupta. 2010. Effect of light, gibberellic acid and abscisic acid on germination of guayule (*Parthenium argentatum* 'Gray') seed. Ind. Crops Prod. 32:111-117.

Dobrowolska A. and D. Janicka. 2007. The effect of growth regulators on flowering and decorative value of *Impatiens hawkeri* W. Bull belonging to Riviera group. Rocz. AR Pozn. Ogrodn. 41:35-39.

Downs, R.J., H.A. Borthwick, and A.A. Piringer. 1958. Comparison of incandescent and fluorescent lamps for lengthening photoperiods. Proc. Amer. Soc. Hort. Sci. 71:568-578.

Feng, S., C. Martinez, G. Gusmaroli, Y. Wang, J. Zhou, and F. Wang. 2008. Coordinated regulation of *Arabidopsis* thaliana development by light and gibberellins. Nature 451:475-479.

Fisher, P. and C. Donnelly. 2001. Evaluating supplemental light for your greenhouse. http://www.greenhouse.cornell.edu/crops/factsheets/SuppLight.pdf. Accessed 9 October 2017.

Foo, E., J.D. Platten, J.L. Weller, and J.B. Reid. 2006. PhyA and cry1 act redundantly to regulate gibberellin levels during de-etiolation in blue light. Physiol. Plant. 127:149-156.

Griffiths, J., K. Murase, and I. Rieu. 2006. Genetic characterization and functional analysis of the *GID1* gibberellin receptors in *Arabidopsis*. Plant Cell 18:3399-3414.

Gupta, R. and S.K. Chakrabarty. 2013. Gibberellic acid in plant: Still a mystery unresolved. Plant Signal Behav. 8(9):1-5.

Hahn, E.J., T. Kozai, and K.Y.J. Paek. 2000. Blue and red light-emitting diodes with or without sucrose and ventilation affect in vitro growth of *Rehmannia glutinosa* plantlets. Plant Biol. 43(4):247-250.

Heo, J., C. Lee, D. Chakrabarty, and K. Paek. 2002. Growth responses of marigold and salvia bedding plants as affected by monochromic or mixture radiation provided by a light-emitting diode (LED). Plant Growth Regul. 38:225-230.

Ho, C.H., C.M. Yang, and C.L. Hsiao. 2012. Effects of nighttime lighting with specific wavebands on flowering of chrysanthemum. Crop Environ. Bioinformatics 9:265-277.

Hu J.H., M.G. Mitchum, and N. Barnaby. 2008. Potential sites of bioactive gibberellin production during reproductive growth in *Arabidopsis*. Plant Cell 20(2):320-336.

Ishikawa, R., S. Tamaki, S. Yokoi, N. Inagaki, T. Shinomura, and M. Takano. 2005. Suppression of the floral activator *Hd3a* is the principal cause of the night break effect in rice. Plant Cell. 17:3326-3336.

Jones R.L. and I.D. Phillips. 1966. Organs of gibberellin synthesis in light-grown sunflower plants. Plant Physiol. 41:1381-1386.

Kaaz, S. and O. Karaguzel. 2010. Influence of growth regulators on the growth and flowering characteristics of Goldenrod (*Solidago* x *hybrida*). Eur. J. Sci. Res. 45(3):498-507.

Kim, H.H., R.M. Wheeler, J.C. Sager, N.C. Yorio, and G.D. Goins. 2005. Light-emitting diodes as an illumination source for plants: A review of research at Kennedy Space Center. Habitation (Elmsford) 10:71-78.

Kim, H.H., R.M. Wheeler, J.C. Sager, J. Norikane, and N.C. Yorio. 2007. Electric lighting considerations for crop production in space. Acta Hort. 761:193-202.

Kobayashi, Y. and D. Weigel. 2007. Move on up, it's time for change: Mobile signals controlling photoperiod-dependent flowering. Genes Devel. 21:2371-2384.

Kohyama, F., C. Whitman, and E. Runkle. 2014. Comparing flowering responses of long-day plants under incandescent and two commercial light-emitting diode lamps. HortTechnology 24(4):490-495.

Kristiansen, K. 1988. Light quality regulates flower initiation, differentiation and development of *Campanula carpatica* Jacq. Forster, Karl. Sci. Hort. 35:275-283.

Lang, A. 1956. Induction of flower formation in biennial *Hyoscyamus* by treatment with gibberellin. Naturwissenschaften 43:284-285.

Lee, J.J. and J.H. Hwang. 2014. Effect of day-length extension treatment using LED on growth and flowering of *Freesia* hybrid 'Yvonne'. Kor. J. Hort. Sci. Technol. 32(6):794-802.

Lin, R., Y. Teng, H.J. Park, L. Ding, C. Black, P. Fang, and H. Wang. 2008. Discrete and essential roles of the multiple domains of *Arabidopsis FHY3* in mediating phytochrome: a signal transduction. Plant Physiol. 148:981-992.

Lockhart, J. 1956. A reversal of the light inhibition of pea stem growth by the gibberellins. Prec. Nat. Acad. Sci. 42:841-848.

Lona, F. and A. Bocchi. 1956. Luterferenza dell'acido gibberellieo nell'effecto della lute rossa e rosso-estrema sull'allungamento dell fusto di Perilla ocy~noides L. L'ateneo Parmense 7:645-649.

Lund, J.B., T.J. Blom, and J.M. Aaslyng. 2007. End-of-day lighting with different red/far-red ratios using light-emitting diodes affects plant growth of *Chrysanthemum* × *morifolium* Ramat. 'Coral Charm'. HortScience 42:1609-1611.

Marcelis, L.F.M., A. Elings, and M.J. Bakker. 2006. Modelling dry matter production and partitioning in sweet pepper. Acta Hort. 718:121-128.

Massa, G.D., H.H. Kim, R.M. Wheeler, and C.A. Mitchell. 2008. Plant productivity in response to LED lighting. HortScience 43:1951-1956.

McDonald, M.S. 2003. Photobiology of higher plants. Wiley. West Sussex, England.

Meng, Q. and E.S. Runkle. 2014. Controlling flowering of photoperiodic ornamental crops with light-emitting diode lamps: A coordinated grower trial. HortTechnology 24:702-711.

Meng, Q. and E.S. Runkle. 2016. Choosing the right LEDs to regulate flowering. http://lighthort.com/2016/07/21/choosing-right-leds-regulate-flowering/. Accessed 9 October 2017.

Miyashita, Y., Y. Kitaya, C. Kubota, T. Kozai, and T. Kimura. 1995. Effects of red and far-red light on the growth and morphology of potato plantlets in-vitro: Using light emitting diodes as a light source for micropropagation. Acta Hort. 393:189-194.

Nelson, J.A. and B. Bugbee. 2014. Economic analysis of greenhouse lighting: Light-emitting diodes vs. high intensity discharge fixtures. PLoS ONE 9(6):1-10.

Nelson, P.V. 2012. *Greenhouse operation and management, 7th Edition*. Boston, MA: Pearson.

Nishidate, K., Y. Kanayama, M. Nishiyama, T. Yamamoto, Y. Hamaguchi, and K. Kanahama. 2012. Far-red light supplemented with weak red light promotes flowering of *Gypsophila paniculata*. J. Jpn. Soc. Hort. Sci. 81:198-203.

Park, Y. and E.S. Runkle. 2016. Investigating the merit of including far-red radiation in the production of ornamental seedlings grown under sole-source lighting. Acta Hort. 1134:259-266.

Philips. 2017. Tailor-made light recipes for growers. Retrieved from http://www.usa.lighting.philips.com/products/horticulture. Accessed 9 October, 2017.

Pobudkiewicz, A. and J. Nowak. 1992. The effect of gibberellic acid on growth and flowering of *Gerbera jamesonii* Bolus. Folia Hort. 4(2):35-42.

Porwal, R., C.L. Nagda, and J.P.S. Pundir. 2002. Influence of plant growth regulators on vegetative growth and flower earliness of damask rose. South Ind. Hort. 50(1-3):119-123.

Pudelska, K. and E. Podgajna. 2013. Decorative value of three dahlia cultivars (*Dahlia ×cultorum* Thorsr. et Reis) treated with gibberellin. Modern Phytomorphology 4:83-86.

Rabiza-Swider, J., E. Skutnik, A. Jedrzejuk, A. Lukaszewska, and K. Lewandowska. 2015. The effect of GA_3 and the standard preservative on keeping qualities of cut LA hybrid lily 'Richmond'. Acta Sci. Pol. Hortorum Cultus. 14(4):51-64.

Rantanen, M., T. Kurokura, K. Mouhu, P. Pinho, E. Tetri, L. Halonen, P. Palonen, P. Elomaa, and T. Hytönen. 2014. Light quality regulates flowering in *FvFT1*/*FvTFL1* dependent manner in the woodland strawberry *Fragaria vesca*. Front. Plant Sci. 271(5):1-11.

Ranwala, A.P., G. Legnani, M. Reitmeier, B.B. Stewart, and W.B. Miller. 2002. Efficacy of plant growth retardants as preplant bulb dips for height control in LA and oriental hybrid lilies. HortTechnology 12(3):426-431.

Reid, J.B., N.A. Botwright, J.J. Smith, D.P. O'Neil, and L.H.J. Kerckhoffs. 2002. Control of gibberellins levels gene expression during de-etiolation in pea. Plant Physiol. 128:734-741.

Riley, J. 1987. Gibberellic acid for fruit set and seed germination. CRFG J. 19:10-12.

Runkle, E.S. and R.D Heins. 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(3):275-282.

Runkle, E.S. and R.D. Heins. 2006. Manipulating the light environment to control flowering and morphogenesis of herbaceous plants. Acta Hort. 711:51-60.

Sager, J.C., W.O. Smith, J.L. Edwards, and K.L. Cyr. 1988. Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. Trans. Amer. Soc. Agr. Eng. 31:1882-1889.

Schmidt C., A.B. Bellé, C. Nardi, and A.K. Toledo. 2003. The gibberellic acid (GA_3) in the cut chrysanthemum (*Dedranthema grandiflora* Tzevelev.) 'Viking': planting summer/autumn. Ciência Rural, Santa Maria 33(2):267-274.

Shillo, R., G. Valis, and A.H. Halevy. 1981. Promotion of flowering by photoperiodic lighting in winter-grown gladiolus planted at high densities. Sci. Hort. 14:367-375.

Simpson, G.G. and C. Dean. 2002. *Arabidopsis*, the Rosetta stone of flowering time. Science 296:285-289.

Singh, D.P., A.M. Jermakow, and S.M. Swain. 2002. Gibberellins are required for seed development and pollen tube growth in *Arabidopsis*. Plant Cell 14:3133-3147.

Singh, J.K. and R. Jitendra 2009. Effect of GA_3, CCC and inorganic fertilizers on growth and flowering in chrysanthemum (*Dendranthema grandiflora* Ramet.) cv. Ann. Hort. 2(2):232-233.

Snowden, M.C., K.R. Cope, and B. Bugbee. 2016. Sensitivity of seven diverse species to blue and green light: Interactions with photon flux. PLoS ONE 11(10):1-32.

Sung, J.W., S. Park, J. Sung-Jin, O-N. Seo, G-S. Kim, Y-H. Kim. H. Bae, G. Lee, S-T. Kim, W-S. Lee, and S-C. Shin. 2012. Influences of four different light-emitting diode lights on flowering and polyphenol variations in the leaves of chrysanthemum (*Chrysanthemum morifolium*). Agr. Food Chem. 60(39):9793-980.

Tan, Z.G. and Y.L. Qian. 2003. Light intensity affects gibberellic acid content in Kentucky bluegrass. HortScience 38(1):113-116.

Toyomasu, T., H. Tsuji, H. Yamane, M. Nakayama, I. Yamaguchi, N. Murofushi, N. Takahasi, and Y. Inoue. 1993. Light effect on endogenous levels of gibberellins in photoblastic lettuce seeds. J. Plant Growth Regul. 12:85-90.

Vince, D. 1967. Gibberellic acid and light inhibition of stem elongation. Planta (Berl.) 75:291-308.

White, J.W., H. Chen, and D.J. Beattie. 1990. Gibberellin, light, and low temperature effects on flowering of *Aquilegia*. HortScience 25(11):1422-1424.

Whitman, C.M., R.D. Heins, A.C. Cameron, and W.H. Carlson. 1998. Lamp type and irradiance level for daylength extensions influence flowering of *Campanula carpatica* 'Blue Clips', *Coreopsis grandiflora* 'Early Sunrise', and *Coreopsis verticillata* 'Moonbeam'. J. Amer. Soc. Hort. Sci. 123:802-807.

Williams, E.A. and P.W. Morgan. 1979. Floral initiation in sorghum hastened by gibberellic acid and far-red light. Planta 145:269-272.

Williams, L. and P.W. Morgan. 1977. Gibberellic acid role in floral initiation in sorghum. (Abstr.) Plant Physiol. 59:73.

Wollaeger, H.M and E.S. Runkle. 2015. Growth and acclimation of *impatiens*, *salvia*, *petunia*, and tomato seedlings to blue and red light. HortScience 50:522-529.

Yamada, A., T. Tanigawa, T. Suyama, T. Matsuno, and T. Kunitake. 2009. Red:far-red light ratio and far-red light integral promote or retard growth and flowering in *Eustoma grandiflorum* (Raf.). Shinn. Sci. Hort. 120:101-106.

Yamaguchi, S. and Y. Kamiya. 2001. Gibberellins and light-simulated seed germination. J. Plant Growth Regul. 20(4):369-376.

Yano, A. and K. Fujiwara. 2012. Plant lighting system with five wavelength-band light-emitting diodes providing photon flux density and mixing ratio control. Plant Meth. 8:1-12.

Zalewska, M., A. Żabicka, and I. Wojciechowska. 2008. The influence of gibberellic acid on the growth and flowering of cascade chrysanthemum cultivars in outside glasshouse. Zesz. Probl. Post. Nauk Roln. 525:525-533.

Zalewska, M. and M. Antkowiak. 2013. Gibberellic acid effect on growth and flowering of *Ajania pacifica*. J. Hort. Res. 21(1):21-27.

CHAPTER III

EFFECT OF SILICON SUPPLEMENTATION ON GROWTH AND FLOWERING OF CUT FLOWERS

Abstract

The role of silicon (Si) as a needed supplement in soilless media is gaining interest. This research studied the effects of diatomaceous earth (DE) as a supplemental Si source on growth and flower characteristics, physiology, and nutrient uptake of cut flowers such as *Dahlia* spp. (Cav) ‘Dahlinova Montana’, *Rudbeckia hirta* (L.) ‘Denver Daisy’, and *Gerbera jamesonii* (L.) ‘Festival Light Eye White Shades’. Nine Si treatments were established, and plants were either well-watered at 10 centibars or water-stressed at 20 centibars. Silicon treatments included application of DE across the top of the pots (top-dressed) as well as incorporated, and Metro-Mix 360 media with and without Si. There were six pots per Si treatment which were randomized within irrigation (well-watered or water-stressed). Significant effects were seen from Si supplementation, irrigation, and interaction in all plants. Growth and flower characteristics, leaf nutrient content as well as tolerance to stress were improved mostly by application of DE.

Introduction

Silicon (Si) is the second most abundant element on earth and is present in various forms. In plants, except for members of the family Equisetaceae, Si is a nonessential and beneficial element, meaning that plants can complete their life cycles without the mineral nutrient (Epstein, 1994). However, plants deprived of Si are often weaker structurally and more prone to abnormalities of growth, development, and reproduction. The benefits of Si are mostly evident when plants are under stress conditions (Ma and Yamaji, 2006). Several studies show that plants benefit in many important ways from supplemental soluble Si including greater tolerance of environmental stresses, such as cold, heat, drought, salinity, mineral toxicity or deficiency, improved growth rates, and resistance to insects and fungi (Cherif et al., 1994; Ma, 2004; Liang et al., 2006).

