Using Light to Improve Ornamental Plant Propagation in Controlled Environments

by

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ABSTRACT

USING LIGHT TO IMPROVE ORNAMENTAL PLANT PROPAGATION IN CONTROLLED ENVIRONMENTS

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Light-emitting diodes (LEDs) can provide different spectrum and spectral combinations. This thesis investigated the effects of different monochromatic light spectra on seed germination of some commercially important ornamental plants, explored optimal light recipes for gerbera seedling production, and investigated the effects of dynamic red (R) and blue (B) lighting to improve campanula stock plant morphology and cutting quality. Generally, the monochromatic lights did not affect the seed germination response compared to darkness. Among the monochromatic lights, R, G, and UVB were the most promotive. Gerbera seedlings grown under RB-LED had as good a quality as those under fluorescent light and including a third light spectrum did not affect their growth and morphology. Dynamic R and B lighting can promote plant elongation without negatively affecting cutting quality, and with a mix of photoperiods, can be used as an effective lighting strategy for producing campanula stock plants for machine-harvest of cuttings.

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

B – Blue

CCI – Chlorophyll content index

D – Dark

DLI – Daily light integral ($mol \cdot m^{-2} \cdot d^{-1}$)

DW – Dry weight

FL – Fluorescent light

FR – Far-red

FW – Fresh weight

G – Green

LDP – Long-day plant

LED – Light-emitting diode

PFD – Photon flux density ($\mu mol \cdot m^{-2} \cdot s^{-1}$)

PPFD – Photosynthetic photon flux density ($\mu mol \cdot m^{-2} \cdot s^{-1}$)

PPS – Phytochrome photostationary state

QI – Quality index

R – Red

SB – Side branch

SD – Standard deviation

SE – Standard error

SSL – Sole-source lighting

UVA – Ultraviolet A

UVB – Ultraviolet B

CHAPTER ONE

INTRODUCTION

1.1 Ornamental plant production

Ornamental plants include bedding plants, potted plants and cut flowers, to name just a few types, that are valued for their aesthetic quality and wide range of colours from multiple species, such as gerbera (*Gerbera* spp.) and campanula (*Campanula* spp.) (Andreasen et al., 2014; Seglie et al., 2012). Ornamental plants accounted for approximately 50% ($1.6 billion) of total Canadian greenhouse sales in 2019, and total ornamental plant sales have been increasing with an 8.5% increase over the five-year span from 2014 to 2019 (Statistics Canada, 2020a).

In ornamental plant production, a large number of uniform seedlings from seeds or rooted cuttings in a short time period (Hartmann et al., 2002a) is ideal in propagation, and subsequent transplants are considered high-quality if they have characteristics such as compactness with a healthy root system, a thick stem, and can flower early (Pramuk and Runkle, 2005; Randall and Lopez, 2014). Many ornamental species are propagated in greenhouses year-round, commonly during late winter and early spring to meet high consumer demand in spring and summer (Pramuk and Runkle, 2005). Natural light conditions change depending on the time of year and outdoor climate conditions, and in Canada and other northern regions, low natural light during the propagation period can be a limiting factor in producing high-quality plants (Faust and Logan, 2018; Randall and Lopez, 2015). To meet daily photosynthetic light requirements (i.e., daily light integral, DLI) in northern regions, supplemental light (SL) is used in greenhouses when natural light levels are low (Llewellyn et al., 2019; Randall and Lopez, 2014). An

alternative to greenhouse production is using an indoor controlled environment with sole-source lighting (SSL), such as a growth chamber, as it allows for year-round production when outdoor climate conditions are unfavourable (Craver et al., 2018; Gómez et al., 2019). According to a recent survey by Gibson et al. (2020), indoor propagation for ornamentals is an area of interest for growers for reasons such as the ability to produce more plants in the same land area, faster seed germination or rooting, and improving plant quality and labour efficiency.

1.2 Light and controlled environment plant production

Light is one of the most important environmental factors for plant growth, as it provides energy for photosynthesis and acts as a signal for morphological development, i.e., photomorphogenesis (Huché-Thélier et al., 2016). There are three ways to describe the light environment: spectrum (i.e., light quality or colour), intensity (i.e., light quantity or amount), and photoperiod (daily duration of light) (Hopkins and Hüner, 2004). The ultimate effect on plants depends on all three factors but generally, light quality regulates plant morphology, light intensity affects photosynthesis, and photoperiod controls flowering (Lopez and Runkle, 2017).

Controlled environments are indoor environments such as greenhouses, growth chambers, and multi-level propagation facilities, where environmental factors such as temperature, carbon dioxide, humidity and light can be controlled (Bantis et al., 2018; Gómez et al., 2019). As a result, conditions can be modified to increase production efficiency and improve plant quality. In controlled environments, high-pressure sodium (HPS), metal halide, and fluorescent (FL) light have traditionally been used as an electrical light source for SL or SSL (Gómez et al., 2019). Recently, light-emitting diodes (LEDs) are increasingly being used instead

of traditional light sources due to their many advantages such as long operating life, low heat output, and adjustable light spectral quality and light intensity (Massa et al., 2008; Morrow, 2008; Zheng, 2016). Adjustable light spectral quality enables researchers to investigate plant morphological responses to different light spectra to find optimal light quality combinations (i.e., recipes) for plant growth and development, and makes it possible for commercial growers to implement different light recipes to achieve desired plant characteristics or production goals (Massa et al., 2008; Mitchell and Stutte, 2017). As mentioned above, plant production in a growth chamber with SSL enables year-round production independent of outdoor climate, and plants have shown to be of better quality (i.e., more compact, higher chlorophyll content, and higher root biomass) than those grown in a greenhouse with SL (Randall and Lopez, 2015). Considering the positive characteristics of LED lights, ornamental plant propagation in a growth chamber with LED SSL has the potential to be an alternative to traditional greenhouse propagation (Craver et al., 2018; Randall and Lopez, 2015).

1.3 Light quality and photoreceptors

Plants perceive light spectra from ultraviolet B and A (UVB and UVA, 280–400 nm) to far-red (FR, 700–800 nm), and different spectra are absorbed by different photoreceptors (Huché-Thélier et al., 2016). These include red (R, 600–700 nm) and FR light-sensing phytochromes, UVA (320–400 nm) and blue (B, 400–500 nm) light-sensing cryptochromes, phototropins and Zeitlupe family, and UVB (280–320 nm) light-sensing UVR8 (Heijde and Ulm, 2012; Huché-Thélier et al., 2016; Shinomura et al., 1996). Although the green (G, 500–600 nm) light photoreceptor is unknown, G light can be absorbed by cryptochromes and/or phytochromes,

depending on the light environment, and can affect developmental processes such as seed germination and photosynthesis (Golovatskaya and Karnachuk, 2015).