Common use of soilless substrates in greenhouse and nursery production limits the availability of Si to plants (Voogt and Sonneveld, 2001). Plants grown under production systems often appear weaker structurally compared to crops grown in the field (Kamenidou, 2008). Therefore, adding Si-related compounds as an amendment has been highly recommended. Miyake and Takahashi (1978) brought interest to Si nutrition of horticultural crops when observing Si deficient tomatoes. In the Netherlands, the use of Si supplementation in a hydroponic system is recommended for crops such as cucumber (*Cucumus sativus* L.) and roses (*Rosa hybrida*. L.) (Kamenidou et al., 2010; De Kreij et al., 1999). Plants with Si added to the nutrient formula also showed a decrease in leaf and flower senescence (Reezi, 2009). The shelf life of cut flowers, specialty pot crops, and plugs was also extended (Carvalho-Zanão, 2012). Hydroponically produced gerbera supplemented with Si had improved overall crop and flower quality (Savvas et al., 2002).

Other considerations such as solubility, availability, physical properties, and contaminants must be considered before choosing a source. Silicon is available from natural resources, fertilizers (organic and inorganic), and industrial by-products. Most horticultural studies use Si from by-products such as liquid silicates, slag, and basalt dust (Berthelsen et al., 2003; Muir et al., 2001; Savant et al., 1999). Diatomaceous earth (DE) is a sedimentary rock from the deposition of silica-rich diatoms. The cell walls of diatoms contain amorphous silica ($SiO_2 \cdot H_2O$). There is limited research focusing on the effects of DE regarding growth and flower characteristics, as well as water-stress related issues in horticultural crops. Most studies utilizing DE focused on retention of water or circulation of oxygen in plant media (Meerow and Broschat, 1996). However, supplementation of DE has been proven to improve plant growth, quality, and nutrient uptake in agronomic crops such as rice (Pati et al., 2016). Use of DE to improve plant growth of ornamentals is limited, thus the objectives of this work were to determine the effects of DE as a Si supplement on *Rudbeckia hirta* (L.) ‘Denver Daisy’, *Dahlia* spp. (Cav.) ‘Dahlinova Montana’, and *Gerbera jamesonii* (L.) ‘Festival Light Eye White Shades’.

Materials and Methods

On 8 May 2015, two 128 plug cell trays of *Rudbeckia hirta* L. ‘Denver Daisy’, five 51 plug cell trays of *Dahlia* Cav. ‘Dahlinova Montana’, and two 128 plug cell trays of *Gerbera jamesonii* L. ‘Festival Light Eye White Shades’ were obtained from Park Seed (Greenwood, SC). Before transplanting, all species were placed on a mist bench. Cuttings and plugs were transplanted into standard 15-centimeter pots filled with Metro-Mix 360 media (Sun Gro Horticulture, Bellevue, WA) that did not contain silicon (Si) on 28 May 2015, and a single treatment of Metro-Mix 360 media (Sun Gro Horticulture, Bellevue, WA) that contained 20 to 50 ppm soluble Si (RESiLIENCE™) derived from wollastonite (King and Reddy, 2000). A single plant was placed in each pot and plants were grown at the Department of Horticulture and L.A. research greenhouses in Stillwater, OK under natural photoperiods. Temperatures were set at 37°C during the day and 26°C during the night.

Eight Si treatments were established with diatomaceous earth (Perma-Guard, Inc., Kamas, UT) which had 0.09 g/L of soluble Si. Application of DE included top-dressed rates at 20, 40, 60, 80 and incorporated rates at 50, 100, 150, and 200 g. Media with and without (control) Si were used as well. For each species, there were six pots per Si rate per irrigation treatment in which plants were well-watered at 10 centibars and water-stressed at 20 centibars. Tensiometers (IRROMETER, Riverside, CA) were used to control irrigation. Plant species and Si treatments were randomized within irrigation.

Data collected on plants included height from the media surface to the tallest opened flower, width (average of two perpendicular measurements), shoot dry weight, number of flowers, flower diameter, leaf resistance, and transpiration. Shoot weight was determined by cutting the stems at media level then dried for 2 d at 52.2°C. For elemental analyses, leaves were collected from five plants per Si and irrigation treatment of each species. Silicon solubility of DE and nutrient analysis of leaf samples were analyzed by the Soil, Water and Forage Analytical Laboratory (SWFAL) at Oklahoma State University, using a LECO TruSpec Carbon and Nitrogen Analyzer (LECO Corporation, St. Joseph, MI). Soil and leaf Si analysis was performed using five pots per silicon and irrigation treatment of each species by SWFAL at Oklahoma State University, using the 0.5 M ammonium acetate method (Wang et al. 2004). Transpiration and leaf resistance were recorded weekly using a LI-1600 Steady State Porometer (LI-COR Inc., Lincoln, NE) and soil moisture values were collected daily between 13 May 2015 and 20 May 2015 using the FieldScout TDR 200 meter (Plainfield, IL) from one pot per treatment. Analysis of variance methods (PROC MIXED) were used with a two-factor factorial arrangement with irrigation and silicon treatment as the factors of interest. Separate analyses were conducted for each plant species. When interactions of irrigation and Si treatment were significant, simple effects were reported. Mean separations were determined using a DIFF option in an LSMEANS statement and a SLICE option (when appropriate) and with a 0.05 level of significance.

Results

Dahlia spp. (Cav.) 'Dahlinova Montana'

A significant interaction of Si treatment with irrigation was seen for leaf resistance, transpiration, and soil Si (Table 1). Under the well-watered condition, soil Si was greatest when supplemented with 60 and 80 g top-dressed as well as 100, 150, and 200 g incorporated (Table 2). Incorporated at 150 and 200 g were greatest compared to other treatments. Transpiration was greatest in plants under the control as well 40 and 60 g top-dressed. Under the water-stressed condition, leaf resistance was greatest when plants were supplemented 40 and 80 g top-dressed as well as 50, 150, and 200 g incorporated. Top-dressed at 80 g and incorporated at 150 g were the greatest compared to other treatments. Soil Si content was greatest under the incorporated rates compared to top-dressed rates and Metro-Mix with Si. However, 150 and 200 g incorporated yielded the greatest result compared to other treatments. Only plants treated with 100 g incorporated had the greatest transpiration.

The main effect of Si treatment (DE) was seen on height, shoot dry weight, and stem diameter (Table 1). Height was greatest under the control, Metro-Mix with Si, all top-dress treatments, and incorporated treatments at 100 and 200 g (Table 3). However, top-dressed at 60 and 80 g as well as 100 g incorporated were greatest compared to the rest. Shoot dry weight was greatest under the control, all top-dress rates, and incorporated at 100 g. Top-dressed at 20 and 40 g were greatest compared to other treatments. Stem diameter was greatest under all top-dressed rates, incorporated rates at 50 and 100 g. However, top-dressed at 20, 40, and 80 g were greatest compared to other treatments.

The main effect of Si treatment (DE) was seen on leaf nutrient content (Table 1). Total N was greatest under the top-dressed treatments, 100, 150, and 200 g incorporated (Table 4). Phosphorous was greatest under 80 g top-dressed as well as 100, 150, and 200 g incorporated. For both N and P, incorporated at 200 g was greatest compared to other treatments. Sulfur was greatest under all top-dressed treatments and incorporated treatments at 100, 150, and 200 g. However, top-dressed at 80 g was greatest compared to the rest. Magnesium was greatest under top-dressed treatments at 40 and 80 g as well as incorporated treatments at 50, 100, and 150 g. Incorporated at 100 g was greatest compared to other treatments. Calcium was greatest under 50, 100, 150 g incorporated and Metro-Mix with Si, but the latter treatment was greatest compared to the rest. Silicon was greatest under the control, top-dressed rates at 20, 40, and 60 g, incorporated rates at 100 and 150 g, as well as Metro-Mix with Si. However, the control, 100 g incorporated, and Metro-Mix with Si yielded the greatest result. For Cu, the greatest values were seen under top-dressed treatments at 40 and 80 g. Iron was greatest under top-dressed treatments at 40, 60, and 80 g as well as incorporated treatments at 100 and 150 g. For both Cu and Fe, 40 g top-dressed yielded the greatest result. Manganese was greatest under 150 and 200 g incorporated.

A significant effect for irrigation was seen on all growth and flowering characteristics (Table 1). Well-watered plants had greater height, width, shoot dry weight, mean flower number, stem diameter, and flower diameter compared to water-stressed plants (Table 5). Iron was the only nutrient in the leaf tissues affected by irrigation. Plants under the water-stressed condition had the greatest amount (Table 6).

Gerbera jamesonii (Bolus ex Hooker f.) ‘Festival Light Eye White Shades’

A significant interaction of Si treatment with irrigation was seen for soil Si and transpiration (Table 7). Under the well-watered condition, soil Si was greatest when DE was supplemented at 150 and 200 g incorporated (Table 8). However, 200 g incorporated yielded the greatest result compared to other treatments. Under the water-stressed condition, soil Si was greatest under 100 and 150 g incorporated. Transpiration was greatest under the control, top-dressed treatments, and Metro-Mix with Si. However, 80 g top-dressed was the greatest compared to other treatments.

The main effect of Si treatment (DE) was seen on height, width, shoot dry weight, and Ni content in the leaf tissue (Table 7). Height was greatest under 80 g top-dressed as well as 50, 100, and 150 g incorporated (Table 9). Width was greatest under top-dressed rates at 20, 40, and 60 g and all incorporated rates. For both height and width, 100 and 150 g incorporated were the greatest compared to other treatments. Shoot dry weight was greatest under incorporated at 100 and 150 g, but the former treatment was greatest compared to the rest. Nickel content in the leaves was greatest under the control, incorporated rates at 50 and 100 g, as well as Metro-Mix with Si (Table 10). However, the control, 50 and 100 g incorporated yielded the greatest result compared to the other treatments.

A significant effect of irrigation was seen on width, leaf nutrient content, and leaf resistance (Table 7). Well-watered plants had greater widths compared to water-stressed plants (Table 11). Potassium, Ca, Na, and Mn levels were greater in water-stressed plants compared to well-watered plants (Table 12). Leaf resistance was also greater in plants subjected to the water-stressed condition compared to plants under the well-watered condition (data not shown).

Rudbeckia hirta (L.) ‘Denver Daisy’

A significant interaction of Si treatment with irrigation was seen for leaf Si content and leaf resistance (Table 13). Under the well-watered condition, Si in the leaf was greatest under 20 and 60 g top-dressed, 50 and 100 g incorporated as well as Metro-Mix with Si (Table 14). Under the water-stressed condition, Si in the leaf was greatest under 60 g top-dressed and Metro-Mix with Si. Under both irrigation treatments, Metro-Mix with Si yielded the greatest result compared to other treatments. Leaf resistance was greatest in plants supplemented 150 g incorporated.

The main effect of Si (DE) supplementation was seen on height, width, and flower diameter (Table 13). Height was greatest under 60 g top-dressed, 100 g incorporated, and Metro-Mix with Si (Table 15). However, 100 g incorporated was greatest compared to the rest. Width was greatest under all top-dress treatments, incorporated treatments at 50 and 100 g, and Metro-Mix with Si. Top-dressed at 80 g, 100 g incorporated, and Metro-Mix with Si yielded the greatest results. Flower diameter was greatest under 50 g incorporated and Metro-Mix with Si, but the latter was greatest compared to the other treatments.

The main effect of Si (DE) supplementation was seen on leaf nutrient content (Table 13). Total N was greatest when plants were supplemented at 150 and 200 g (Table 16). Phosphorous was greatest under incorporated rates at 100, 150, and 200 g. Greater amounts of K were seen under incorporated rates at 100, 150, and 200 g. Sulfur increased under top-dressed treatments at 20, 40 and 60 g as well and all incorporated treatments, but 50 g top-dressed yielded the greatest result compared the rest. Magnesium was greatest under the control, the top-dressed treatments, and incorporated at 50 and 100 g. However, the control was the greatest compared to the treatments. Copper was greatest under 60 g top-dressed, 50, 100, and 200 g incorporated. Greater amounts Fe were seen under 50 and 200 g incorporated. Manganese was greatest under 150 and 200 g incorporated. For N, P, K, Cu, and Fe incorporated at 200 g yielded the greatest result compared to other treatments.

A significant effect of irrigation was seen on all growth and flower characteristics as well as leaf nutrient content, transpiration, and soil Si (Table 13). Plants that were well-watered grew taller and wider (Table 17). Shoot dry weight and stem diameter were greater in well-watered plants as well as mean flower number and flower diameter. Nutrients such as S, Mg, Ca, and Mn were greater in the leaf tissue of water-stressed plants compared to well-watered plants (Table 18). Soil Si and transpiration were greater in plants under the water-stressed condition compared to those that were well-watered (Table 19).

Discussion

Amending the soilless substrate with varying methods and rates of DE increased plant height, width, shoot dry weight, stem diameter, and flower diameter in dahlia, gerbera, and rudbeckia in this study. Several other studies have reported similar benefits of supplemental Si on growth and flowering characteristics. Hwang et al. (2005) reported that adding 200 mg·L^{-1} of potassium metasilicate increased plant height and shoot dry matter in cut roses (*Rosa hybrid* L.). Stem quality was also improved in cut roses when Si was added to a recirculated nutrient solution in a closed hydroponic system (Ehret et al., 2005). Flower diameter of calibrachoa (*Calibrachoa* x*hybrida* Cerv.), fuchsia (*Fuchsia hybrid* hort. Ex Siebold & Voss), and petunia (*Petunia xhybrida* Vilm.) increased when supplemented with a weekly drench of potassium silicate at 100 mg·L^{-1} (Mattson and Leatherwood, 2010). Silicon supplementation improved growth of two cultivars of French marigolds (*Tagetes patula* L.) by increasing stem diameter, shoots, and dry weights (Sivanesan et al., 2010). Growth and biomass parameters were increased in certain cultivars of begonia (*Begonia semperflorens* Link et Otto) and pansy (*Viola* x *wittrockiana* Hort.) grown *in vitro* when supplemented with potassium silicate (Lim et al., 2012) Savvas et al. (2002) reported a higher percentage of flowers in hydroponically-grown gerbera (*Gerbera jamesonni* L.) supplemented with Si. For growth and flower development, Si is very important especially for plants growing in a soilless substrate.

Amending the soilless substrate with varying methods and rates of DE as supplemental Si increased nutrients in dahlia, gerbera, and rudbeckia in this study. Based on the analysis of Kalra (1997), most of the increases in all nutrients were within the optimum range adequate for plant growth. Levels greater than the maximum range were not considered excess or toxic. Nickel concentrations in dahlia were less than the minimum range (Table 4). However, these levels were not considered insufficient because often there are no symptoms to accurately determine Ni deficiency (Buechel, 2017). Epstein (1994) has noted that the presence of Si does in fact affect absorption and translocation of several macro-nutrients and micro-nutrients. Early studies conducted by Fisher (1929) reported that the addition of Si made P more available in barley (*Hordeum vulgare* L.) plants. Mali and Aery (2008) found that in wheat (*Tritium aestivum* L.) K uptake was improved even at low concentrations of Si by way of the H-ATPase being activated. Phosphorus and K are essential nutrients for flowering characteristics. Friedman et al. (2007) conducted a study on cut flowers such as sunflower (*Helianthus annuus* L.) and celosia (*Celosia argentea* L.) and reported that growth and flower parameters were increased when supplemented with an effluent containing high amounts of N, P, and other nutrients. Kamenidou et al. (2008, 2010) also found an increase in N for sunflowers and gerbera but most of the levels exceeded the range. Nitrogen metabolism is a major factor in stem and leaf growth and too much can delay or prevent flowering. Calcium is part of the structure of cell walls and is necessary for cell growth and division. Ma and Takahashi (1993) reported that there was an antagonistic effect between Si and Ca in rice in which one can decrease the amount of the other. However, our study found the opposite effect in which the Metro-Mix with Si increased Ca content in dahlia (Table 4) and rudbeckia (Table 16). Kamenidou et al. (2010) and Savvas et al. (2002) also reported that supplemental Si increased Ca but within gerbera. There was an increase in metals such as Cu, Fe, and Mn in dahlia (Table 4) and gerbera (Table 10) due to DE having trace amounts of these elements (Pati et al., 2016). However, Si is known to increase tolerance to toxicity effects in which none were observed or reported. The levels of these nutrients did not reach excess and were in optimum range. Muhammad et al. (2015) reported an overall review about how stress from metals can be reduced by several functions in which Si plays an important role such as reducing activity of the metals or stimulating chelation. The levels of these metals seemed relatively low and there may not have been enough to cause negative effects. Silicon levels in the leaf tissue and media for all the plants were low as well. Potentially the plants could be classified as non-accumulators of Si (<0.5%) which was reported for gerbera (Bloodnick, 2017).

Amending the soilless substrate with varying methods and rates of DE improved leaf resistance and transpiration in dahlia, gerbera, and rudbeckia in this study. Improvements in these physiological traits were mostly seen when Si (DE) supplementation interacted with irrigation. An increase in leaf resistance and a decrease in transpiration can benefit the floricultural market by improving quality and shelf life of cut flowers (Jana and Jeong, 2014). A foliar spray of sodium silicate at 100 $mg \cdot L^{-1}$ increased leaf resistance and decreased transpiration in zinnias (Kamenidou et al., 2009). Yoshida and Kitagishi (1962) noted that the effects are related to Si being deposited in the cuticular layers of leaves serving as a barrier which reduces the loss of water. Considering the effect of irrigation, plants under the well-watered condition had greater yield in growth and flowering, which was expected. However, Si is known to maintain growth and flowering characteristics as well as nutrient levels in water-stressed plants. In Kentucky bluegrass (*Poa pratensis* L.), drought stress hindered physiological and quality attributes, but application of Si had alleviated the adverse effects (Saud et al., 2014).

Conclusion

Several growth and flowering characteristics were improved depending on rate and application method of diatomaceous earth (DE). Benefits for dahlia, gerbera, and rudbeckia included increased height, width, shoot dry weight, stem, and flower diameter. An increase in nutrients such as N, P, K, Mg, and Ca was seen mostly for dahlia and rudbeckia. The adverse effects that typically occur under water-stressed conditions were alleviated and plant quality as well as physiological traits such as leaf resistance and transpiration were maintained in all three plants due to Si supplementation. Diatomaceous earth as supplemental Si was beneficial for plant growth, flowering, and nutrient content under well-watered and water-stressed conditions. To conclude, this research supports the fact that DE is beneficial to plants but is dependent upon species, rate, and method of application. Benefits of DE include an increase in growth parameters, leaf nutrient content, tolerance to stress in which plant quality can be maintained. Future studies should further assess the use of DE as there are many sources of this product with varying properties. Also, using DE as a Si supplement in other plants will help to broaden information regarding Si supplementation in the floriculture industry.

Literature Cited

Agarie, S., H. Uchida, W. Agata, F. Kubota, and P.B. Kaufman. 1998. Effects of silicon on transpiration and leaf conductance in rice plants (*Oryza sativa* L.). Plant Prod. Sci. 1(2):89-95.

Agarie, S., H. Uchida, W. Agata, F. Kubota, and P.B. Kaufman. 1998. Effects of silicon on tolerance to water deficit and heat stress in rice plants (*Oryza sativa* L.), monitored by electrolyte leakage. Plant Prod. Sci. 1(2):96-103.

Ahmad, R., S.H. Zaheer, and S. Ismail. 1992. Role of silicon in salt tolerance of wheat (*Tritium aestivum* L.). Plant Sci. 85:43-50.

Al-Aghabary, K., Z.J. Zhu, and Q.H. Shi. 2004. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence, and antioxidative enzyme activities in tomato plants under salt stress. J. Plant Nutr. 27:2101-2115.

Ashraf, M., A. Ahmad, and T. McNeilly. 2001. Growth and photosynthetic characteristics in pearl millet under water stress and different potassium supply. Photosynthetica 39:389-394.

Belanger, R.R., P.A. Bowen, D.L. Ehret, and J.G. Menzies. 1995. Soluble silicon: its role in crop and disease management of greenhouse crops. Plant Dis. 79:329-336.

Berthelsen, S., A.D. Noble, G. Kingston, A. Hurney, A. Rudd, and A. Garside. 2003. Improving yield and ccs in sugarcane through the application of silicon based amendments. Final report on SRDC Project CLW009. http://elibrary.sugarresearch.com.au. Accessed 9 October 2017.

Bloodnick, E. 2017. Role of Silicon in plant culture. http://www.pthorticulture.com/en/training-center/role-of-silicon-in-plant-culture/. Accessed 9 October 2017.

Bowen, P., J. Menzies, D. Ehret, L. Samuels, and A.D. Glass. 1992. Soluble silicon sprays inhibit powdery mildew development on grape leaves. J. Amer. Soc. Hort. Sci. 117(6):906-912.

Bradbury, M. and R. Ahmad. 1990. The effect of silicon on the growth of *Prosopis julifora* growing in saline soil. Plant Soil 125:71-74.

Buechel, T. 2017. Role of Nickel in Plant Culture. http://www.pthorticulture.com/en/training-center/role-of-nickel-in-plant-culture/. Accessed 9 October 2017.

Carvalho-Zanao, M.P., J. LAZ, J.G. Barbosa, J.A.S. Grossi, and V.T. Ávila. 2012. Yield and shelf life of *Chrysanthemum* in response to the silicon application. Hort. Brasileira 30:403-408.

Chérif, M., A. Asselin, and R.R. Bélanger. 1994. Defense responses induced by soluble silicon in cucumber roots infected by *Pythium* spp. Phytopathology 84(3):236-242.

Currie, H.A. and C.C. Perry. 2007. Silica in plants: biological, biochemical, and chemical studies. Ann. Bot. 100:1383-1389.

De Kreij, C. W. Voogt, and R. Baas. 1999. Nutrient solutions and water quality for soilless cultures. Research Station for Floriculture and Glasshouse Vegetables Brochure, Naaldwijk, The Netherlands.

Ehret, D.L., J.G. Menzies, and T. Helmer. 2005. Production and quality of greenhouse roses in recirculating nutrient systems. Sci. Hort. 106:103-113.

Elliott, C.L. and G.H. Snyder. 1991. Autoclave-induced digestion for the colorimetric determination of silicon in rice straw. J. Agr. Food Chem. 39(6):1118-1119.

El-Jaoual, T. and D.A. Cox. 1998. Manganese toxicity in plants. J. Plant Nutr. 21:353-386.

Epstein, E. 1994. The anomaly of silicon in plant biology. Proc. Natl. Acad. Sci. USA. 91:11-7.

Epstein, E. 2009. Silicon: its manifold roles in plants. Ann. Appl. Biol. 155:155-160.

Exley, C. 1998 Silicon in life: A bioinorganic solution to bioorganic essentiality. J. Inorg. Biochem. 69:139-144.

Fernandez, M., B. Woodward, and B. Stromberg. 1998. Effect of diatomaceous earth as an anthelmintic treatment on internal parasites and feedlot performance of beef steers. Anim. Sci. 66(3):635-641.

Fisher, R.A. 1929. A preliminary note on the effect of sodium silicate in increasing the yield of barley. J. Agric. Sci. 19:132-139.

Friedman, H., N. Bernstein, M. Bruner, I. Rot, Z. Ben-Noon, A. Zuriel, R. Zuriel, S. Finklestein, N. Umiel, and A. Hagiladi. 2007. Application of secondary-treated effluents for cultivation of sunflower (*Helianthus annus* L.) and celosia (*Celosia argentea* L.) as cut flowers. Sci. Hort. 115:62-69.

Gascho, G.J. 2001. Silicon sources for agriculture. Stud. Plant Sci. 8:197-207.

Gong, H.K., G. Chen, S. Wang, and C. Zhang. 2003. Effects of silicon on growth of wheat under drought. J. Plant Nutr. 26:1055-1063.

Gunes, A., D.J. Pilbeam, A. Inal, and S. Coban. 2008. Influence of silicon on sunflower cultivars under drought stress. I: growth, antioxidant mechanisms, and lipid peroxidation. Commun. Soil Sci. Plant Anal. 39:1885-1903.

Hammond, K.E., D.E. Evans, and M.J. Hodson. 1995. Aluminum/silicon interactions in barley (*Hordeum vulgare* L.) seedlings. Plant Soil 173:89-95.

Horiguchi, T. 1988. Mechanism of manganese toxicity and tolerance of plants: IV. Effects of silicon on alleviation of manganese toxicity of rice plants. Soil Sci. Plant Nutr. 34(1):65-73.

Horst, W.J. and H. Marschner. 1978. Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil 50(1-3):287-303.

Hwang, S.J., H.M. Park, and B.R. Jeong. 2005. Effects of potassium silicate on the growth of miniature rose Pinnochio grown on rockwool and its cut flower quality. J. Jpn. Soc. Hort. Sci. 74:242-247.

Iannucci, A., M. Russo, L. Arena, N. Di Fonzo, and P. Martiniello. 2002.Water deficit effects on osmotic adjustment and solute accumulation in leaves of annual clovers. Eur. J. Agron. 16:111-122.

Imaizumi, K. and S. Yoshida. 1958. Edophological studies on silicon supplying power of paddy fields. Bulletin Natl. Inst. Agr. Sci. series B. No.8:261-304

Ishibashi, H. 1956. Influence of silica on the growth of rice plant. Jpn. J. Soil Sci. Plant Nutr. 10:244-256.

Iwasaki, K. and A. Matsumura. 1999. Effect of silicon on alleviation of manganese toxicity in pumpkin (*Cucurbita moschata* Duch cv. Shintosa). Soil Sci. Plant Nutr. 45(4):909-920.

Jana, S. and B.R. Jeong. 2014. Silicon: the most under-appreciated element in horticultural crops. Trends Hort. Res. 4:1-19.

Jawardana, R.K., D. Weerahewa, and J. Saparamadu. 2016. The effect of rice hull as a silicon source on anthracnose disease resistance and some growth and fruit parameters of capsicum grown in simplified hydroponics. Intl. J. Recycling Organ. Waste Agr. 5(1): 9-15.

Jones, L.H.P. and K.A. Handreck. 1965. Studies of silica in the oat plant. III-Uptake of silica from soils by the plant. Plant Soil 23:79-96.

Jones, L.H.P. and K.A. Handreck. 1967. Silica in soils, plants, and animals. Adv. Agron. 19:107-149.

Kalra, Y. 1998. *Handbook of reference methods for plant analysis*. Boston, MA: CRC Press.

Kamenidou, S., T.J. Cavins, and S. Marek. 2008. Silicon supplements affect horticultural traits of greenhouse-produced ornamental sunflowers. HortScience 43(1):236-239.

Kamenidou, S., T.J. Cavins, and S. Marek. 2009. Evaluation of silicon as a nutritional supplement for greenhouse zinnia production. Sci. Hort. 119(3):297-301.

Kamenidou, S., T.J. Cavins, and S. Marek. 2010. Silicon supplements affect floricultural quality traits and elemental nutrient concentrations of greenhouse produced gerbera. Sci. Hort. 123(3):390-394.

Kanto, T., A. Miyoshi, T. Ogawa, K. Maekawa, and M. Aino. 2006. Suppressive effect of liquid potassium silicate on powdery mildew of strawberry in soil. J. Gen. Plant Pathol. 72(3):137-142.

Kaya, C., L. Tuna, and D. Higgs. 2006. Effect of silicon on plant growth and mineral nutrition of maize grown under water-stress conditions. J. Plant Nutr. 29:1469-1480.

King, P.A. and S. Reddy, inventors; SunGro Horticulture, Inc., assignee. US patent 6074988. Jun 13, 2000.

Kobayashi, J. 1961. A chemical study on the average quality and characteristics of river waters of Jpn. Nogaku-kenkyu 48:63-106.

Kovda, V.A. 1973. The bases of learning about soils. Moscow: Nayka.

Lewin, J. and B.E.F. Reimann. 1962. Silicon and plant growth. Ann. Rev. Plant Physiol. 20:289-304.

Liang, Y.C., Q.R. Shen, Z.G. Shen, and T.S. Ma. 1996. Effects of silicon on salinity tolerance of two barley cultivars. J. Plant Nutr. 19:173-183.

Liang, Y. 1999. Effects of silicon on enzyme activity and sodium, potassium and calcium concentration in barley under salt stress. Plant Soil 209:217-224.

Liang, Y., W. Sun, Y.G. Zhu, and P. Christie. 2006. Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. Environ. Pollut. 147:422-428.

Lim, M.Y., E.J. Lee, S. Jana, I. Sivanesan, and B.R. Jeong. 2012. Effect of potassium silicate on growth and leaf epidermal characteristics of Begonia and Pansy grown *in vitro*. Korean J. Hort. Sci. Technol. 30:579-585.

Lindsay, W.L. 1979. Chemical equilibria in soil. John Wiley & Sons, New York.

Ma, J.F. and E. Takahashi. 1993. Interaction between calcium and silicon in water-cultured rice plants. Plant Soil. 148:107-113.

Ma, J. F. and E. Takahashi. 2002. *Soil, fertilizer, and plant silicon research in Japan*. Amsterdam, The Netherlands: Elsevier.

Ma, J.F. 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Sci. Plant Nutr. 50(1):11-18.

Ma, J.F. and N. Yamaji. 2006. Silicon uptake and accumulation in higher plants. Trends Plant Sci. 11(8):392-397.

Mali, M. and N.C. Avery. 2008. Influence of silicon on growth, relative water contents and uptake of silicon, calcium and potassium in wheat grown in nutrient solution. J. Plant Nutr. 31:1867-1876.

Matoh, T., P. Kairusmee, and E. Takahashi. 1986. Salt-induced damage to rice plants and alleviation effect of silicate. Soil Sci. Plant Nutr. 32:295-304.

Mattson, N.S. and W.R. Leatherwood. 2010. Potassium silicate drenches increase leaf silicon content and affect morphological traits of several floriculture crops grown in a peat-based substrate. HortScience 45(1):43-47.

Meerow, A.W. and T.K. Broschat. 1996. Growth of *Hibiscus* in media amended with a ceramic diatomaceous earth granule and treated with a kelp extract. HortTechnology 6(1):70-73.

Menzies, J.G., P.A. Bowen, D.L. Ehret, and A.D.M. Glass. 1992. Foliar applications of potassium silicate reduce severity of powdery mildew of cucumber, muskmelon, and zucchini squash. J. Amer. Soc. Hort. Sci. 117:902-905.

Mills, H.A. and B.J. Jones. 1996. *Plant analysis handbook II*. Athens, GA: MicroMacro Publishing Inc.

Mitani, N, J.F. Ma, and T. Iwashita. 2005. Identification of the silicon form in xylem sap of rice (*Oryza sativa* L.). Plant Cell Physiol. 46:279-283.

Mitre, V., I. Mitre, A.F. Sestras, and R.E. Sestras. 2010. New products against apple scab and powdery mildew attack in organic apple production. Not. Bot. Hort. Agrobot. Cluj. 38(3):234-238.

Miyake, Y. and E. Takahashi. 1983. Effect of silicon on the growth of solution-cultured cucumber plant. Soil Sci. Plant Nutr. 29(1):71-83.

Muhammad, A., A. Shafaqat., R. Muhammad, Z.R. Muhammad, I. Muhammad, A. Farhat, F. Mujahid, F.Q. Muhammad, and K.I. Muhammad. 2015. Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: a review. Ecotoxicol. Environ. Saf. 119:186-197.

Muir, S. 2001. Plant-available silicon (Si) as a protectant against fungal diseases in soil-less potting media.

https://www.ngia.com.au/Story?Action=View&Story_id=1782. Accessed 9 October 2017.

Nasseri, M., H. Arouiee, M. Kafi, and H. Neamati. 2012. Effect of silicon on growth and physiological parameters in fenugreek (*Trigonellafoenum-graceum* L.) under salt stress. Int. J. Agr. Crop Sci. 21:1554-1558.

Nonanka, K. and K. Takahashi. 1990. A method for assessing the need of silicate fertilisers in paddy soils. Soil Sci. 4:513-514.

Pati, S., B. Pal, S. Badole, G.C. Hazra, and B. Mandal. 2016. Effect of silicon fertilization on growth, yield, and nutrient uptake of rice. Commun. Soil Sci. Plant Anal. 47(3):284-290.

Perry, C.C. and T. Keeling-Tucker. 1998. Crystalline silica prepared at room temperature from aqueous solution in the presence of intrasilica bioextracts. Chem. Commun. 23:2587-2588.

Reezi, S., M. Babalar, and S. Kalantari. 2009. Silicon alleviates salt stress, decreases malondialdehyde content and affects petal color of salt stressed cut rose (*Rosa xhybrida* L.) Hot Lady. Afr. J. Biotechnol. 8:1502-1508.