Phytochromes exist in an inactive R-absorbing form (P_r) and an active FR-absorbing form (P_{fr}), which interconvert between each other depending on the light environment (Pons, 2014). Phytochromes are involved in many plant responses to light including seed germination, elongation, and flowering (Davis and Burns, 2016). Phytochromes can also absorb UV, B and G light to some extent (Shinomura et al., 1996). Cryptochromes and phototropins control a wide range of plant responses such as phototropism (i.e., growth towards light), promoting photosynthesis, and also flowering (Huché-Thélier et al., 2016). The UVR8 photoreceptor is involved in UV defense mechanisms, but UV light can also affect plant growth, morphology, and secondary metabolism (Neugart and Schreiner, 2018).

1.4 Light quality and seed germination

Seed germination occurs when metabolic activity of the embryo increases leading to radicle emergence, which forms the root of the new seedling (Hartmann et al., 2002b). A seed is considered germinated when the radicle has broken through the seed coat (Carpenter and Boucher, 1992; Vasilean et al., 2018). For seed germination to occur, dormancy needs to be broken and environmental conditions (e.g., temperature, water, and light) need to be favourable (Bentsink and Koornneef, 2008). Light is a particularly important factor for seed germination, and can interact with other environmental factors to either promote or inhibit germination (Pons, 2014).

Propagation is the first stage in ornamental plant production, and improving propagation efficiency through adjusting light quality, can impact subsequent seedling quality and flowering (Davis and Burns, 2016; Hutchinson et al., 2012). R and B lights are mostly used in light recipes for controlled environment plant production as these wavelengths are most readily absorbed and utilized by plant leaves (McCree, 1972). Monochromatic R LED light has been reported in promoting seed germination of kale (*Brassica oleracea*) (Hawley, 2013) and *Bletilla ochracea* (Godo et al., 2011). Monochromatic B LED light has been reported in promoting seed germination of green lentils (*Lens culinaris*) and broad beans (*Vicia faba*) (Vasilean et al., 2018) but inhibited germination of wheat (*Triticum durum*) (Hawley, 2013). Compared to R light, B light promoted seed germination of stevia (*Stevia rebaudiana*) (Simlat et al., 2016) and inhibited seed germination of subterranean clover (*Trifolium subterraneum*) (Costa et al., 2016), but soybean (*Glycine max*) seed germination was similar under R and B light at the same intensity and photoperiod (Hawley, 2013), suggesting the response varies with plant species. Also, Costa et al. (2016) found that if the seeds were dry, as opposed to imbibed, final germination was similar under R and B, showing how other environmental factors can interact with light quality.

Plant photoreceptors and pigment molecules absorb G light to a lesser extent than R and B (Smith et al., 2017), and G LEDs have lower efficiency than R and B LEDs (Kusuma et al., 2020). However, monochromatic G LED light has promoted seed germination of barley (*Hordeum vulgare*) (Hoang et al., 2014) and *B. ochracea* (Godo et al., 2011), but inhibited seed germination of wheat (Hawley, 2013). Similar to G, FR LEDs are less efficient than R and B LEDs but FR light can have promotive effects on plant growth (Demotes-Mainard et al., 2016; Kusuma et al., 2020). There is a lack of information on seed germination under FR LED light,

possibly because FR light can deactivate phytochromes, the main photoreceptor involved in seed germination (Pons, 2014), and studies on tomato (*Lycopersicon esculentum*) (Appenroth et al., 2006) and lettuce (*Lactuca sativa*) (Contreras et al., 2009) have found that FR light from coloured filters inhibited seed germination. Hawley (2013) found that monochromatic FR LED light can promote or inhibit germination depending on species. UVB light is rarely used in plant production because of its harmful effects to both humans and plants (Neugart and Schreiner, 2018), however very low intensities of UVB light can cause a morphological response and UVB light has promoted seed germination of some vegetables (Noble, 2002). From the aforementioned studies, the seed germination response to light varies depending on light quality, environmental conditions, and plant species. Also, there have been fewer studies on ornamental plant production using LEDs compared to edible crops (Ouzounis et al., 2018). Therefore, studies on using LED light quality on ornamental plant propagation are needed to help commercial ornamental growers take better advantage of using light.

1.5 Light environment and plant growth and morphology

A high-quality seedling has a thick stem, strong roots, high biomass, and is relatively compact (Pramuk and Runkle, 2005; Randall and Lopez, 2014). Generally, increasing light intensity during seedling production decreases plant height, increases biomass production and side branch number, and accelerates flowering (Craver et al., 2018; Kong and Zheng, 2019; Pramuk and Runkle, 2005). Previous research on ornamentals has shown that a DLI of 10–12 $mol \cdot m^{-2} \cdot d^{-1}$ is recommended for production of high-quality ornamental seedlings (Randall and Lopez, 2014, 2015). Increasing DLI by extending photoperiod can either accelerate or delay flowering, depending on a plant's flowering response (Owen et al., 2018). Long- and short-day

plants (LDP and SDP, respectively) flower when the photoperiod is longer or shorter than a certain length, respectively. However, light quality can play a role in a plant's flowering response, regardless of photoperiod (Owen et al., 2018; Runkle and Heins, 2001).

Plants grown under monochromatic R LED light display undesirable characteristics such as delayed flowering and impaired photosynthetic functioning (Goins et al., 1997; Hogewoning et al., 2010; Kong and Zheng, 2020). Monochromatic B LED light also causes some undesirable characteristics, such as plant elongation and decreased branching (Heo et al., 2002; Kong et al., 2018a; Schwend et al., 2015). Combining R and B, i.e., RB-LED, has been shown to be a better light recipe for plant growth and development than monochromatic R or B light. For example, RB-LED increased chlorophyll content and fruit yield of strawberry (*Fragaria* × *ananassa*) (Choi et al., 2015) and increased FW, DW and photosynthetic rate of chrysanthemum (*Dendranthema grandiflorum*) (Kim et al., 2004a) compared to R and B at the same respective intensities and photoperiods. In some cases, alternating R and B LED light (i.e., dynamic lighting) can be better than either monochromatic or combined RB-LED. Lettuce plants grown under alternated R and B light in a daily cycle had greater FW, DW, and/or plant elongation compared to RB-LED (Kuno et al., 2017; Ohtake et al., 2018; Shimokawa et al., 2014). There is a lack of data around the use of dynamic lighting to modify ornamental plant morphology. Since monochromatic R and B LED light can have contrasting effects on plant growth and morphology (Kong et al., 2018a), to achieve certain morphological characteristics, such as increased branching or plant elongation without comprising plant growth, investigating dynamic lighting at different stages may be worthwhile.

Compared to traditionally used FL light, the responses to RB-LED light vary with plant species. RB-LED light increased FW and DW of vanilla (*Vanilla planifolia*) (Bello-Bello et al., 2016), chili pepper (*Capsicum annuum*) (Gangadhar et al., 2012), and lettuce (Johkan et al., 2010). However, some plant species under FL light were either more compact (i.e., shorter) and had similar or greater DW and leaf area than those under RB-LED (Hernández et al., 2016; Wollaeger and Runkle, 2014). RB-LED is commonly used in controlled environment plant production (Davis and Burns, 2016; Mitchell and Stutte, 2017), and specifically for ornamental plants, a ratio of approximately 85% R and 15% B is used to produce high-quality seedlings (Llewellyn et al., 2019; Ouzounis et al., 2018; Randall and Lopez, 2014, 2015).