Rohanipoor, A., M. Norouzi, A. Moezzi, and P. Hassibi. 2013. Effect of silicon on some physiological properties of maize (*Zea mays*) under salt stress. J. Biol. Environ. Sci. 7(20):71-79.

Rogalla, H and V. Romheld. 2002. Role of leaf apoplast in silicon-mediated manganese tolerance of *Cucumis sativus* L. Plant Cell Environ. 25:549-555.

Saud, S., X. Li, Y. Chen, L. Zhang, S. Fahad, S. Hussain, A. Sadiq, and Y. Chen. 2014. Silicon application increases drought tolerance of Kentucky bluegrass by improving plant water relations and morphophysiological function. Sci. World J. 23(17):17647-17655.

Savant, N.K., G.H. Snyder, and L.E. Datnoff. 1996. Silicon management and sustainable rice production. Adv. Agron. 58:151-199.

Savvas, D., G. Manos, A. Kotsiras, and S. Souvaliotis. 2002. Effects of silicon and nutrient-induced salinity on yield, flower quality and nutrient uptake of gerbera grown in a closed hydroponic system. J. Appl. Bot. 76(5-6):153-158.

Scarbrough, S. 2007. Silica in plant nutrition. http://www.firt.org/sites/default/files/Scarbrough_Silica_in_Plant_Nutrition_presentation.pdf. Accessed 9 October 2017.

Shen, X., Y. Zhou, L. Duan, Z. Li, A.E. Eneji, and J. Li. 2010. Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. J. Plant Phys. 167:1248-1252.

Singh, A.K., R. Singh, and K. Singh. 2005. Growth, yield, and economics of rice (*Oryza sativa*) as influenced by level and time of silicon application. Ind. J. Agron. 50:190-93.

Sivanesan, I., M.S. Son, J.P. Lee, and B.R. Jeong. 2010. Effects of silicon growth of *Tagetes patula* L. Boy orange and Yellow boy seedlings cultured in an environment controlled chamber. Propag. Ornam. Plants 10:136-140.

Sivanesan, I. and S.W. Park. 2014. The role of silicon in plant tissue culture. Front. Plant Sci. 5:1-4.

Sonobe, K., T. Hattorri, P. An, W. Tsuji, A.E. Eneji, S. Kobayashi, Y. Kawamura, K. Tanaka, and S. Inanaga. 2010. Effect of silicon application on sorghum root responses to water stress. J. Plant Nutr. 34:71-82.

Subramanian, S. and A. Gopalswamy. 1990. Effect of moisture, organic matter, phosphate, and silicate on availability of silicon and phosphorus in rice soils. J. Indian Soc. Soil Sci. 39:99-103.

Taiz, L. and E. Zeiger. 2002. *Plant physiology, Third Edition*. Sunderland, MA: Sinauer Associates.

Trenholm, L.E., L.E. Datnoff, and R.T. Nagata. 2004. Influence of silicon on drought and shade tolerance of St. Augustinegrass. HortTechnology. 14(4):487-490.

Tubana, B.S., B. Tapasya, and L.E. Datnoff. 2016. Review of silicon in soils and plants and its role in US agriculture: History and future perspectives. Soil Sci. 181:393-411.

Voogt, W. and C. Sonneveld. 2001. *Silicon in agriculture*. Amsterdam, The Netherlands: Elsevier.

Wehtje, G.R., J.N. Shaw, R.H. Walker, and W. Williams. 2003. Bermudagrass growth in soil supplemented with inorganic amendments. HortScience 38(4):613-617.

Whitted-Haag, B., D.E. Kopsell, D.A. Kopsell, and R.L. Rhykerd. 2014. Foliar silicon and titanium applications influence growth and quality characteristics of annual bedding plants. Open Hort. J. 7:6-15.

Yildiz, N. 2008. Diatomite: A new substrate for hydroponics. International Meeting on Soil Fertility Land Management and Agroclimatology, Special Issue, 527-536.

Yoshida, S., Y. Ohnishi, and K. Kitagishi. 1962. Chemical forms, mobility and deposition of silicon in rice plant. Soil Sci. Plant Nutr. 8(3):15-21.

Yoshida, S., D.A. Forno, J.H. Cock, and K.A. Gomez. 1976. Laboratory manual for physiological studies of rice. IRRI Press, Manila. 61-66.

Zhu, Z.J., G.Q. Wei, J. Li, Q.Q. Qian, and J.P. Yu. 2004. Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (*Cucumis sativus* L.). Plant Sci. 167:527-533.

Appendix

Table 1. Analysis of variance for growth, flowering, leaf nutrient content, soil silica, and physiology of *Dahlia* spp. (Cav.) ‘Dahlinova Montana’.

Source	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Si Treatment	*[z]	ns	**	***	ns	ns
Irrigation	****	****	****	***	****	****
Si Treatment x Irrigation	ns	ns	ns	ns	ns	ns

Source	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Si Treatment	**	*	*	ns	***	****	ns	****	ns	***	**	****	ns
Irrigation	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns
Si Treatment x Irrigation	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Source	Leaf resistance (sec·cm^{-1})	Transpiration	Soil silica (ppm)
Si Treatment	***	ns	****
Irrigation	****	****	****
Si Treatment x Irrigation	**	****	**

[z]NS, *, **, ***, **** indicate non-significant or significant at P ≤ 0.05, 0.01, 0.001, 0.0001, respectively.

Table 2. Leaf resistance, transpiration, and soil Si of *Dahlia* spp. (Cav.) ‘Dahlinova Montana’ affected by interaction of Si treatment with irrigation.

		Well-watered (10 cb)		Water-stressed (20 cb)		
Source	Rate (g/pot)	Soil Si (ppm)	Transpiration	Leaf resistance ($\text{sec}\cdot\text{cm}^{-1}$)	Soil Si (ppm)	Transpiration
Control	0	47.8e[z]	8.9a	6.6d	53.5bcd	4.8b
DE Top-dressed	20	56.1de	6.8bc	7.7bcd	49.5d	4.5b
	40	59.7bcd	9.0a	9.4abc	51.5cd	2.9cd
	60	65.8abc	8.9a	7.5bcd	47.8d	4.2bc
	80	65.1abc	6.8bc	10.9a	49.7d	3.3cd
DE Incorporated	50	58.8cd	7.0b	8.8abcd	62.0ab	4.9b
	100	67.9ab	5.2d	6.8cd	59.3abc	6.5a
	150	70.1a	7.3b	11.4a	63.1a	3.2cd
	200	72.7a	5.7cd	9.8ab	63.6a	2.9d
Metro Mix w/Si		53.1de	6.7bc	7.9bcd	50.3d	4.6b

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 3. Growth and flowering characteristics of *Dahlia* spp. (Cav.) 'Dahlinova Montana' affected by Si treatment averaged across irrigation.

Source	Rate (g/pot)	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Control	0	24.9ab^{z}	26.9a	15.8abcd	3.8bc	7.1a	5.7a
DE Top-dressed	20	24.1ab	29.1a	18.9a	4.5a	8.0a	5.8a
	40	24.8ab	27.9a	19.0a	4.5a	8.5a	5.4a
	60	26.9a	29.3a	17.9ab	4.3ab	5.7a	4.9a
	80	26.8a	26.9a	16.2abc	4.5a	7.0a	5.3a
DE Incorporated	50	22.2b	24.3a	14.5bcd	3.9abc	5.9a	4.9a
	100	26.6a	27.5a	15.2abcd	4.3ab	6.3a	6.3a
	150	22.1b	25.9a	11.8d	3.4c	5.4a	5.3a
	200	23.9ab	25.1a	12.6cd	3.4c	5.5a	5.4a
Metro Mix w/Si		24.9ab	27.4a	13.1cd	3.8bc	6.4a	5.4a

^{z}Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 4. Leaf nutrient content of *Dahlia* spp. (Cav.) ‘Dahlinova Montana’ affected by Si treatment averaged across irrigation.

Source	Rate (g/pot)	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Control	0	3.55bcd^{z}	0.29c	0.33bc	3.51a	0.92bc	1.74de	0.02a	84.1a	38.5a	12.0d	92.2d	151.6d	0.007a
DE Top-dressed	20	3.88ab	0.33bc	0.39ab	3.33a	0.91bc	1.81cd	0.03a	69.1abc	46.6a	14.4cd	106.6cd	149.3d	0.004a
	40	4.11ab	0.34bc	0.39ab	3.19a	0.97ab	1.75de	0.03a	77.3ab	53.6a	18.2a	232.7a	163.9cd	0.004a
	60	4.09ab	0.33bc	0.35abc	3.23a	0.84c	1.61e	0.02a	69.7abc	39.5a	14.4cd	161.7abcd	150.2d	0.004a
	80	3.83ab	0.34abc	0.41a	3.47a	0.96ab	1.85bcd	0.02a	38.1c	44.9a	17.5ab	171.5abc	188.8bc	0.003a
DE Incorporated	50	3.21cd	0.29c	0.34bc	3.48a	0.98ab	1.93abc	0.02a	47.9bc	45.2a	14.8bcd	133.8bcd	189.9bc	0.007a
	100	3.75abcd	0.35abc	0.39ab	3.54a	1.03a	1.99ab	0.03a	82.9a	57.9a	15.1bc	188.6ab	204.6b	0.010a
	150	3.79abc	0.38ab	0.37ab	3.81a	0.98ab	2.00ab	0.03a	67.5abc	42.2a	14.1cd	163.1abcd	272.1a	0.057a
	200	4.27a	0.39a	0.37ab	3.54a	0.92bc	1.88bcd	0.02a	45.8bc	39.9a	13.3cd	104.5cd	250.4a	0.010a
Metro Mix w/Si		3.19d	0.33bc	0.31c	3.44a	0.82c	2.07a	0.03a	94.3a	42.5a	11.9d	97.1d	194.7b	0.340a
Optimum levels		2.5	0.20	0.25	1.50	0.25	1.00	y	y	27.0	5.0	100.0	20.0	0.050
		4.5	0.75	1.00	5.50	1.00	4.00			100.0	30.0	500.0	300.0	5.00

^{z}Means (n=6) with the same letter within the same column are not statistically significant at P ≤ 0.05.

^{y}Optimum levels not reported.

Table 5. Growth and flowering characteristics of *Dahlia* spp. (Cav.) ‘Dahlinova Montana’ affected by irrigation averaged across Si treatments.

Source	Rate (cb)	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Well-watered	10	27.4a^{z}	29.7a	19.8a	4.3a	8.4a	6.8a
Water-stressed	20	22.0b	24.2b	11.2b	3.8b	4.8b	4.1b

^{z}Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 6. Leaf nutrient content of *Dahlia* spp. (Cav.) 'Dahlinova Montana' affected by irrigation averaged across Si treatments.

Source	Rate (cb)	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Well-watered	10	3.73a[z]	0.35a	0.37a	3.39a	0.93a	1.83a	0.028a	68.1a	46.1a	15.1a	116.6b	186.0a	0.006a
Water-stressed	20	3.79a	0.33a	0.35a	3.52a	0.94a	1.89a	0.025a	67.2a	44.1a	13.9a	176.4a	197.2a	0.084a
Optimum levels		2.50	0.20	0.25	1.50	0.25	1.00	y	y	27.0	5.0	100.0	20.0	0.050
		4.50	0.75	1.00	5.50	1.00	4.00			100.0	30.0	500.0	300.0	5.00

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Optimum levels not reported.

Table 7. Analysis of variance for growth, flowering, leaf nutrient content, soil silica, and physiology of *Gerbera jamesonii* (L.) ‘Light Eye White Shades’.

Source	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Si Treatment	*[z]	*	*	ns	ns	ns
Irrigation	ns	**	ns	ns	ns	ns
Si Treatment x Irrigation	ns	ns	ns	ns	ns	ns

Source	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Si Treatment	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**
Irrigation	ns	ns	ns	ns	*	*	**	*	ns	ns	ns	ns	ns
Si Treatment x Irrigation	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Source	Leaf resistance (sec·cm^{-1})	Transpiration	Soil silica (ppm)
Si Treatment	ns	ns	****
Irrigation	*	****	*
Si Treatment x Irrigation	ns	**	**

[z] NS, *, **, ***, **** indicate non-significant or significant at P ≤ 0.05, 0.01, 0.001, 0.0001, respectively.

Table 8. Soil Si and transpiration of *Gerbera jamesonii* (L.) ‘Festival Light Eye White Shades’ affected by interaction of Si treatment with irrigation.

		Well-watered (10 cb)	Water-stressed (20 cb)	
Source	Rate (g/pot)	Soil Si (ppm)	Soil Si (ppm)	Transpiration
Control	0	43.6bc[z]	32.7cd	7.3abc
DE Top-dressed	20	41.3c	30.4d	8.2ab
	40	45.5bc	35.8cd	8.5ab
	60	43.0bc	48.2b	8.5ab
	80	47.2bc	47.6b	8.7a
DE Incorporated	50	42.3c	41.5bc	6.9bc
	100	50.4bc	59.5a	6.1c
	150	52.1ab	59.4a	7.0bc
	200	56.9a	45.3b	5.8c
Metro Mix w/Si		43.6bc	36.3cd	7.2abc

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 9. Growth and flowering characteristics of *Gerbera jamesonii* (L.) ‘Festival Light Eye White Shades’ affected by Si treatment averaged across irrigation.

Source	Rate (g/pot)	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Control	0	8.9b[z]	20.8b	3.9c	0.9a	0.4a	0.6a
DE Top-dressed	20	11.1b	21.7ab	5.9bc	1.2a	1.1a	2.1a
	40	11.2b	22.5ab	4.9bc	0.7a	0.5a	1.1a
	60	10.4b	22.4ab	5.4bc	0.6a	0.3a	0.2a
	80	11.8ab	20.0b	5.9bc	0.3a	0.8a	1.2a
DE Incorporated	50	12.1ab	21.6ab	5.7bc	1.3a	0.6a	1.0a
	100	15.1a	25.2a	8.6a	1.5a	1.2a	2.8a
	150	15.3a	24.9a	7.2ab	1.5a	1.0a	2.1a
	200	10.8b	23.1ab	5.0bc	1.5a	1.0a	1.6a
Metro Mix w/Si		10.8b	19.5b	4.9bc	0.8a	0.8a	0.6a

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 10. Leaf nutrient content of *Gerbera jamesonii* (L.) 'Festival Light Eye White Shades' affected by Si treatment averaged across irrigation.

Source	Rate (g/pot)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Control	0	0.26a[z]	0.40a	2.63a	0.62a	1.45a	0.07a	107.6a	46.6a	24.8a	591.1a	145.4a	2.29a
DE Top-dressed	20	0.31a	0.48a	3.18a	0.66a	1.55a	0.08a	253.4a	56.6a	31.5a	392.1a	129.8a	0.128b
	40	0.28a	0.39a	3.30a	0.62a	1.48a	0.07a	185.2a	52.8a	20.9a	235.6a	129.2a	0.002b
	60	0.46a	1.01a	3.06a	0.77a	2.12a	0.16a	308.0a	84.1a	133.8a	390.6a	156.9a	0.191b
	80	0.54a	1.03a	3.31a	0.79a	2.02a	0.14a	264.7a	115.2a	171.8a	566.7a	190.8a	0.066b
DE Incorporated	50	0.29a	0.42a	3.10a	0.73a	1.71a	0.07a	223.7a	57.9a	14.4a	649.9a	165.3a	2.12a
	100	0.27a	0.38a	3.06a	0.62a	1.42a	0.12a	263.2a	51.8a	20.3a	736.4a	161.9a	2.23a
	150	0.26a	0.32a	3.03a	0.55a	1.26a	0.07a	172.1a	43.9a	11.6a	305.9a	161.8a	0.103b
	200	0.26a	0.31a	2.97a	0.56a	1.33a	0.06a	163.9a	43.6a	10.5a	291.1a	219.1a	0.131b
Metro Mix w/Si		0.37a	0.62a	3.10a	0.70a	1.88a	0.08a	308.1a	79.2a	67.9a	742.7a	198.8a	1.48ab
Optimum levels		0.20	0.25	1.50	0.25	1.00	y	y	27.0	5.0	100.0	20.0	0.05
		0.75	1.00	5.50	1.00	4.00			100.0	30.0	500.0	300.0	5.0

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Optimum levels not reported.