Including a third colour (e.g., UVB, UVA, G or FR) with RB-LED light, i.e., tri-chromatic light, can have positive effects on plant growth and morphology. Plants grown under solar radiation with UV filtered out have lower stress tolerance due to decreased synthesis of UV-absorbing compounds (Lazzeri et al., 2012; Neugart and Schreiner, 2018). Few studies have looked at including UV with RB-LED light or using solely UV light in plant production. Including UVA LED light with RB-LED (Chang and Chang, 2014) or with RBFR-LED (Chen et al., 2019) increased aboveground biomass of different cultivars of lettuce. In a study on microgreens, including UVA with RBFR-LED light generally increased FW and leaf area, but the effect was species-dependent (Brazaitytė et al., 2015). UVB light can cause compact plants by decreasing height and leaf area (Rodríguez-Calzada et al., 2019), and including UVB light with RB-W (white) LED light inhibited growth of lettuce plants (Lee et al., 2014). However, there is a lack of information on the effects of either UVA or UVB radiation added to RB-LED on ornamental plants.

G light can penetrate deeper into the plant canopy than R and B and increase photosynthesis (Davis and Burns, 2016). FR light added to RB-LED can also increase photosynthetic rate (Jiang et al., 2018), and both G and FR can cause shade-avoidance responses, such as plant elongation and accelerated flowering (Demotes-Mainard et al., 2016; Wang and Folta, 2013). Including G light with RB-LED increased leaf area of tomato (*Solanum lycopersicum*) (Wollaeger and Runkle, 2014) and increased FW of lettuce (Lin et al., 2018). However, for coreopsis (*Coreopsis grandiflora*), pansy (*Viola* × *wittrockiana*), and petunia (*Petunia* × *hybrida*), including G with RB-LED did not affect plant biomass or morphology, except for increasing leaf area of coreopsis (Craver et al., 2018). Compared to RB, including FR with RB-LED light increased leaf area and biomass of lettuce (Lee et al., 2016), plant height and leaf area of snapdragon (*Antirrhinum majus*) (Park and Runkle, 2016), and accelerated flowering of pansy and petunia (Craver et al., 2018). Since the effects of tri-chromatic light can vary with ornamental plant species, more research is needed to explore the responses of other commercially important plants such as gerbera.

1.6 Thesis objectives

Compared to edible crops, there is a lack of information on the effects of light quality on ornamental plant growth and morphology, and based on the above information, the responses might be species-specific. Some commercial growers are moving their propagation to indoor controlled environments, such as growth chambers or multi-level propagation facilities with electrical light. Knowing the optimal light quality or light recipe to use will help increase production efficiency and improve plant quality. The goal of this thesis was to determine the

effects of different light qualities on plant propagation of some commercially important ornamental plant species.

The specific objectives were to:

1. Investigate the seed germination response of multiple cultivars from five ornamental species to different narrow-band monochromatic light qualities and darkness.
2. Investigate the effects of various light recipes on the growth and morphology of gerbera seedlings in a controlled environment using SSL.
3. Investigate whether short-term 24-h dynamic lighting can promote elongation growth without inducing flowering, and to explore how to apply a dynamic lighting strategy to modify stock plant morphology of campanula to improve cutting quality and rooting in a controlled environment.

This research was intended to provide recommendations to ornamental growers to improve their plant growth and morphology during the propagation stage by using different light qualities in an indoor controlled environment (i.e., growth chambers and multi-level propagation facilities). The optimal light quality/recipe may differ between plant species, and possibly even between cultivars within a species, and may change depending on production goals or timelines. As a result of these differences, the results of this research will add to the current knowledge on the effects of light quality on ornamental plant production.

Note: All experimental chapters in this thesis (2, 3, and 4) follow the American Society for Horticultural Science's journal, HortScience, style guidelines and are intended to be submitted to this scientific journal for publication.

CHAPTER TWO

SEED GERMINATION RESPONSES TO LOW-INTENSITY MONOCHROMATIC LIGHTING OF DIFFERENT SPECTRA RELATIVE TO DARKNESS FOR 14 ORNAMENTAL PLANT GENOTYPES FROM FIVE SPECIES

Abstract

Electric lights such as light-emitting diodes (LEDs) are increasingly being used for production of ornamental seedling transplants in controlled environments. However, the optimal light spectral quality is unclear for seed germination. To investigate germination response to narrow-band monochromatic light, seeds of 14 genotypes from begonia, echinacea, gerbera, petunia, and vinca were germinated under red (R), blue (B), green (G), far-red (FR), ultraviolet B (UVB) light, or darkness. LED lighting provided the aforementioned monochromatic lights except for UVB, which was sourced from narrow-band fluorescent light. The average photon flux density (PFD) at seed level was approximately 18 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for R, B, G and FR, and 0.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for UVB. Based on the daily recorded germination data, the cumulative germination percentages were plotted against the days after seeding for each plant genotype. Also, four germination parameters (i.e., final germination percentage, germination onset time, germination time spread, and germination speed) were compared among different light treatments for all the plant genotypes. The shapes of the temporal variation curves of cumulative germination varied with different light treatments or plant genotypes. Based on the four germination parameters, generally, the monochromatic lights did not promote germination compared with darkness. In all cases, B had a similar effect as darkness on seed germination. In many cases, FR inhibited seed germination relative to darkness. In some cases, under R, G, and UVB compared to darkness, germination speed was promoted for begonia ‘Apricot Shade’ (a positively photoblastic

genotype) and inhibited for vinca ‘Burgundy’ (a negatively photoblastic genotype). However, the contrasting responses were not observed in the other three germination parameters. Among the monochromatic lights, not including darkness, R, G, or UVB generally appear to be the most promotive for promoting seed germination of the tested species, although the response varied with plant genotypes and germination parameters.

2.1 Introduction

Controlled environments using electric light as the sole light source have been increasingly used for seedling transplant production of ornamental plants (Gómez et al., 2019; Lopez et al., 2017). Light-emitting diodes (LEDs) have become an alternative to traditional horticultural lighting technology, such as high-pressure sodium (HPS) lamps due to their many advantages (Llewellyn et al., 2019; Martineau et al., 2012; Massa et al., 2008). One of the main advantages is adjustable light spectral quality, which makes it possible to optimize light recipes based on production goals (Mitchell and Stutte, 2017). High seed germination is the first step for the successful transplant production of seed-propagated ornamental plants in a controlled environment (Hartmann et al., 2002c). However, the optimal light recipe, specifically spectral qualities, is unclear for seed germination of many ornamental plants. Clarifying the effects of monochromatic lights with different spectra on seed germination first can provide a foundation to study the coactions of these lights, and thus is beneficial to further looking into optimizing light spectral combinations.

Monochromatic light with different spectra can affect seed germination through their respective photoreceptors. The photoreceptors involved in seed germination include at least

phytochromes, cryptochromes, phototropins, and unknown green light receptors (Casal et al., 1998; Demotes-Mainard et al., 2016; Goggin and Steadman, 2012). Red light (R; 600–700 nm) can activate phytochromes, but far-red light (FR; 700–800 nm) can deactivate phytochromes (Demotes-Mainard et al., 2016). Blue (B; 400–500 nm) and ultraviolet A (UVA; 320–400 nm) light have common photoreceptors such as cryptochromes and phototropins, which can be activated by either B or UVA (Huché-Thélier et al., 2016). Green light (G; 500–600 nm) can reduce cryptochromes activity, and may also activate unknown green light photoreceptors (Golovatskaya and Karnachuk, 2015). Although it is unknown whether UVR8, the photoreceptor for ultraviolet B (UVB; 280–320 nm) light (Neugart and Schreiner, 2018), is involved in seed germination, UVB has been reported to promote germination by causing seed coating to breakdown (Kovács and Keresztes, 2002; Noble, 2002). Based on the potential photoreceptors involved in seed germination, at least R, B, FR, G and UVB should be considered for studying seed germination responses to monochromatic lights.

The seed germination response to monochromatic lights at specific wavebands has been investigated in many previous studies (Basto and Ramírez, 2015; Lindig-Cisneros and Zedler, 2001; Sharma and Sen, 1975). However, the traditional light sources (e.g., fluorescent lights or coloured filters) provided monochromatic light which may be contaminated by low-levels of other light spectra (i.e., unpure and not monochromatic light) (Bergstrand et al., 2014). The emission of narrow-band light by LEDs provides the opportunity to re-evaluate the effects of pure light spectra on plant growth and development (Gómez et al., 2019; Smith et al., 2017). For example, using LED lighting, our research group recently found that monochromatic B light promoted plant elongation which contrasts previous studies on plant morphological responses

under broad-band (i.e., unpure, containing low-levels of other light spectra) B lights (Kong et al., 2018a, 2020).

To date, limited information has been available on seed germination responses to narrow-band monochromatic R, B, FR, G or UVB light, and inconsistent results have also been reported in the previous studies. Using continuous LED lighting at 60 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for stevia (*Stevia rebaudiana*) seed germination, B light generally resulted in an approximately 8–15% and 15–30% higher final germination percentage than R light and darkness, respectively (Simlat et al., 2016). Similarly, in another study on green lentils (*Lens culinaris*) and broad beans (*Vicia faba*), B LED light led to an approximately 3–16% higher seed germination percentage compared to darkness, R, G, and FR light, but the light intensity and photoperiod were not provided (Vasilean et al., 2018). In contrast, at an intensity of 57.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$, continuous B LED light inhibited germination of barley (*Hordeum vulgare*) grains compared to darkness, and the inhibitory effect was attenuated with B light intensities decreasing within the range of 36.5–54.8 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Hoang et al., 2014). Another study on a different cultivar of barley (*H. vulgare*) indicated that germination was approximately 25% higher under FR LED light or darkness compared to other light treatments (including R, B, and G light), all at 280 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16-h (Hawley, 2013). Continuous G LED light at 57.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ promoted germination of barley (*H. vulgare*) grains compared to B light, despite a similar effect as darkness (Hoang et al., 2014). In *Bletilla ochracea*, continuous G LED light at 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$ led to a ≈13% higher seed germination percentage compared to darkness, but B and R LED light showed no difference from G light and darkness (Godo et al., 2011). Continuous UVB light promoted seed germination of kale (*Brassica napus*), cabbage (*Brassica oleracea*), radish (*Raphanus sativus*), and agave (*Agave*

americana), but caused subsequent damage to the seedlings and the dosage was not provided (Noble, 2002). However, UVB light inhibited germination of *Verbascum* spp. and *Echium* spp. seeds (Hock et al., 2015), or had no effect on seed germination of multiple vegetables under continuous irradiation (Sugimoto, 2013). It appears that the optimal monochromatic light(s) for seed germination may vary with plant genotype (including species or cultivars), as well as light intensity and photoperiod. However, in each of the above studies, only a few non-ornamental plant genotypes were used for investigating the seed germination responses under part of monochromatic light spectra. Furthermore, different light intensities and/or photoperiods among the above studies might also partly contribute to the inconsistent results.

Begonia (*Begonia* × *tuberosa*), echinacea (*Echinacea* spp.), gerbera (*Gerbera jamesonii*), petunia (*Petunia* × *hybrida*), and vinca (*Catharanthus roseus*) are important seed-propagated ornamental species, and based on light sensitivity of seed germination, they can be roughly divided into three groups: (1) positively photoblastic, or light-requiring (begonia and gerbera), (2) negatively photoblastic, or light-inhibited (vinca), and (3) light insensitive (echinacea and petunia) (Ball, 1998; Carta et al., 2017; Zheng et al., 2007). Using low intensity, continuous (i.e., 24-h) lighting is an economical way of producing plants in a controlled environment (Sysoeva et al., 2010). However, the seed germination response for the above ornamental plant species under continuous low-level, narrow-band monochromatic light of different spectra is unknown. For light-requiring species, continuous light at a low intensity of 15 $\mu mol \cdot m^{-2} \cdot s^{-1}$ has been used for testing seed germination compared to darkness with no promotive effect (Carpenter et al., 1995). Possibly increasing the intensity slightly (e.g., 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$) could promote germination. For UVB light, this intensity (i.e., 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$) may cause damage to plants and intensities below

1 μmol·m^{-2}·s^{-1} of UVB are enough to trigger normal biological responses in plants (Dotto and Casati, 2017). The objective of this study was to investigate the seed germination response of multiple cultivars from five ornamental species to different narrow-band monochromatic light qualities and darkness. It was hypothesized that if using continuous low intensity lighting, approximately 20 μmol·m^{-2}·s^{-1} of R, B, FR, and G, or 0.5 μmol·m^{-2}·s^{-1} of UVB, for the above five ornamental plant species with different light sensitivities in seed germination response, and for their respective different cultivars, there is an optimal light environment for seed germination of each ornamental species.

2.2 Materials and Methods

2.2.1 Plant materials and germination conditions

The experiment was conducted in a 29 m^2 walk-in growth chamber at the University of Guelph, Guelph, ON, Canada for three time replicates during January to June of 2019. In total, 14 genotypes (2–4 cultivars from each of five plant species) were selected for the germination experiment (Table 2.1).

Table 2. 1. Ornamental plant genotypes used in seed germination experiment.