Table 11. Growth and flowering characteristics of *Gerbera jamesonii* (L.) 'Festival Light Eye White Shades' affected by irrigation averaged across Si treatments.

Source	Rate (cb)	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Well-watered	10	12.3a[z]	23.6a	6.2a	1.1a	0.9a	1.4a
Water-stressed	20	11.2a	20.8b	5.3a	0.9a	0.6a	1.1a

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 12. Leaf nutrient content of *Gerbera jamesonii* (L.) 'Festival Light Eye White Shades' affected by irrigation averaged across Si treatments.

Source	Rate (cb)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Well-watered	10	0.27a^z	0.41a	3.01b	0.61a	1.45b	0.068b	184.2a	51.5a	26.1a	402.0a	154.8b	0.67a
Water-stressed	20	0.24a	0.66a	3.14a	0.72a	1.79a	0.117a	265.6a	74.8a	75.4a	578.4a	177.1a	1.07a
Optimum levels		0.20	0.25	1.50	0.25	1.00	y	y	27.0	5.0	100.0	20.0	0.05
		0.75	1.00	5.50	1.00	4.00			100.0	30.0	500.0	300.0	5.0

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Optimum levels not reported.

Table 13. Analysis of variance for growth, flowering, leaf nutrient content, soil silica, and physiology of *Rudbeckia hirta* (L.) 'Denver Daisy'.

Source	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Si Treatment	*[z]	*	ns	ns	ns	**
Irrigation	**	****	****	***	****	****
Si Treatment x Irrigation	ns	ns	ns	ns	ns	ns

Source	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Si (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Si Treatment	****	****	***	***	***	**	ns	****	ns	ns	*	****	ns
Irrigation	ns	ns	***	ns	****	****	ns	****	ns	**	ns	*	ns
Si Treatment x Irrigation	ns	ns	ns	ns	ns	ns	ns	***	ns	ns	ns	ns	ns

Source	Leaf resistance (sec·cm^{-1})	Transpiration	Soil silica (ppm)
Si Treatment	****	ns	****
Irrigation	****	****	****
Si Treatment x Irrigation	****	ns	ns

[z] NS, *, **, ***, **** indicate non-significant or significant at P ≤ 0.05, 0.01, 0.001, 0.0001, respectively.

Table 14. Soil Si and transpiration of *Rudbeckia hirta* (L.) ‘Denver Daisy’ affected by interaction of Si treatment with irrigation.

		Well-watered (10 cb)	Water-stressed (20 cb)	
Source	Rate (g/pot)	Leaf Si (ppm)	Leaf Si (ppm)	Leaf resistance (sec·cm^{-1})
Control	0	276.6bc[z]	345.7bc	11.2c
DE Top-dressed	20	281.5abc	373.4bc	6.5ef
	40	260.2bc	357.8bc	6.4ef
	60	313.8abc	412.0ab	5.3ef
	80	261.9bc	321.3bcd	4.9f
DE Incorporated	50	292.3abc	346.3bc	7.de
	100	377.4ab	261.1cd	9.8cd
	150	196.4cd	208.9d	18.5a
	200	91.4c	201.6d	14.8b
Metro Mix w/Si		406.5a	522.4a	6.6ef

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 15. Growth and flowering characteristics of *Rudbeckia hirta* (L.) 'Denver Daisy' affected by Si treatment averaged across irrigation.

Source	Rate (g/pot)	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Control	0	30.8bc[z]	23.0bc	12.8a	4.3a	6.4a	6.2b
DE Top-dressed	20	31.1bc	26.9ab	17.6a	4.4a	10.5a	5.4bc
	40	30.9bc	26.9ab	18.1a	3.9a	9.8a	5.5bc
	60	34.8abc	27.2ab	23.4a	4.7a	11.1a	5.9bc
	80	30.9bc	28.2a	24.2a	4.5a	9.7a	6.4b
DE Incorporated	50	32.2bc	26.1abc	18.2a	4.2a	9.6a	6.5ab
	100	46.4a	27.8a	19.9a	3.8a	8.9a	5.9bc
	150	25.3c	21.9c	15.5a	4.0a	7.0a	4.9bc
	200	27.4bc	23.1bc	16.1a	3.7a	8.5a	4.5c
Metro Mix w/Si		39.2ab	29.2a	20.2a	4.3a	11.1a	8.1a

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 16. Leaf nutrient content of *Rudbeckia hirta* (L.) 'Denver Daisy' affected by Si treatment averaged across irrigation.

Source	Rate (g/pot)	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Control	0	2.40de[z]	0.20e	0.41cd	3.09d	1.21a	3.35b	0.02a	39.7a	6.03de	97.9c	137.6bc	0.002a
DE Top-dressed	20	2.79cde	0.22cde	0.49abc	3.31bcd	1.20ab	3.33b	0.02a	40.4a	8.0bcde	130.9bc	131.7bcd	0.002a
	40	2.98bc	0.26bcd	0.48abc	3.53bcd	1.10ab	2.89bc	0.02a	42.7a	8.9bcde	134.5bc	114.4d	0.002a
	60	2.94bc	0.23cde	0.52ab	3.25cd	1.13ab	3.28bc	0.04a	39.8a	8.6abcd	132.6bc	125.7cd	0.003a
	80	2.87cd	0.21de	0.44bcd	3.29bcd	1.12ab	3.17bc	0.04a	33.1a	7.5cde	91.7c	129.5cd	0.462a
DE Incorporated	50	2.82cde	0.24bcde	0.55a	3.27bcd	1.15ab	3.27bc	0.02a	44.2a	10.9ab	209.2ab	137.1bc	0.533a
	100	2.96bc	0.27abc	0.53ab	3.74ab	1.12ab	3.26bc	0.03a	36.8a	10.0abc	168.8bc	152.1b	0.308a
	150	3.38ab	0.28ab	0.48abc	3.72abc	1.09bc	3.26bc	0.03a	37.6a	7.6cde	139.5bc	208.7a	0.145a
	200	3.51a	0.31a	0.50abc	4.13a	0.97cd	2.79c	0.03a	43.6a	11.4a	285.2a	203.8a	0.575a
Metro Mix w/Si		2.37e	0.21de	0.34d	3.14d	0.96d	4.01a	0.01a	37.1a	5.1e	105.9bc	140.3bc	0.002a
Optimum levels		2.50	0.20	0.25	1.50	0.25	1.00	y	27.0	5.0	100.0	20.0	0.050
		4.50	0.75	1.00	5.50	1.00	4.00		100.0	30.0	500.0	300.0	5.00

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Optimum levels not reported.

Table 17. Growth and flowering characteristics of *Rudbeckia hirta* (L.) 'Denver Daisy' affected by irrigation averaged across Si treatments.

Source	Rate (cb)	Height (cm)	Width (cm)	Shoot dry weight (g)	Stem diameter (cm)	Mean flower number	Flower diameter (cm)
Well-watered	10	36.8a^z	29.9a	25.0a	4.6a	12.6a	7.9a
Water-stressed	20	22.0b	24.2b	11.2b	3.7b	4.8b	4.1b

^{z}Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 18. Leaf nutrient content of *Rudbeckia hirta* (L.) 'Denver Daisy' affected by irrigation averaged across Si treatments.

Source	Rate (cb)	TN (%)	P (%)	S (%)	K (%)	Mg (%)	Ca (%)	Na (%)	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Ni (ppm)
Well-watered	10	2.88a[z]	0.25a	0.43b	3.48a	1.03b	2.82b	0.029a	37.5a	8.3a	140.4a	141.9b	0.24a
Water-stressed	20	2.92a	0.24a	0.52a	3.42a	1.18a	3.70a	0.223a	41.5a	8.4a	158.8a	154.3a	0.17a
Optimum levels		2.50	0.20	0.25	1.50	0.25	1.00	y	27.0	5.0	100.0	20.0	0.05
		4.50	0.75	1.00	5.50	1.00	4.00		100.0	30.0	500.0	300.0	5.00

[z] Means (n=6) with the same letter within the same column are not statistically significant at P ≤ 0.05.

[y] Optimum levels not reported.

Table 19. Soil Si and transpiration of *Rudbeckia hirta* (L.) ‘Denver Daisy’ affected by irrigation averaged across Si treatments.

Source	Rate (cb)	Soil Si (ppm)	Transpiration
Well-watered	10	35.8b[z]	4.56b
Water-stressed	20	47.7a	8.10a

[z] Means (n=6) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

CHAPTER IV

EFFECT OF LED LIGHTING ON GROWTH AND FLOWERING OF CUT FLOWERS

Abstract

Use of light emitting diodes (LED) technology is beginning to replace traditional lighting in greenhouses. This research focused on the effects of LED lighting and GA_3 supplementation on growth and flowering of cut flowers. *Dahlia* spp. (Cav.) 'Karma Serena' and 'Karma Maarten Zwaan', *Liatris spicata* (Gaertn. ex Schreb) 'Kobold', and *Lilium asiatic* (L.) 'Yellow Cocotte' and 'Montreux' were subjected to varying light treatments including LED flowering lamps and halogen lamps. The flowering lamps emitted a combination of red + far-red + white and red + white. Photoperiod was extended by operating all lamps for 7 hours in the night and the experiment ran from late fall to early spring. Results varied within species and cultivars in response to light and GA_3. Light was the most effective on growth and flowering characteristics especially in liatris and both cultivars of dahlia. In liatris, flowering occurred 2 weeks early under sole LED lighting than under other light treatments and no light. Although flowering occurred earliest in both cultivars of dahlias under no light, plants under light treatments had greater height, width, and shoot weight. There were significant effects of GA_3 on growth and flowering characteristics in dahlia cultivars and lily cultivars such as greater height, width, and flower number. A significant interaction of light with GA_3 influenced height,

width, mean flower number, flower diameter, days to anthesis, and flowering percentage in dahlia and lily cultivars.

Introduction

Light is the single most important variable with respect to plant growth and development and is often the most limiting factor (Nelson, 2012). Therefore, using artificial lighting (AL) or grow lights (GL) in commercial greenhouses is beneficial for plants and growers. Altering photoperiod and increasing light levels are reasons for using these lights. The different lighting sources that growers can use include incandescent (INC) lamps, fluorescent lamps (FL), and high intensity discharge (HID) lamps. Light emitting diodes (LED) are fourth generation lighting sources and are the emerging technology in horticulture (Morrow, 2008). Before choosing a lighting device, several factors such as efficiency, total energy emissions, life expectancy, and costs are considered. In addition, it is important to know the three most important light factors that affect plant growth which are light quality, light quantity, and light duration (Nelson, 2012). LEDs have proven to be advantageous in all these factors when compared to the traditional lighting sources (Bourget, 2008).

Energy inputs range from 10 to 30% of total production costs for the greenhouse industry (Bessho and Shimizu, 2012). Thus, any new lighting technology that significantly reduces consumption of electricity for crop lighting while maintaining or improving crop value is of great interest to growers. Light sources such as fluorescent, metal halide, high pressure sodium, and incandescent lamps are generally used for plant growth under greenhouse conditions and have been around for half a century (Hahn et al., 2000). However, these light sources have disadvantages of having less suitable wavelength spectra for plant growth, limited lifetime of operation, require high amounts of electricity, and produce heat that can burn plant foliage (Singh et al., 2014).

In the 1990s, light-emitting diodes (LEDs) were investigated for the first time for plant growth, and were found to be efficient alternatives to traditional lamps used in lighting systems (Briggs and Christie, 2002). Compared with conventional lamps, LEDs are smaller in size and weight, have a long lifetime, low heat emissions, wavelength specificity, and much lower energy consumption (Massa et al., 2008). In addition to changes in plant productivity, increased suppression of pathogens in tomato and cucumber have been noted (Kim et al., 2005). Physiological and morphological effects of LEDs have been studied on several plants including potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.), lily (*Lilium candidum* L.), lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), strawberry (*Fragaria* × *ananassa* Duchesne), marigold (*Tagetes erecta* L.), chrysanthemum (*Chrysanthemum indicum* L.), and salvia (*Salvia divinorum* Epling & Játiva) using various LED products (Jeong et al., 2012).

Light-emitting diodes have the potential to shorten the crop time, reduce costs, and add new plants for specialty cut flower production during the winter (Massa, 2008). This light source may also induce greater flowering for winter crops, however research is limited to propagation, vegetables, and seedling production. Commercial LED fixtures for photoperiodic lighting have been recently developed for flowering applications and are alternatives to INC lamps. Craig and Runkle (2013) quantified how red to far red ratio of photoperiodic lighting from LEDs influenced flowering and extension growth of short-day plants. Investigation on the efficacy of commercial LED products developed for flowering applications on long-day plants (Kohyma et al., 2014). A coordinated grower trial conducted with five commercial greenhouse growers to investigate the efficacy of red + white + far red LEDs to regulate flowering of daylength-sensitive ornamental crops (Meng and Runkle, 2014).

Gibberellic acid is a hormone found in plants that is produced in low amounts. Gibberellic acid is a very influential hormone that can control plant development, promote growth and elongate cells. There are studies that show valid interactions between light and GA_3 which mostly affects germination of seedlings (Dissanayake et al., 2010; Toyomasue et al.,1993). Flower initiation can also be affected (Lona and Bocchi, 1956; Lockhart, 1956), though more research needs to be conducted to further assess this regulation. Only in certain plant species, can GA_3 act as a mobile signal transmitting photoperiodic flowering stimulus (Kobayashi and Weigel, 2007; Simpson and Dean, 2002). The objectives of this study were to evaluate the use of LED flowering lamps, traditional lamps, and a combination of both as well as the plant hormone GA_3 on *Lilium asiatic* L. ('Yellow Cocotte' and 'Montreux'), *Dahlia* spp. Cav. ('Karma Serena' and 'Karma Maarten Zwaan'), and *Liatris spicata* Gaertn. ex Schreb ('Kobold').

Materials and Methods

On 15 September 2015, bulbs of *Lilium asiatic* (L.) 'Yellow Cocotte' and 'Montreux' were received and graded at 12 to 14 and 16 to 19 cm, respectively. Cuttings of *Dahlia* spp. (Cav.) 'Karma Serena' and 'Karma Maarten Zwaan', which are short-day plants arrived 14 October 2015. *Liatris spicata* (Gaertn. ex Schreb) 'Kobold' corms, which are long-day plants arrived 12 November 2015 and were graded at 8 to 10 cm.

Plant material were obtained from Gloeckner & Company Incorporated (Harrison, NY). Before transplanting, both cultivars of dahlia were placed on a mist bench and 'Yellow Cocotte' and 'Montreux' were placed in a cooler at 4°C upon arrival for 1 month. Liatris were not placed in the cooler and were immediately treated. All bulbs and corms were soaked in aqueous solution of different gibberellic acid (GA_3) (Plant Hormones LLC, St. Augustine, WA) concentrations for 30 minutes (min). Dahlia leaves were sprayed to glisten once with different rates of GA_3 solution after potting. Tween-20 was also added in the GA_3 solution as a surfactant at a concentration of 0.01%. Rates for liatris were 50, 170, and 250 ppm with 12 pots per rate. Asiatic lily 'Yellow Cocotte' had rates of 40, 140, and 340 ppm with 12 pots per rate, while 'Montreux' had rates of 20, 50, 70, 100, 120, 150, 170, 200, and 250 ppm with five pots per rate. Dahlia 'Karma Serena' rates were 50, 100, and 150 ppm with 10 pots per rate and 'Maarten de Zwaan' had a rate of 150 ppm with seven pots. All species and cultivars included a control rate in which water was used. Standard 15-centimeter pots filled with Metro-Mix 360 media (Sun Gro Horticulture, Bellevue, WA) were used for all plant material with a single plant per pot. All were grown at the Department of Horticulture and L.A. research greenhouses in Stillwater, OK. For each greenhouse, temperatures were 23°C during the day and 18°C during night with a photosynthetic photon flux density (PPFD) between 600 to 1200 $\mu mol \cdot m^2 \cdot s^{-1}$.

Four light treatments were established in four different but similar greenhouses. Philips GreenPowered LED Flowering lamps (Amsterdam, Netherlands) and standard halogen bulbs were used and installed 0.914 meters above bench area and 0.914 meters apart. In the first light treatment, there were 19 14-W LED lamps with a spectrum of red

+ white + far-red. The second light treatment had 11 15-W LED lamps with a spectrum of red + white and 12 40-W halogen bulbs—lamps and bulbs were installed alternatively. The third light treatment included 23 40-W halogen bulbs and the fourth treatment did not have lights (control). Plant species and GA_3 rates were randomized within light treatments.