Scientific name	Genotype	Seed size[z] (g/1000 seeds)	Seed source[y]
Begonia × *tuberosa*	Begonia 'Tuberous Illumination Apricot Shade' (coated)	0.47	Ball
Begonia × *tuberosa*	Begonia 'Tuberous Nonstop Red' (coated)	0.47	Ball
Echinacea × *hybrida*	Echinacea 'Lakota Santa Fe'	4.56	PanAm
Echinacea × *purpurea*	Echinacea 'PowWow Wild Berry'	3.90	PanAm
Gerbera jamesonii	Gerbera 'Midi Dark Purple'	4.40	Florist
Gerbera jamesonii	Gerbera 'Maxi White'	4.04	Florist
Gerbera jamesonii	Gerbera 'Maxi Pink'	4.34	Florist
Gerbera jamesonii	Gerbera 'Majorette Red Dark Eye'	4.19	Sakata
Petunia × *hybrida*	Petunia 'Easy Wave White'	0.19	PanAm
Petunia × *hybrida*	Petunia 'Easy Wave Coral Reef'	0.14	PanAm
Petunia × *hybrida*	Petunia 'Easy Wave Red Velour'	0.11	PanAm
Catharanthus roseus	Vinca 'Mediterranean XP Red Dark'	2.41	PanAm
Catharanthus roseus	Vinca 'Pacifica XP Magenta Halo'	1.96	PanAm
Catharanthus roseus	Vinca 'Pacifica XP Burgundy'	1.83	PanAm

[z]Three samples of ~50 seeds were weighed, and the seed size (g/1000 seeds) was subsequently calculated for each genotype.

[y]Ball = Ball Horticulture, Chicago, IL, USA; PanAm = PanAmerican Seed, Chicago, IL, USA; Florist = Florist Holland, De Kwakel, The Netherlands; Sakata = Sakata Seed America Inc., Morgan Hill, CA, USA.

A simple germination system was developed for this study to compare seed germination of the 14 genotypes under the different treatments. Rockwool growing media sheets (1″ A-OK; Grodan, Kingsville, ON, Canada) were cut into 8 × 9 cm pieces and soaked in tap water for a minimum of 24 hours before seeding. Filter paper discs (P5; Fisher Scientific, Ottawa, ON, Canada) were cut into 6.4 × 6.4 cm squares and were placed on the tops of the fully soaked rockwool pieces (one filter paper per rockwool piece) within a plastic tray (27 × 56 × 5 cm). When the filter paper pieces were fully wet, seeds were manually sown on the surface of the filter paper. Once the seeding of a genotype was completed, the sown seeds were placed under the different light treatments (Fig. 2.1). For each of the three replicates, under each light treatment, there were two plastic trays and each tray contained 14 pieces of rockwool with filter paper (two pieces for each genotype, and 24 seeds for each piece, giving a total of 48 seeds per genotype).

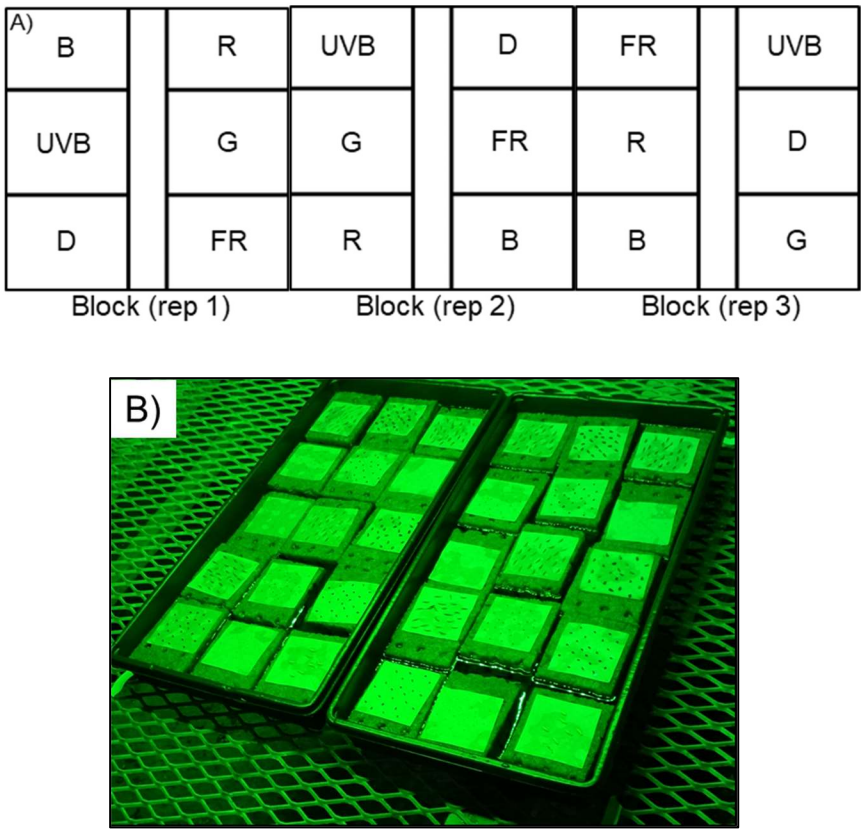

Figure 2. 1. Experimental design and setup for seed germination under different light treatments. A) Schematic of experimental growth chamber divided into six compartments each with two trays under one treatment for three replicates (D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light). B) Rockwool and filter paper setup under each treatment (G pictured). One filter paper piece with 24 seeds of one genotype was placed on a rockwool piece. Each tray contained all 14 genotypes and in total there were 48 seeds per genotype under each treatment per time replicate. One genotype was not included in the experiment and was used as an extra (15th filter paper and rockwool piece).

Prior to seeding, the seeds were stored in a dark room at 4°C, a common storage method for all species examined. When seeding, each plastic tray was filled with ≈1500 mL of tap water to ensure the filter papers on the top of the rockwool pieces were kept fully moistened. After

starting the light treatment, more water was added to the trays as needed to maintain the moisture level of the filter papers. During the light treatment period, the environmental conditions in the growth chamber were controlled by an Argus control system (Argus Controls Systems Ltd., Surrey, BC, Canada) and the actual air temperature and relative humidity across all three replications averaged 23.9 ± 0.1 ˚C and 69.4 ± 5.4 %, respectively.

2.2.2 Experimental design and treatment arrangement

The experiment was conducted as a randomized complete block design (RCBD) with one factor (i.e., light quality) and three replicates over time. Treatments included: 1) Dark (D); 2) Red (R; 660 nm); 3) Blue (B; 449 nm); 4) Far-red (FR; 735 nm); 5) Green (G; 525 nm); and 6) Ultraviolet B (UVB; 310 nm) light. The average photon flux density (PFD) at seed level was approximately 18 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for R, B, G and FR, and 0.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for UVB. Continuous 24-h lighting was used for all the above monochromatic light treatments. The UVB light was provided by a narrow-band UVB fluorescent tube (PL-L-36W; Philips, Solarc Systems Inc., Minesing, ON, Canada) and the others were LED lights (YNS9810-820A; Yunustech Inc., Mississauga, ON, Canada). The LED and UVB light fixtures were hung 60 cm and 76 cm above the bench, respectively. For the dark treatment, no light fixtures were used, and black cloth was used to prevent light contamination from neighbouring light treatments. Light contamination was checked by measuring light bleed at the borders of each growth chamber compartment. For the monochromatic light treatments, the light spectral distributions can be found in Fig. 2.2.

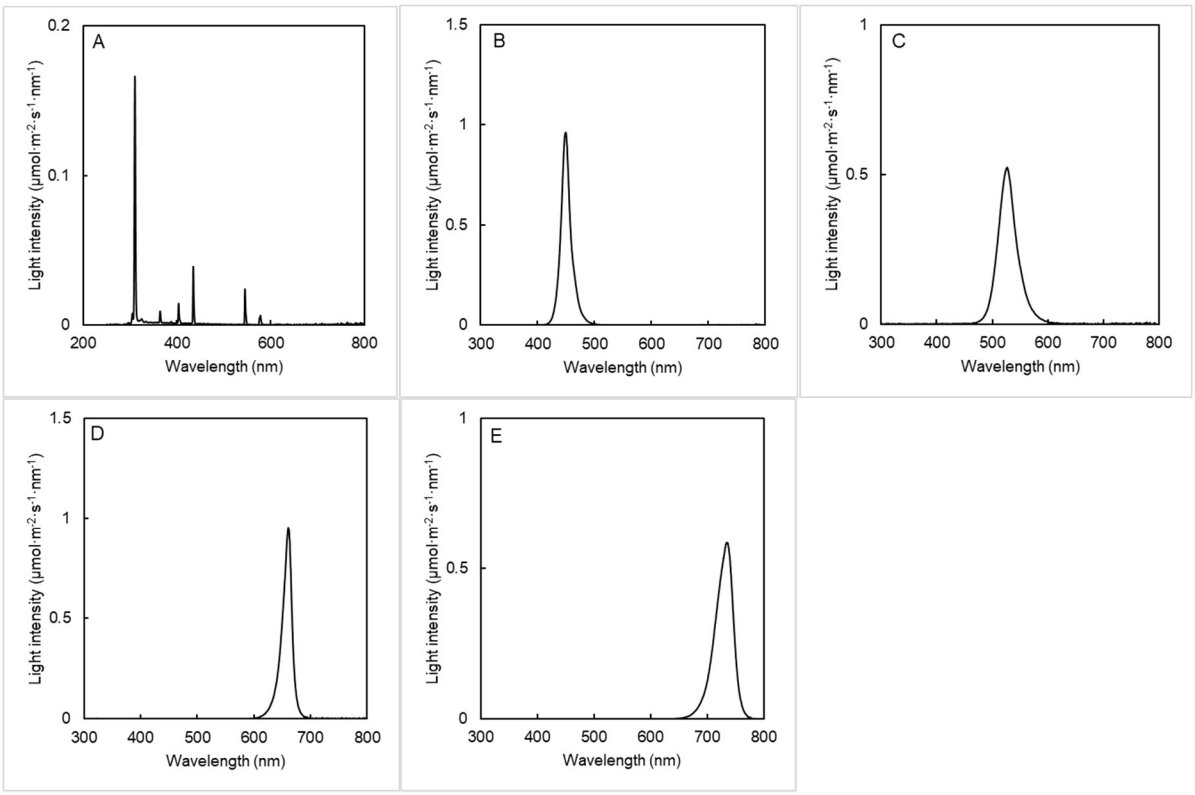

Figure 2. 2. The spectral distribution of five monochromatic light treatments, A) UVB, B) blue, C) green, D) red, and E) far-red, delivered by narrow-band light-emitting diodes (LEDs) or fluorescent lights. The average photon flux density (PFD) at seed level was ≈18 μmol·m^{-2}·s^{-1} for red, blue, green and far-red, and ≈0.4 μmol·m^{-2}·s^{-1} for UVB light.

For each replicate, the six treatments were randomly allocated to six compartments inside the chamber, which were separated from each other by opaque white curtains to prevent neighbouring light effects. The light treatments were replicated three times by changing the light treatments within the six compartments. Light spectra and intensities were set up and verified using a USB2000+UV-vis spectrometer (Ocean Optics, Inc., Dunedin, FL, USA). The target intensity was achieved at seed level by adjusting fixture height or applying layers of neutral-density mesh for the UVB light treatment, and by changing electric power output for other light treatments.

2.2.3 Germination

After sowing, the number of germinated seeds (defined as having visible radicle protrusion) on each piece of filter paper was counted and recorded daily until all seeds had germinated or the germination percentage was stable for five consecutive days. The germination check for all treatments was assisted with a handheld magnifier under a green safe light (peak wavelength of 520 nm, <1.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

The cumulative germination percentage was calculated and plotted over time, and at the end of the experiment, the final germination percentage, germination onset time, germination time spread, and germination speed were determined. Final germination percentage (%) was calculated as number of germinated seeds out of 48 seeds sown. Germination onset time (d) was defined as days from the sowing date to the first day of observed seed germination. Germination time spread was the time (d) from the first day of observed seed germination to the day germination percentage became stable (i.e., the first of the five days). Germination speed was calculated as the inverse of t50, which was the time (d) required to reach median germination (around 50% of the seeds germinated).

2.2.4 Statistical analysis

Data were subjected to analysis of variance using SAS statistical software (University Edition; SAS Institute, Cary, NC, USA) and were presented as means ± SE (standard error). Comparisons of means for different light treatments were performed separately for each genotype using Tukey's HSD test at a significance level of 0.05. Residuals were tested for

normality using the Shapiro-Wilk test. Final germination percentage values were transformed to arcsine degree values before statistical analysis.

2.3 Results

2.3.1 Cumulative germination dynamics

In all tested genotypes, the temporal variation of cumulative germination under all the treatments followed a similar trend, with a slow start, a linear increase, and a final plateau (Fig. 2.3-7). However, the shapes of the trend curves varied with different light treatments for each genotype. This indicated the possibility of different germination onset time, germination speed, final germination percentage, or time spread under all the treatments for each genotype.