Plants were supplemented 7 hours of light after sunset. Before daylight savings time (08 November 2015), lighting was delivered above the bench areas from 1900 to 0200 HR. After daylight savings time, lighting was delivered between 1700 to 2400 HR. Lights were on during this time frame up until the end of the study. Standard timers were used to switch the lights on and off and standard light strings were used in which bulbs were installed.

A quantum sensor (LI-250A; LI-COR Biosciences, Lincoln, NE) measured photon output of the LED lamps and halogen bulbs. In each greenhouse where light was supplemented, measurements were randomly recorded across the bench area and were taken at pot level. The mean photon outputs were 0.030, 0.020, and 0.030 $\mu mol \cdot s^{-1} \cdot m^{-2}$ for LED emitting red + white + far-red, LED emitting red + white, and halogen, respectively. According to Meng and Runkle (2016), relative spectral distribution (wavelength) of the LED flowering lamps is between 600 and 800 nm.

Data collected from plants included date of first flower (anthesis), flower diameter, number of flowers, plant height (from media surface to tallest flower or bud), width (average of two perpendicular measurements), and shoot dry weight. The date of first flower was only recorded when petals were fully opened. A digital caliper (Tresna

Instrument., LTD, Guangxi Province, China) measured flower diameter. Shoot weight was determined by cutting the stems at media level and then dried for 3 days at 54.4°C. Data was analyzed with SAS version 9.4 software (SAS Institute, Cary, NC). Analysis of variance methods (PROC MIXED) were used with a two-factor factorial arrangement with light and GA_3 as the factors of interest. Separate analyses were conducted for each plant species. When interactions of light with GA_3 were significant, simple effects were reported. Mean separations were determined using a DIFF option in an LSMEANS statement and a SLICE option (when appropriate) and with a 0.05 level of significance.

Results

Liatris spicata (Gaertn. Ex Schreb) 'Kobold'

A main effect of light was seen on all growth characteristics as well as mean flower number and days to anthesis (Table 1). Plants under LED and halogen flowered the earliest (Table 2). Average number of terminal spikes was greatest under the control and halogen lighting. However, the control yielded the greatest result. Plant height was greatest under LED and LED + halogen lighting compared to plants under halogen and the control. Plant width was greater under LED and LED + halogen. However, LED was greatest. Shoot weight was greatest under halogen compared to the control, LED, and LED + halogen.

Gibberellic acid rates had a significant effect on plant width, shoot weight, and mean flower number (Table 1). For width, plants receiving 0, 50, and 170 ppm GA_3 had greater widths (Table 3). Shoot weight was greatest under 0, 50, and 250 ppm GA_3. For width and shoot dry weight, the control rate yielded the greatest results compared to the rest. Average number of terminal spikes was greatest at 0, 170, and 250 ppm GA_3, but the latter rate was greatest.

Dahlia spp. (Cav.) ‘Karma Serena’

The interaction of light with GA_3 had a significant effect on mean flower number and flowering percentage (Table 4). Within the 0 ppm GA_3 rate, plants under halogen had the greatest flower number compared to the control, LED, and LED + halogen (Table 5). Flower number within the 50 ppm GA_3 rate was greatest for plants under halogen and LED + halogen. Within the 100 ppm GA_3 treatment, halogen, LED + halogen, and LED had the greatest flower number. However, halogen and LED + halogen yielded the greatest results. Flowering percentage within the 50 and 150 ppm GA_3 rates was greatest under the control, halogen, and LED + halogen. Within the 100 ppm GA_3 treatment, flowering was greatest under the control, LED, and halogen lighting.

Light had a significant effect on height, width, shoot dry weight, and days to anthesis (Table 4). Time to flower was longest under halogen and LED + halogen (Table 8). Height was greatest under halogen and LED + halogen compared to control and LED. Plant width and shoot dry weight was greatest under LED + halogen compared to the control, LED and halogen.

Only height and flower diameter were significantly affected by GA_3 (Table 4). Gibberellic acid rates at 50, 100, and 150 ppm produced the tallest plants compared to the 0 ppm. The 0, 50, and 150 ppm GA_3 rates resulted in the greatest flower diameter. However, the control yielded the greatest result.

Dahlia spp. (Cav.) 'Karma Maarten Zwaan'

A significant interaction of light with GA_3 was seen on height (Table 4). Within the 0 GA_3 rate, height was greatest under LED compared to the control, halogen, and LED + halogen (Table 7). Within the 150 ppm GA_3 rate, plant height was greatest under halogen and LED + halogen. However, halogen yielded the greatest result.

A significant effect of light was seen on width, shoot dry weight, mean flower number, and days to anthesis (Table 4). Time to flower was longest under LED and LED + halogen (Table 8). However, LED + halogen was the greatest. Flower number was greatest under halogen and LED + halogen. However, halogen yielded the greatest result. Plant width was greatest under LED and LED + halogen, but the latter light treatment yielded the greatest result. Shoot dry weight was the greatest under LED, halogen, and LED + halogen.

The main effect of GA_3 was seen on days to anthesis and flowering percentage (Table 4). Time to flower was longest under 0 GA_3 rate compared to the 150 ppm GA_3 rate (Table 9). Flowering percentage was greatest also under the 0 GA_3 rate compared to the 150 ppm GA_3 rate.

Lilium asiatic (L.) 'Yellow Cocotte' and 'Montreux'

No significant effects were seen by light or GA_3 as main effects on growth and flowering characteristics of 'Yellow Cocotte' cultivar, though an interaction of light with GA_3 was seen on flower diameter and flowering percentage (Table 10). Within the 0 ppm GA_3 rate, LED and LED + halogen had the greatest flower diameter (Table 11). Plants within the 40 ppm GA_3 rate had the greatest flower diameter under LED + halogen.

Within 340 ppm GA_3 rate, plants under LED and LED + halogen had the greatest flower diameters. However, LED + halogen yielded the greatest result. Flowering percentage was greatest under LED and halogen within the 0 ppm GA_3 rate (Table 12). However, LED was greatest. Within the 40 ppm GA_3 rate, plants under halogen and LED + halogen had the greatest flowering percentage. Within the 140 ppm GA_3 rate, plants under LED and LED + halogen had the greatest flowering percentage, with the former light treatment yielding the greatest result. Within the 340 ppm GA_3 rate, plants under LED + halogen had the greatest flowering percentage.

For 'Montreux', an interaction of light with GA_3 was seen for height, width, mean flower number, and anthesis (Table 10). For height, plants within the 150 and 170 ppm GA_3 rates were tallest under halogen and LED + halogen (Table 13). However, LED + halogen yielded the greatest result under both GA_3 rates. Plants within the 0 ppm GA_3 rate under LED and halogen had the greatest widths (Table 14). However, LED was greatest. Mean flower number was greatest within the 0 ppm GA_3 rate under halogen and LED + halogen (Table 15). However, halogen yielded the greatest result. Within the 20 ppm GA_3 rate, plants under the control, halogen, and LED + halogen produced the most flowers. However, the control and halogen were the greatest. Within the 50 ppm GA_3 rate, plants under the control, LED, and halogen had the greatest flower number, but the control yielded the greatest result. Within the 120 ppm GA_3 rate, plants under the control and halogen produced the most flowers compared to plants under LED. Within the 150 ppm GA_3 rate, time to flower was shortest under halogen and LED + halogen (Table 16).

No significant effect of light was seen on any growth or flower characteristics (Table 17). A significant effect was seen for GA_3 on flower diameter and flowering percentage (Table 10). Flower diameter was greatest when plants were supplemented GA_3 at 0, 20, 150, and 170 ppm (Table 18). Flowering percentage was greatest under 20, 50, 120, and 170 ppm. However, 20 ppm GA_3 yielded the greatest result for both flower diameter and flowering percentage.

Discussion

The use of sole LED, LED + halogen, and sole halogen lamps emitting red (R) and far-red (FR) light effectively promoted growth and flowering in liatris, dahlia (‘Karma Serena’ and ‘Karma Maarten Zwaan’), and Asiatic lily (‘Yellow Cocotte’ and ‘Montreux’). Red light is most effective at inhibiting flowering in short-day plants (SDP). This was true for ‘Karma Serena’ and ‘Karma Maarten Zwaan’ under LED, halogen, and LED + halogen (Table 8). Craig and Runkle (2013) reported that flowering in SDPs such as chrysanthemum (*Chrysanthemum indicum* L.) and dahlia was delayed under incandescent and LED lights. Inhibition of flowering by R light was also seen in cocklebur (*Xanthium strumarium* L.), chrysanthemum, and soybean (*Glycine max* L. Merr.) (Borthwick et al., 1952; Cathey and Borthwick, 1957; Downs, 1958). Delaying flowering in SDPs such as dahlia especially during the winter months is ideal. During this season, the days are shorter and the nights are longer. Therefore, SDPs will want to spend photosynthates in the production of reproductive organs, which will result in lack of growth and development of vegetative parts. Extension growth and greater biomass is promoted under R light and this was seen for liatris (Table 2) and ‘Karma Serena’ under LED flowering lamps and halogen lamps (Table 8). Miyashita et al., (1995) noted that red light from LEDs increased shoot length of potato (*Solanum tuberosum* L.) plantlets. Height was also greatest under either LED flowering lamps emitting R + W or R + W +

FR as well as incandescent lamps in ageratum (*Ageratum houstonianum* L.), calibrachoa (*Calibrachoa* x *hybrida* Cerv.), dianthus, and petunia. Height and shoot dry weight was greatest for salvia (*Salvia splendens* Sellow ex J.A. Schultes) and tomato (*Solanum lyopersicum* L.) under LEDs emitting red (Wollaeger and Runkle, 2014). Meng and Runkle (2014) reported that stem length of verbena (*Verbena* x *hybrid* L.) increased under incandescent and LED flowering lamps compared to control. Dry weight and plant width were increased in poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) when grown under supplementary LED lighting emitting R and B (Bergstrand et al., 2015). An increase in all these growth parameters are necessary cut flower qualities. Far-red + R are most effective for promoting flowering in long-day plants (LDP). This was true for liatris that were under sole LED lighting emitting R + W + FR (Table 2). Meng and Runkle (2014) have also reported that photoperiodic lighting with a mixture of R and FR light from LEDs and incandescent lamps was most effective at promoting flowering in LDPs. Flowering of *Gypsophila paniculata* (L.) 'Baby's Breath' and *Eustoma grandiflorum* (Salisb.) 'Lisianthus' was also promoted under a combination of R and FR light (Nishidate et al., 2012; Yamada et al., 2009). The presence of FR in LED lamps shortened the flowering time and increased number of flowers in petunia (*Petunia* x *hybrida* Juss.). Hastening of flowering while maintaining plant quality will decrease the costs of labor and inputs as well as assure an early market season. Neither R nor FR light from the lamps influenced flowering of 'Yellow Cocotte' and 'Montreux'. Bieleski et al. (2000) also reported that the use of R light in a night-break setting was not effective for increasing anthesis or flower bud opening in multiple cultivars of Asiatic lilies. It was also noted that flowering in lilies was more influenced by variations in day-length and not during a night break with supplemental lighting.

Gibberellic acid (GA_3) effectively promoted growth and flowering characteristics in liatris, ‘Karma Serena’, ‘Karma Maarten Zwaan’, and ‘Montreux’. Research conducted has noted the presence and influence of GA_3 in growing tissues, shoot apices, leaves, and flowers (Jones and Phillips, 1966). Cell division and expansion are stimulated by GA_3 especially in response to light or darkness (Feng et al., 2008). Flower initiation, development, sex expression, and number are also regulated by GA_3 (Griffiths, 2006). Bulyalert (1998) reported that exogenous applications of GA_3 increased width and height as well as flowering percentage in liatris. The significant effect of GA_3 on flower diameter and height in three cultivars of dahlia was not analyzed, but an increase in these features was observed and reported (Pudelska and Podgajna, 2013). Flower diameter was also increased in Asiatic hybrid cut lily flowers when treated with GA_3 and a standard preservative (Rabiza-Swider et al., 2015). The following studies have reported similar results in other cut flowers.

Application of GA_3 promoted shoot elongation in different cultivars of chrysanthemums (Schimdt et al., 2003; Zalewska et al., 2008). Foliar application of GA_3 increased stem length in a variety of cut flower cultivars that were field-grown (Bergmann et al., 2016). Bultynck and Lambers (2004) reported that the addition of exogenous GA_3 promoted leaf elongation and increased shoot biomass in *Aegilops caudata* (L.) and *Aegilops tauschii* (L.). Pobudkiewicz and Nowak (1992) found that flowering size of gerbera (*Gerbera jamesonni* Hooker f.) was enhanced when GA_3 was applied at 200 ppm. Mean flower number was increased in philodendron (*Philodendron*

Schott) 'Black Cardinal' as GA_3 concentrations increased (Chen et al., 2003). Dobrowolska and Janicka (2007) also reported that application of GA_3 at concentration of 10 mg·dm^{-3} increased flower number in *Impatiens hawkeri* (L.) 'Riviera Pink'.

Interaction of light with GA_3 effectively promoted growth and flowering characteristics of 'Karma Serena', 'Karma Maarten Zwaan', 'Montreux' and 'Yellow Cocotte'. Yamaguchi and Kamiya (2001) have concluded that light and GA_3 are highly interactive and are involved in the same pathways that regulate germination and dormancy. Light and GA_3 are likely interacting within similar pathways regulating growth and flowering. A study reported that cell expansion was promoted in the leaves of dwarf bean (*Phaseolus vulgaris* L.) and stem elongation was increased in garden peas (*Pisum sativa* L.) when exposed to FR light and saturated with GA_3 (Vince, 1967). In Kentucky bluegrass (*Poa pratensis* L.), shoot elongation was increased when endogenous levels of GA_3 interacted with light (Tan and Qian, 2003). Williams and Morgan (1979) noted that the exposure of GA_3 to FR light hastened flowering in sorghum (*Sorghum bicolor* L.). White et al. (1990) reported that although greenhouse potted plants *Aquilegia ×hybrida* (L.) 'Bluebird' and 'Robin' all flowered when treated with 100 mg·L^{-1} exogenous GA_3, there was no synergistic effect with the supplemental lights emitting R and FR. An increase in flower number was also observed but not due to an interaction of light with GA_3. Another study reported that GA_3 should be applied to plants before cold temperature exposure and light treatments should be applied after cold temperature exposure to improve floral development. There could be even more of an effect between light and GA_3 on lily bulbs based on exposure to cold temperatures before or after. 'Yellow Cocotte' and 'Montreux' were the only plants exposed to a cold treatment before applications of GA_3 and light. Possibly, the cold treatment contributed to the lack of growth and flowering rates in both cultivars in which we applied GA_3 after cold exposure. If there is a relationship among light, GA_3, and cold temperature, additional research needs to be conducted with more cut flowers to further assess the hypothesized reaction to these three factors.

Conclusion

LED flowering lamps are equally effective as incandescent/halogen lamps at regulating growth and flowering. Although the LED flowering lamps and halogen bulbs have similar light intensity, energy consumption from LEDs was 14 to 15 watts per lamp whereas incandescent/halogen used about 75 watts per bulb. A 46 to 50 percent decrease in energy consumption occurred which is valuable for growers concerned with energy costs. Not only was there improvement in energy use, but quality of plants was maintained and improved with the use of LED flowering lamps. Results of this study and that of many others show that GA_3 plays an important role in flowering stimulation as well as plant growth. In addition, light and GA_3 have a synergistic relationship with each other regarding plant and flower development of plants. More research needs to be conducted using and evaluating an array of LED flowering lamps considering costs and other factors along with the use of the plant hormone GA_3 on a variety of plants.

Literature Cited

Bergmann, B.A., J.M. Dole, and I. McCall. 2016. Gibberellic acid shows promise for promoting flower stem length in four field-grown cut flowers. HortTechnology 26(3):287-292.

Bergstrand, K.J., H. Asp, E.H. Larsson-Jonsson, and H.K. Schussler. 2015. Plant developmental consequences of lighting from above or below in the production of poinsettia. Europ. J. Hort. Sci. 80(2):51-55.