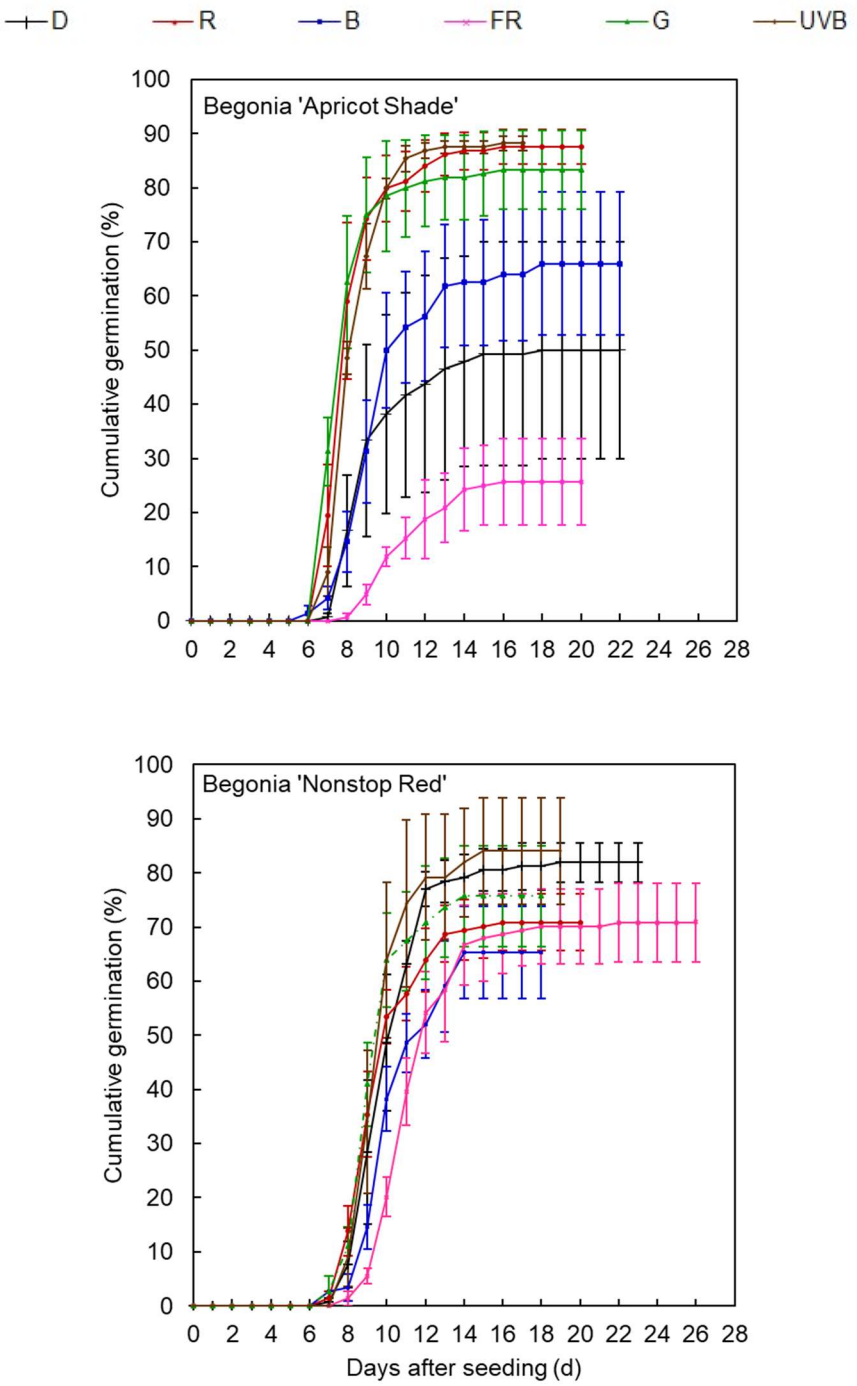

Figure 2. 3. Temporal variation of cumulative seed germination (%) of begonia genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light.

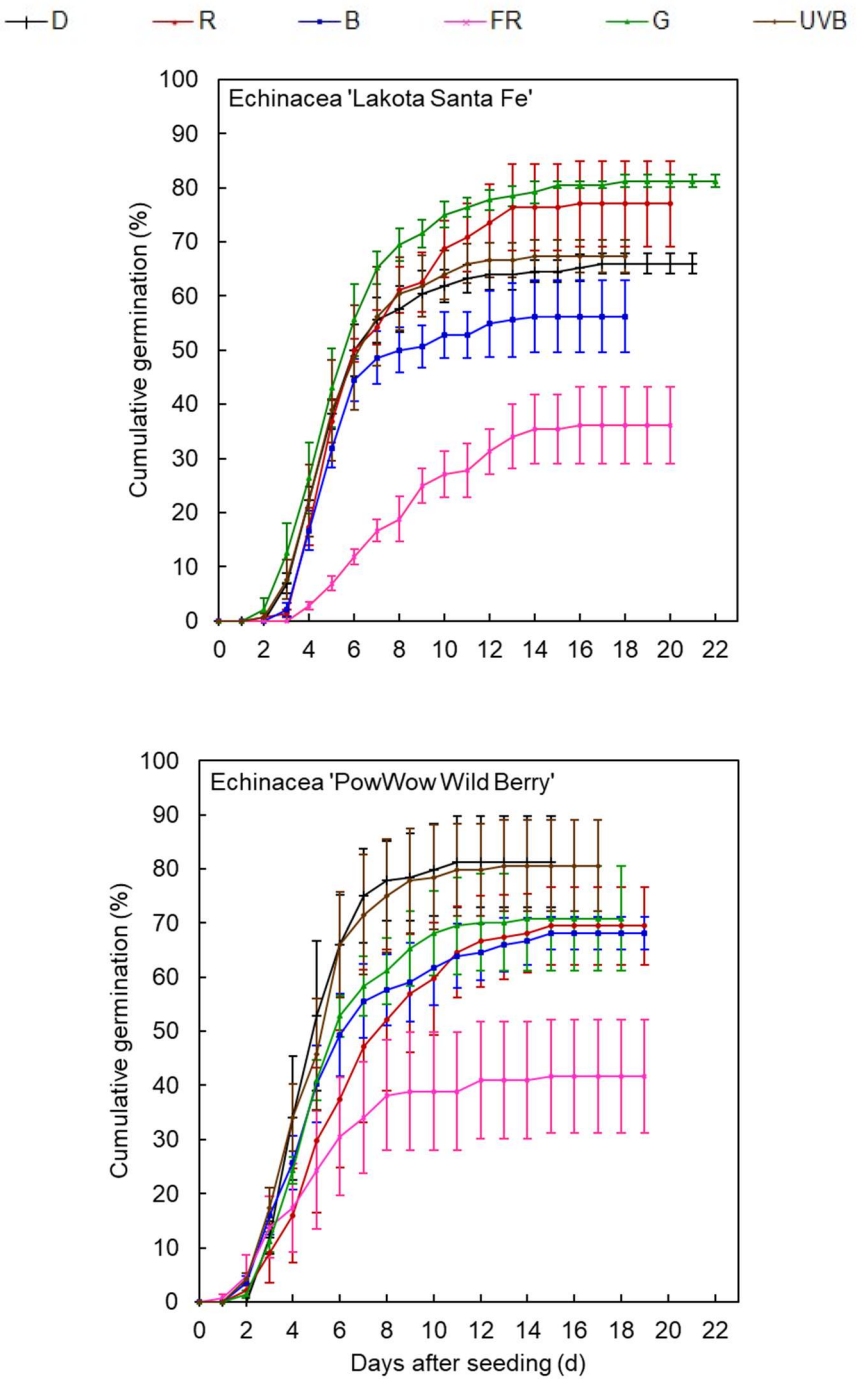

Figure 2. 4. Temporal variation of cumulative seed germination (%) of echinacea genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light.