Bessho, M. and K. Shimizu. 2012. Latest trends in LED lighting. Electronics and Comm. Jpn. 95(1):315-320.

Bieleski, R., J. Elgar, J. Heyes, and A. Woolf. 2000. Flower opening in Asiatic lily is a rapid process controlled by dark-light cycling. Ann. Bot. 86:1169-1174.

Bjorn, L.F 2002. *Photobiology: the science of light and life*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Blanchard, M.G. and E.S. Runkle. 2010. Influence of NIR-reflecting shading paint on greenhouse environment, plant temperature, and growth and flowering of bedding plants. Trans. ASABE. 53(3):939-944.

Boodley, J. and S.E. Newman. 2009. *The commercial greenhouse, 3rd edition*. Clifton Park, NY: Delmar Cengage Learning.

Borthwick, H.A., S.B. Hendricks, and M.W. Parker. 1952. The reaction controlling floral initiation. Proc. Natl. Acad. Sci. USA 38:929-934.

Briggs, W.R. and J.M. Christie. 2002. Phototropin 1 and phototropin 2: Two versatile plant blue-light receptors. Trends Plant Sci. 7:204-209.

Bula, R.J., R.C. Morrow, T.W. Tibbitts, D.J. Barta, R.W. Ignatius, and T.S. Martin. 1991. Light-emitting diodes as a radiation source for plants. HortScience 26:203-205.

Bullough, J.D., Y. Zhu, and N. Narendran. 2011. Characteristics of light-emitting diodes sources: Relevance for visual signal detection. http://www.nfpa.org/~/media/files/news-and-research/resources/research-foundation/foundation-proceedings/2012-supdet/13bullough-presentation.pdf?la=en. Accessed 9 October 2017.

Bultynck, L. and H. Lambers. 2004. Effects of applied gibberellic acid and paclobbutraol on leaf expansion and biomass allocation in two *Aegilops* species with contrasting leaf elongation rates. Physiol. Plantarum 122:143-151.

Bulyalert, O. 1988. Effect of gibberellic acid on growth and flowering of liatris corm (*Liatris spicata*) c.v. "Florist violet" propagated from seed (Abstract). http://agris.fao.org/agris-search/search.do?recordID=TH9220028. Accessed 9 October 2017.

Casal, J.J. 2000. Phytochromes, cryptochromes, phototropin: Photoreceptor interactions in plants. Photochem Photobiol. 71:1-11.

Cathey, H.M. and H.A. Borthwick. 1957. Photoreversibility of floral initiation in *Chrysanthemum*. Bot. Gaz. 119:71-76.

Cavins, T.J. and J.M. Dole. 2001. Photoperiod, juvenility and high intensity lighting affect flowering and cut stem qualities of *Campanula* and *Lupinus*. HortScience 36:1192-1196.

Chauhan, R.V., K.P. Kava, V.J. Babariya, P.B. Pansuria, and A.B. Savaliya. 2014. Effect of gibberellic acid on flowering and cut flower yield in gerbera under protected condition. Asian J. Hort. 9(2):404-407.

Chen, R.J. Henny, D.B. McConnell, and R.D. Caldwell. 2003. Gibberellic acid affects growth and flowering of *Philodendron* 'Black Cardinal'. J. Plant Growth Regul. 41:1-6.

Chhun, T., K. Aya, K. Asano, E. Yamamoto, Y. Morinaka, M. Watanabe, H. Kitano, M. Ashikari, M. Matsuoka, and M. Ueguchi-Tanaka. 2007. Gibberellin regulates pollen viability and pollen tube growth in rice. Plant Cell 19:3876-3888.

Craig, D.S. and E.S. Runkle. 2013. A moderate to high red to far-red light ratio from light-emitting diodes controls flowering of short-day plants. J. Amer. Soc. Hort. Sci. 138:167-172.

Currey, C.J. and R.G. Lopez. 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(4):428-434.

Delvadia, D.V., T.R. Ahlawat, and B.J. Meena. 2009. Effect of different GA_3 concentration and frequency on growth, flowering and yield in Gaillardia (*Gaillardia pulchella* Foug.) cv. Lorenziana. J. Hort. Sci. 4(1):81-84.

Dennis, D.J., J. Doreen, and T. Ohteki. 1994. Effect of gibberellic acid 'quick-dip' and storage on the yield and quality of blooms from hybrid *Zantedeschia* tubers. Sci. Hort. 57:133-142.

Devesh, S., C. Basu, M. Meinhardt-Wollweber, and B. Roth. 2014. LEDs for energy efficient greenhouse lighting. https://arxiv.org/abs/1406.3016. Accessed 9 October 2017.

Devlin, P.F. and S.A. Kay. 2000. Cryptochromes are required for phytochrome signaling to the circadian clock but not for rhythmicity. Plant Cell. 12:2499-2510.

Dissanayake, P., D.L. George, and M.L. Gupta. 2010. Effect of light, gibberellic acid and abscisic acid on germination of guayule (*Parthenium argentatum* 'Gray') seed. Ind. Crops Prod. 32:111-117.

Dobrowolska, A. and D. Janicka. 2007. The effect of growth regulators on flowering and decorative value of *Impatiens hawkeri* W. Bull belonging to Riviera group. Rocz. AR Pozn. Ogrodn. 41:35-39.

Downs, R.J., H.A. Borthwick, and A.A. Piringer. 1958. Comparison of incandescent and fluorescent lamps for lengthening photoperiods. Proc. Amer. Soc. Hort. Sci. 71:568-578.

Feng, S., C. Martinez, G. Gusmaroli, Y. Wang, J. Zhou, and F. Wang. 2008. Coordinated regulation of *Arabidopsis* thaliana development by light and gibberellins. Nature 451:475-479.

Fisher, P. and C. Donnelly. 2001. Evaluating supplemental light for your greenhouse. http://www.greenhouse.cornell.edu/crops/factsheets/SuppLight.pdf. Accessed 9 October 2017.

Foo, E., J.D. Platten, J.L. Weller, and J.B. Reid. 2006. PhyA and cry1 act redundantly to regulate gibberellin levels during de-etiolation in blue light. Physiol. Plant. 127:149-156.

Griffiths, J., K. Murase, and I. Rieu. 2006. Genetic characterization and functional analysis of the *GID1* gibberellin receptors in *Arabidopsis*. Plant Cell 18:3399-3414.

Gupta, R. and S.K. Chakrabarty. 2013. Gibberellic acid in plant: Still a mystery unresolved. Plant Signal Behav. 8(9):1-5.

Hahn, E.J., T. Kozai, and K.Y.J. Paek. 2000. Blue and red light-emitting diodes with or without sucrose and ventilation affect in vitro Growth of *Rehmannia glutinosa* plantlets. Plant Biol. 43(4):247-250.

Heo, J., C. Lee, D. Chakrabarty, and K. Paek. 2002. Growth responses of marigold and salvia bedding plants as affected by monochromic or mixture radiation provided by a light-emitting diode (LED). Plant Growth Regul. 38:225-230.

Ho, C.H., C.M. Yang, and C.L. Hsiao. 2012. Effects of nighttime lighting with specific wavebands on flowering of chrysanthemum. Crop Environ. Bioinformatics 9:265-277.

Hu J.H., M.G. Mitchum, and N. Barnaby. 2008. Potential sites of bioactive gibberellin production during reproductive growth in *Arabidopsis*. Plant Cell 20(2):320-336.

Ishikawa, R., S. Tamaki, S. Yokoi, N. Inagaki, T. Shinomura, and M. Takano. 2005. Suppression of the floral activator *Hd3a* is the principal cause of the night break effect in rice. Plant Cell. 17:3326-3336.

Jones, R.L. and I.D. Phillips. 1966. Organs of gibberellin synthesis in light-grown sunflower plants. Plant Physiol. 41:1381-1386.

Kaaz, S. and O. Karaguzel. 2010. Influence of growth regulators on the growth and flowering characteristics of Goldenrod (*Solidago* x *hybrida*). Eur. J. Sci. Res. 45(3):498-507.

Kim, H.H., R.M. Wheeler, J.C. Sager, N.C. Yorio, and G.D. Goins. 2005. Light-emitting diodes as an illumination source for plants: A review of research at Kennedy Space Center. Habitation (Elmsford) 10:71-78.

Kim, H.H., R.M. Wheeler, J.C. Sager, J. Norikane, and N.C. Yorio. 2007. Electric lighting considerations for crop production in space. Acta Hort. 761:193-202.

Kobayashi, Y. and D. Weigel. 2007. Move on up, it's time for change: Mobile signals controlling photoperiod-dependent flowering. Genes Devel. 21:2371-2384.

Kohyama, F., C. Whitman, and E. Runkle. 2014. Comparing flowering responses of long-day plants under incandescent and two commercial light-emitting diode lamps. HortTechnology 24(4):490-495.

Kristiansen, K. 1988. Light quality regulates flower initiation, differentiation and development of *Campanula carpatica* Jacq. Forster, Karl. Sci. Hort. 35:275-283.

Lang, A. 1956. Induction of flower formation in biennial *Hyoscyamus* by treatment with gibberellin. Naturwissenschaften 43:284-285.

Lee, J.J. and J.H. Hwang. 2014. Effect of day-length extension treatment using LED on growth and flowering of *Freesia* hybrid 'Yvonne'. Kor. J. Hort. Sci. Technol. 32(6):794-802.

Lin, R., Y. Teng, H.J. Park, L. Ding, C. Black, P. Fang, and H. Wang. 2008. Discrete and essential roles of the multiple domains of *Arabidopsis FHY3* in mediating phytochrome: a signal transduction. Plant Physiol. 148:981-992.

Lockhart, J. 1956. A reversal of the light inhibition of pea stem growth by the gibberellins. Prec. Nat. Acad. Sci. 42:841-848.

Lona, F. and A. Bocchi. 1956. Luterferenza dell'acido gibberellieo nell'effecto della lute rossa e rosso-estrema sull'allungamento dell fusto di Perilla ocy~noides L. L'ateneo Parmense 7:645-649.

Lund, J.B., T.J. Blom, and J.M. Aaslyng. 2007. End-of-day lighting with different red/far-red ratios using light-emitting diodes affects plant growth of *Chrysanthemum* × *morifolium* Ramat. 'Coral Charm'. HortScience 42:1609-1611.

Marcelis, L.F.M., A. Elings, and M.J. Bakker. 2006. Modelling dry matter production and partitioning in sweet pepper. Acta Hort. 718:121-128.

Massa, G.D., H.H. Kim, R.M. Wheeler, and C.A. Mitchell. 2008. Plant productivity in response to LED lighting. HortScience 43:1951-1956.

McDonald, M.S. 2003. Photobiology of higher plants. Wiley. West Sussex, England.

Meng, Q. and E.S. Runkle. 2014. Controlling flowering of photoperiodic ornamental crops with light-emitting diode lamps: A coordinated grower trial. HortTechnology 24:702-711.

Meng, Q. and E.S. Runkle. 2016. Choosing the right LEDs to regulate flowering. http://lighthort.com/2016/07/21/choosing-right-leds-regulate-flowering/. Accessed 9 October 2017.

Miyashita, Y., Y. Kitaya, C. Kubota, T. Kozai, and T. Kimura. 1995. Effects of red and far-red light on the growth and morphology of potato plantlets in-vitro: Using light emitting diodes as a light source for micropropagation. Acta Hort. 393:189-194.

Nelson, J.A. and B. Bugbee. 2014. Economic analysis of greenhouse lighting: Light-emitting diodes vs. high intensity discharge fixtures. PLoS ONE 9(6):1-10.

Nelson, P.V. 2012. *Greenhouse operation and management, 7th Edition*. Boston, MA: Pearson.

Nishidate, K., Y. Kanayama, M. Nishiyama, T. Yamamoto, Y. Hamaguchi, and K. Kanahama. 2012. Far-red light supplemented with weak red light promotes flowering of *Gypsophila paniculata*. J. Jpn. Soc. Hort. Sci. 81:198-203.

Park, Y. and E.S. Runkle. 2016. Investigating the merit of including far-red radiation in the production of ornamental seedlings grown under sole-source lighting. Acta Hort. 1134:259-266.

Philips. Tailor-made light recipes for growers. Retrieved from http://www.usa.lighting.philips.com/products/horticulture. Accessed 9 October 2017.

Pobudkiewicz, A. and J. Nowak. 1992. The effect of gibberellic acid on growth and flowering of *Gerbera jamesonii* Bolus. Folia Hort. 4(2):35-42.

Porwal, R., C.L. Nagda, and J.P.S. Pundir. 2002. Influence of plant growth regulators on vegetative growth and flower earliness of damask rose. South Ind. Hort. 50(1-3):119-123.

Pudelska, K. and E. Podgajna. 2013. Decorative value of three dahlia cultivars (*Dahlia ×cultorum* Thorsr. et Reis) treated with gibberellin. Modern Phytomorphology 4:83-86.

Rabiza-Swider, J., E. Skutnik, A. Jedrzejuk, A. Lukaszewska, and K. Lewandowska. 2015. The effect of GA_3 and the standard preservative on keeping qualities of cut LA hybrid lily ‘Richmond’. Acta Sci. Pol. Hortorum Cultus. 14(4):51-64.

Rantanen, M., T. Kurokura, K. Mouhu, P. Pinho, E. Tetri, L. Halonen, P. Palonen, P. Elomaa, and T. Hytönen. 2014. Light quality regulates flowering in *FvFT1*/*FvTFL1* dependent manner in the woodland strawberry *Fragaria vesca*. Front. Plant Sci. 271(5):1-11.

Ranwala, A.P., G. Legnani, M. Reitmeier, B.B. Stewart, and W.B. Miller. 2002. Efficacy of plant growth retardants as preplant bulb dips for height control in LA and oriental hybrid lilies. HortTechnology 12(3):426-431.

Reid, J.B., N.A. Botwright, J.J. Smith, D.P. O'Neil, and L.H.J. Kerckhoffs. 2002. Control of gibberellins levels gene expression during de-etiolation in pea. Plant Physiol. 128:734-741.

Riley, J. 1987. Gibberellic acid for fruit set and seed germination. CRFG J. 19:10-12.

Runkle, E.S. and R.D Heins. 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(3):275-282.

Runkle, E.S. and R.D. Heins. 2006. Manipulating the light environment to control flowering and morphogenesis of herbaceous plants. Acta Hort. 711:51-60.

Sager, J.C., W.O. Smith, J.L. Edwards, and K.L. Cyr. 1988. Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. Trans. Amer. Soc. Agr. Eng. 31:1882-1889.

Schmidt, C., A.B. Bellé, C. Nardi, and A.K. Toledo. 2003. The gibberellic acid (GA_3) in the cut chrysanthemum (*Dedranthema grandiflora* Tzevelev.) 'Viking': planting summer/autumn. Ciência Rural, Santa Maria 33(2):267-274.

Shillo, R., G. Valis, and A.H. Halevy. 1981. Promotion of flowering by photoperiodic lighting in winter-grown gladiolus planted at high densities. Sci. Hort. 14:367-375.

Simpson, G.G. and C. Dean. 2002. *Arabidopsis*, the Rosetta stone of flowering time. Science 296:285-289.

Singh, D.P., A.M. Jermakow, and S.M. Swain. 2002. Gibberellins are required for seed development and pollen tube growth in *Arabidopsis*. Plant Cell 14:3133-3147.

Singh, J.K. and R. Jitendra 2009. Effect of GA_3, CCC and inorganic fertilizers on growth and flowering in chrysanthemum (*Dendranthema grandiflora* Ramet.) cv. Ann. Hort. 2(2):232-233.

Snowden, M.C., K.R. Cope, and B. Bugbee. 2016. Sensitivity of seven diverse species to blue and green light: Interactions with photon flux. PLoS ONE 11(10):1-32.

Sung, J.W., S. Park, J. Sung-Jin, O-N. Seo, G-S. Kim, Y-H. Kim. H. Bae, G. Lee, S-T. Kim, W-S. Lee, and S-C. Shin. 2012. Influences of four different light-emitting diode lights on flowering and polyphenol variations in the leaves of chrysanthemum (*Chrysanthemum morifolium*). Agr. Food Chem. 60(39):9793-980.

Tan, Z.G. and Y.L. Qian. 2003. Light intensity affects gibberellic acid content in Kentucky bluegrass. HortScience 38(1):113-116.

Toyomasu, T., H. Tsuji, H. Yamane, M. Nakayama, I. Yamaguchi, N. Murofushi, N. Takahasi, and Y. Inoue. 1993. Light effect on endogenous levels of gibberellins in photoblastic lettuce seeds. J. Plant Growth Regul. 12:85-90.

Vince, D. 1967. Gibberellic acid and light inhibition of stem elongation. Planta (Berl.) 75:291-308.

White, J.W., H. Chen, and D.J. Beattie. 1990. Gibberellin, light, and low temperature effects on flowering of *Aquilegia*. HortScience 25(11):1422-1424.

Whitman, C.M., R.D. Heins, A.C. Cameron, and W.H. Carlson. 1998. Lamp type and irradiance level for daylength extensions influence flowering of *Campanula carpatica* ‘Blue Clips’, *Coreopsis grandiflora* ‘Early Sunrise’, and *Coreopsis verticillata* ‘Moonbeam’. J. Amer. Soc. Hort. Sci. 123:802-807.

Williams, E.A. and P.W. Morgan. 1977. Gibberellic acid role in floral initiation in sorghum. (Abstr.) Plant Physiol. 59:73.

Williams, E.A. and P.W. Morgan. 1979. Floral initiation in sorghum hastened by gibberellic acid and far-red light. Planta 145:269-272.

Wollaeger, H.M and E.S. Runkle. 2015. Growth and acclimation of *impatiens*, *salvia*, *petunia*, and tomato seedlings to blue and red light. HortScience 50:522-529.

Yamada, A., T. Tanigawa, T. Suyama, T. Matsuno, and T. Kunitake. 2009. Red:far-red light ratio and far-red light integral promote or retard growth and flowering in *Eustoma grandiflorum* (Raf.). Shinn. Sci. Hort. 120:101-106.

Yamaguchi, S. and Y. Kamiya. 2001. Gibberellins and light-simulated seed germination. J. Plant Growth Regul. 20(4):369-376.

Yano, A. and K. Fujiwara. 2012. Plant lighting system with five wavelength-band light-emitting diodes providing photon flux density and mixing ratio control. Plant Meth. 8:1-12.

Zalewska, M., A. Żabicka, and I. Wojciechowska. 2008. The influence of gibberellic acid on the growth and flowering of cascade chrysanthemum cultivars in outside glasshouse. Zesz. Probl. Post. Nauk Roln. 525:525-533.

Zalewska, M. and M. Antkowiak. 2013. Gibberellic acid effect on growth and flowering of *Ajania pacifica*. J. Hort. Res. 21(1):21-27.

Appendix

Table 1. Analysis of variance for growth and flowering characteristics of *Liatris spicata* (Gaertn. ex Schreb) 'Kobold'.

Source	Height (cm)	Width (cm)	Shoot dry weight (g)	Number of terminal spikes	Days to anthesis	Flowering %
Light	****[z]	****	****	****	****	ns
GA_3	ns	**	*	*	ns	ns
Light x GA_3	ns	ns	ns	ns	ns	ns

[z] NS, *, **, ***, **** indicate non-significant or significant at $P \leq 0.05$, 0.01, 0.001, 0.0001, respectively.

Table 2. Growth and flowering characteristics of *Liatris spicata* (Gaertn. ex Schreb) 'Kobold' affected by light averaged across GA_3.

Light Type	Height (cm)	Width (cm)	Shoot dry weight (g)	Number of terminal spikes	Days to anthesis	Flowering %
Control	47.3b[z]	35.2c	13.9b	3.5a	88a	96a
LED	64.7a	49.4a	17.2b	2.3bc	70b	100a
Halogen	52.1b	40.9bc	22.0a	3.1ab	73b	98a
LED + Halogen	65.9a	44.9ab	16.8b	1.8c	77ab	98a

[z] Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 3. Growth and flowering characteristics of *Liatris spicata* (Gaertn. ex Schreb) ‘Kobold’ affected by GA_3 averaged across light.

GA_3 Rate (ppm)	Height (cm)	Width (cm)	Shoot dry weight (g)	Number of terminal spikes	Days to anthesis	Flowering %
0	59.7a^z	47.4a	19.8a	2.4ab	77a	98a
50	59.5a	43.2ab	17.6ab	2.3b	76a	94a
170	54.6a	40.6ab	15.2b	2.6ab	78a	100a
250	56.3a	39.3b	17.3ab	3.5a	76a	100a

^{z}Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 4. Analysis of variance for growth and flowering characteristics of *Dahlia* spp. (Cav.) 'Karma Serena' and 'Karma Maarten Zwaan'.

Cultivar	Source	Height (cm)	Width (cm)	Shoot dry weight (g)	Mean flower number	Flower diameter (cm)	Days to anthesis	Flowering %
Karma Serena	Light	****[z]	****	****	****	ns	****	*
	GA_3	****	ns	ns	**	*	ns	ns
	Light x GA_3	ns	ns	ns	*	ns	ns	*
Karma Maarten Zwaan	Light	***	****	****	*	ns	**	ns
	GA_3	ns	ns	ns	ns	ns	*	*
	Light x GA_3	***	ns	ns	ns	ns	ns	ns

[z] NS, *, **, ***, **** indicate non-significant or significant at $P \leq 0.05$, 0.01, 0.001, 0.0001, respectively.

Table 5. Mean flower number of *Dahlia* spp. (Cav.) ‘Karma Serena’ affected by interaction of light with GA_3.

Source	0	50	100	150
Control	3.1c^z	2.4b	2.3b	2.8a
LED	2.2c	2.9b	3.1ab	3.1a
Halogen	6.6a	5.4a	4.4a	3.7a
LED + Halogen	5.1b	4.5a	4.4a	2.3a

^{z}Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 6. Flowering percent of *Dahlia* spp. (Cav.) 'Karma Serena' affected by interaction of light with GA_3.

Source	0	50	100	150
Control	100a[z]	100a	100a	100a
LED	100a	89b	100a	80b
Halogen	100a	100a	100a	100a
LED + Halogen	100a	100a	80b	100a

[z] Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 7. Height (cm) of *Dahlia* spp. (Cav.) 'Karma Maarten Zwaan' affected by interaction of light with GA_3.

Source	0	150
Control	37.8c^z	75.2c
LED	97.0a	88.4bc
Halogen	83.1b	104.9a
LED + Halogen	81.0b	95.5ab

^{z}Means (n=7) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 8. Growth and flowering characteristics of *Dahlia* spp. (Cav.) 'Karma Serena' and 'Karma Maarten Zwaan' affected by light averaged across GA_3.

Cultivar	Light Type	Height (cm)	Width (cm)	Shoot dry weight (g)	Mean flower number	Flower diameter (cm)	Days to anthesis	Flowering %
Karma Serena	Control	58.9b[z]	32.5c	9.1d	X	7.1a	46c	X
	LED	67.1b	43.9b	35.0c	X	7.1a	61b	X
	Halogen	95.8a	46.7b	43.6b	X	8.5a	74a	X
	LED + Halogen	85.9a	56.9a	52.9a	X	7.9a	80a	X
Karma Maarten Zwaan	Control	X	23.4c[y]	5.7b	2.4b	8.4a	46b	100a
	LED	X	43.9ab	34.4a	2.3b	8.1a	60ab	92a
	Halogen	X	34.5bc	32.5a	4.7a	8.7a	57b	100a
	LED + Halogen	X	55.9a	44.0a	3.4ab	9.1a	82a	93a

[z] Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Means (n=7) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[X] Interaction was significant for these factors.

Table 9. Growth and flowering characteristics of *Dahlia* spp. (Cav.) ‘Karma Serena’ and ‘Karma Maarten Zwaan’ affected by GA$_3$ averaged across light.

Cultivar	GA$_3$ Rate (ppm)	Height (cm)	Width (cm)	Shoot dry weight (g)	Mean flower number	Flower diameter (cm)	Days to anthesis	Flowering %
Karma Serena	0	65.0b[z]	45.5a	30.5a	X	8.6a	67a	X
	50	81.0a	45.7a	35.8a	X	7.3ab	62a	X
	100	81.3a	45.5a	38.5a	X	6.8b	64a	X
	150	80.3a	43.4a	35.7a	X	7.8ab	69a	X
Karma Maarten Zwaan	0	X	41.1a[y]	27.5a	3.3a	9.4a	69a	100a
	150	X	37.6a	30.8a	3.1a	7.8a	54b	92b

[z] Means (n=12) with the same letter within the same column are not statistically significant at $P \le 0.05$. X

[y] Means (n=7) with the same letter within the same column are not statistically significant at $P \le 0.05$.

[X] Interaction was significant for these factors.

X

Table 10. Analysis of variance for growth and flowering characteristics of *Lilium asiatic* (L.) ‘Yellow Cocotte’ and ‘Montreux’.

Cultivar	Source	Height (cm)	Width (cm)	Shoot dry weight (g)	Mean flower number	Flower diameter (cm)	Days to anthesis	Flowering %
Yellow Cocotte	Light	ns[z]	ns	ns	ns	ns	ns	ns
	GA_3	ns	ns	ns	ns	ns	ns	ns
	Light x GA_3	ns	ns	ns	ns	*	ns	*
Montreux	Light	ns	ns	ns	ns	ns	ns	ns
	GA_3	ns	ns	ns	ns	**	ns	*
	Light x GA_3	**	**	ns	*	ns	*	ns

[z] NS, *, **, ***, **** indicate non-significant or significant at P ≤ 0.05, 0.01, 0.001, 0.0001, respectively.

Table 11. Flower diameter (cm) of *Lilium asiatic* (L.) ‘Yellow Cocotte’ affected by interaction of light with GA_3.

Source	0	40	140	340
Control	8.9b^z	9.2b	9.7a	9.7b
LED	10.4a	9.8b	10.4a	10.1ab
Halogen	9.8b	9.4b	10.1a	9.5b
LED + Halogen	10.5a	10.7a	10.0a	10.9a

^{z}Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 12. Flowering percent of *Lilium asiatic* (L.) 'Yellow Cocotte' affected by interaction of light with GA_3.

Source	0	40	140	340
Control	58b^z	67b	58bc	75ab
LED	100a	67b	75a	50bc
Halogen	75ab	75a	33c	33c
LED + Halogen	58b	75a	67ab	100a

^{z}Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

Table 13. Height (cm) of *Lilium asiatic* (L.) 'Montreux' affected by interaction of light with GA_3.

Source	0	20	50	70	100	120	150	170	200	250
Control	y	58.4a	50.8a	y	76.2a	62.9a	47.5b	38.1b	50.8a	58.4a
LED	67.3a[z]	68.6a	62.9a	69.3a	54.1a	53.3a	y	y	y	y
Halogen	68.6a	63.5a	43.2a	y	y	54.6a	57.2ab	55.9ab	60.9a	y
LED + Halogen	63.5a	73.2a	26.7a	y	77.5a	y	85.1a	76.9a	85.1a	90.2a

[z] Means (n=5) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Bulbs did not germinate prior to termination of experiment.

Table 14. Width (cm) of *Lilium asiatic* (L.) 'Montreux' affected by interaction of light with GA_3.

Source	0	20	50	70	100	120	150	170	200	250
Control	y	20.1a	18.8a	y	24.1a	21.8a	24.9a	29.2a	27.4a	26.2a
LED	38.1a^z	42.7a	29.9a	36.3a	33.0a	19.1a	y	y	y	y
Halogen	25.4ab	23.6a	25.4a	y	y	21.8a	24.9a	29.2a	27.4a	y
LED + Halogen	13.5b	25.4a	y	y	20.1a	y	24.9a	24.1a	28.7a	27.9a

^{z}Means (n=5) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

^{y}No leaves to measure.

Table 15. Mean flower number of *Lilium asiatic* (L.) 'Montreux' affected by interaction of light with GA_3.

Source	0	20	50	70	100	120	150	170	200	250
Control	y	6.0a	6.5a	y	y	6.0a	5.0a	4.0a	7.0a	5.0a
LED	3.0b[z]	3.0b	5.0ab	4.3a	3.0a	2.0b	y	y	y	y
Halogen	5.3a	5.8a	5.0ab	y	y	4.0a	5.0a	4.5a	6.0a	y
LED + Halogen	4.0ab	3.7ab	3.5b	y	4.5a	y	5.5a	4.0a	4.0a	5.0a

[z] Means (n=5) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Inflorescences did not reach anthesis prior to termination of experiment.

Table 16. Days to anthesis of *Lilium asiatic* (L.) ‘Montreux’ affected by interaction of light with GA$_3$.

Source	0	20	50	70	100	120	150	170	200	250
Control	y	121a	106a	y	y	114a	132a	142a	104a	122a
LED	131a[z]	135a	104a	119a	124a	87a	y	y	y	y
Halogen	103a	119a	y	y	y	130a	90b	107a	107a	
LED + Halogen	114a	104a	99a	y	114a	y	103b	106a	114a	103a

[z] Means (n=5) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Days to anthesis not recorded.

Table 17. Growth and flowering characteristics of *Lilium asiatic* (L.) ‘Yellow Cocotte’ and ‘Montreux’ by light averaged across GA$_3$.

Cultivar	Light Type	Height (cm)	Width (cm)	Shoot dry weight (g)	Mean flower number	Flower diameter (cm)	Days to anthesis	Flowering %
Yellow Cocotte	Control	[z]45.5a[z]	15.0a	4.0a	2.4a	X	54a	X
	LED	44.5a	19.6a	3.5a	2.0a	X	47a	X
	Halogen	38.4a	16.3a	4.2a	2.0a	X	43a	X
	LED + Halogen	54.1a	19.8a	4.8a	2.1a	X	55a	X
Montreux	Control	X	X	3.2a[y]	X	3.0a	X	0.24a
	LED	X	X	3.3a	X	2.8a	X	0.30a
	Halogen	X	X	3.8a	X	3.2a	X	0.26a
	LED + Halogen	X	X	4.1a	X	3.5a	X	0.32a

[z] Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[y] Means (n=5) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

[X] Interaction was significant for these factors.

Table 18. Growth and flowering characteristics of *Lilium asiatic* (L.) 'Yellow Cocotte' and 'Montreux' affected by GA_3 averaged across light.

Cultivar	GA_3 Rate (ppm)	Height (cm)	Width (cm)	Shoot dry weight (g)	Mean flower number	Flower diameter (cm)	Days to anthesis	Flowering %
Yellow Cocotte	0	48.5a^z	19.6a	4.5a	2.1a	X	X	X
	40	47.2a	16.8a	4.4a	2.4a	X	X	X
	140	42.9a	17.3a	3.9a	2.0a	X	X	X
	340	43.4a	17.0a	3.7a	2.0a	X	X	X
Montreux	0	X	X	4.8a^y	X	5.6ab	X	0.35b
	20	X	X	6.9a	X	7.2a	X	0.55a
	50	X	X	4.0a	X	2.8b	X	0.40ab
	70	X	X	2.1a	X	0.8c	X	0.15c
	100	X	X	3.2a	X	0.9c	X	0.20bc
	120	X	X	2.1a	X	2.9b	X	0.30b
	150	X	X	3.9a	X	3.5ab	X	0.40ab
	170	X	X	5.1a	X	5.5ab	X	0.40ab
	200	X	X	2.3a	X	1.6bc	X	0.15c
	250	X	X	1.6a	X	0.7c	X	0.10c

^{z}Means (n=12) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

^{y}Means (n=5) with the same letter within the same column are not statistically significant at $P \leq 0.05$.

^{X}Interaction was significant for these factors.

VITA

Taylor Sharune Mills

Candidate for the Degree of

Master of Science

Thesis: EFFECT OF LED LIGHTING AND SILICON SUPPLEMENTATION ON GROWTH AND FLOWERING OF CUT FLOWERS

Major Field: Horticulture

Biographical:

Education:

Completed the requirements for the Master of Science in Horticulture at Oklahoma State University, Stillwater, Oklahoma in December, 2017.

Completed the requirements for the Bachelor of Science in Plant Science at Southern Arkansas University, Magnolia, Arkansas/United States in 2015.

Experience: Graduate and Teaching Assistant

Professional Memberships: Southern Region ASHS