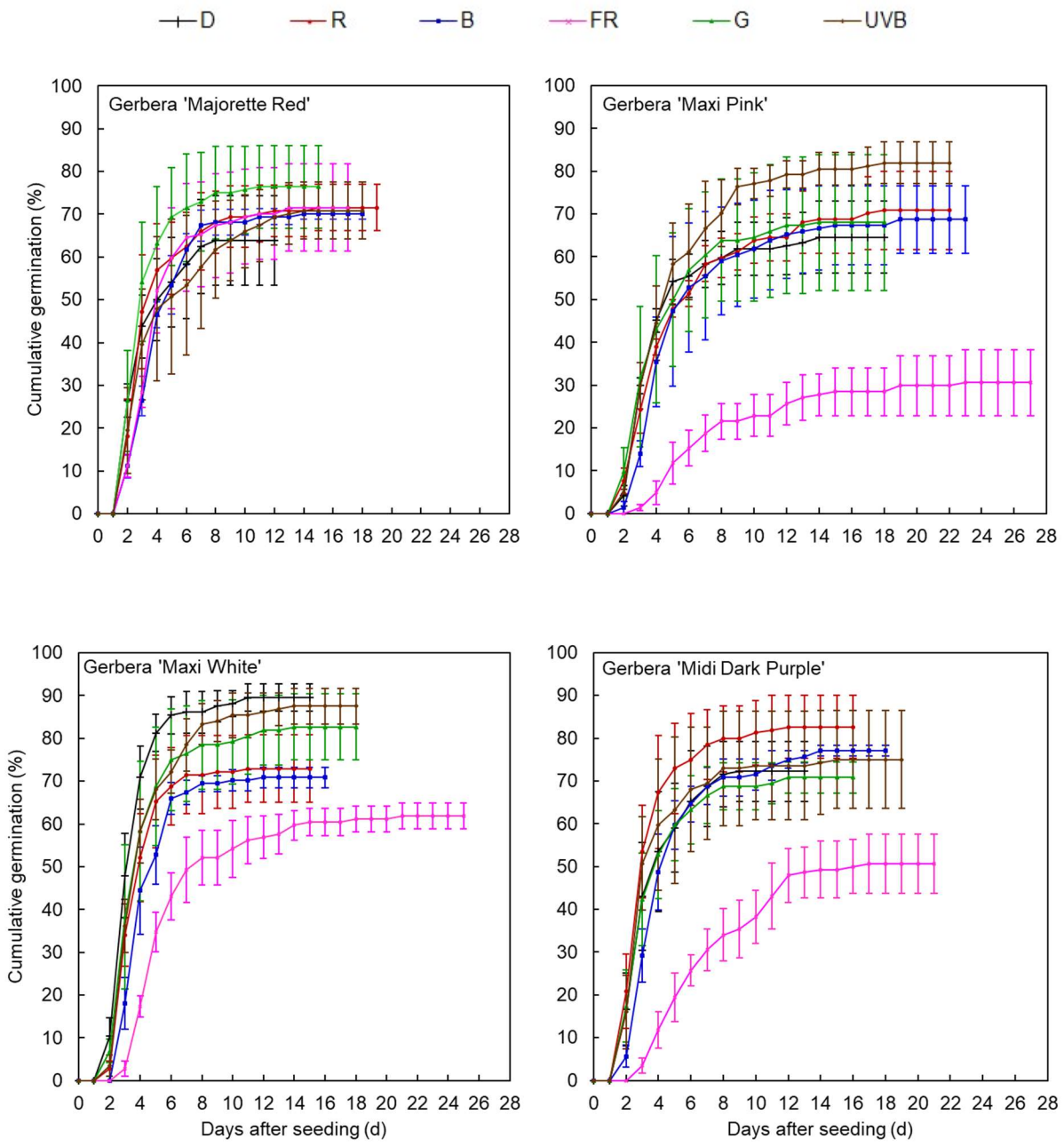

Figure 2. 5. Temporal variation of cumulative seed germination (%) of gerbera genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light.

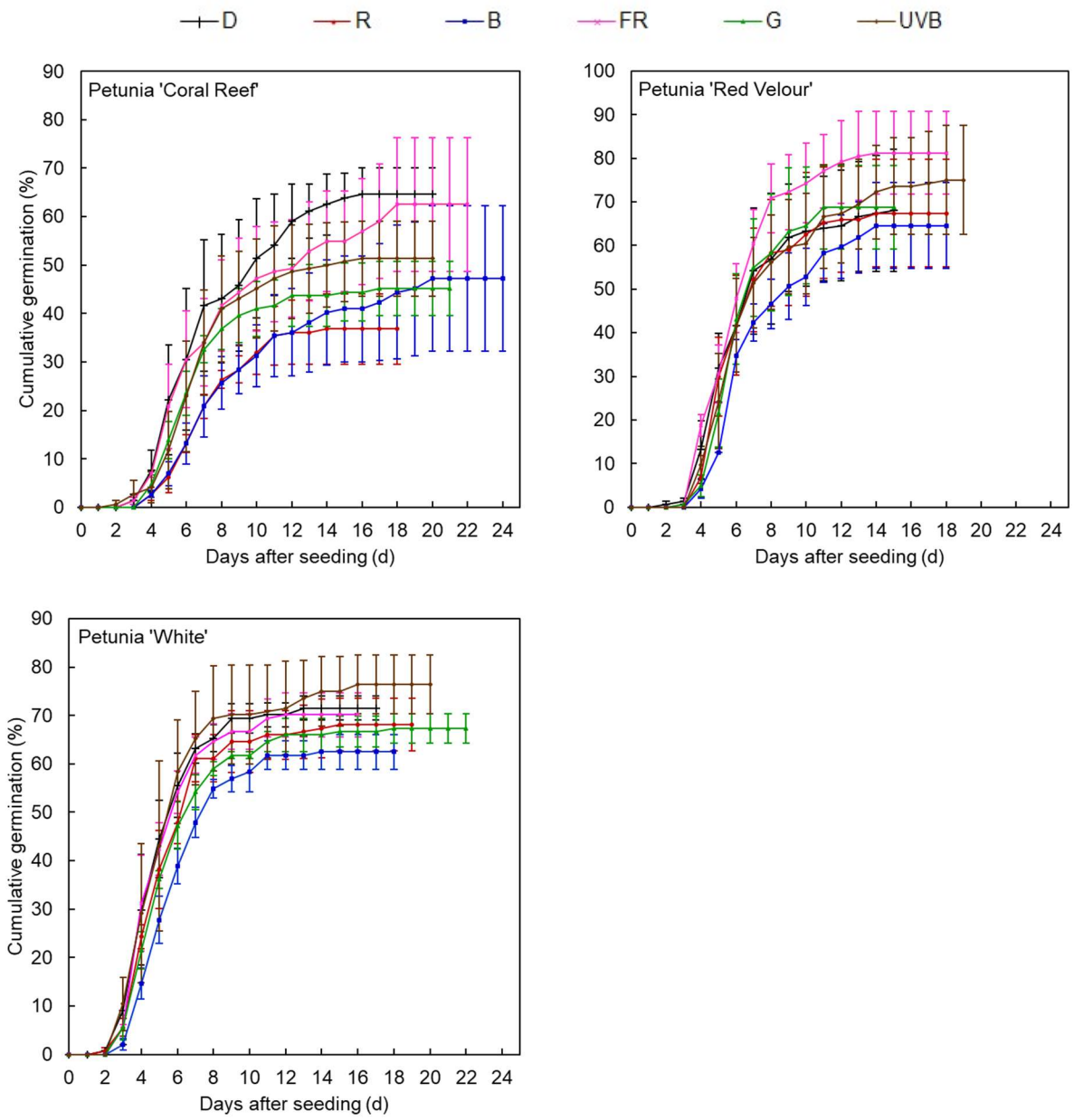

Figure 2. 6. Temporal variation of cumulative seed germination (%) of petunia genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light.

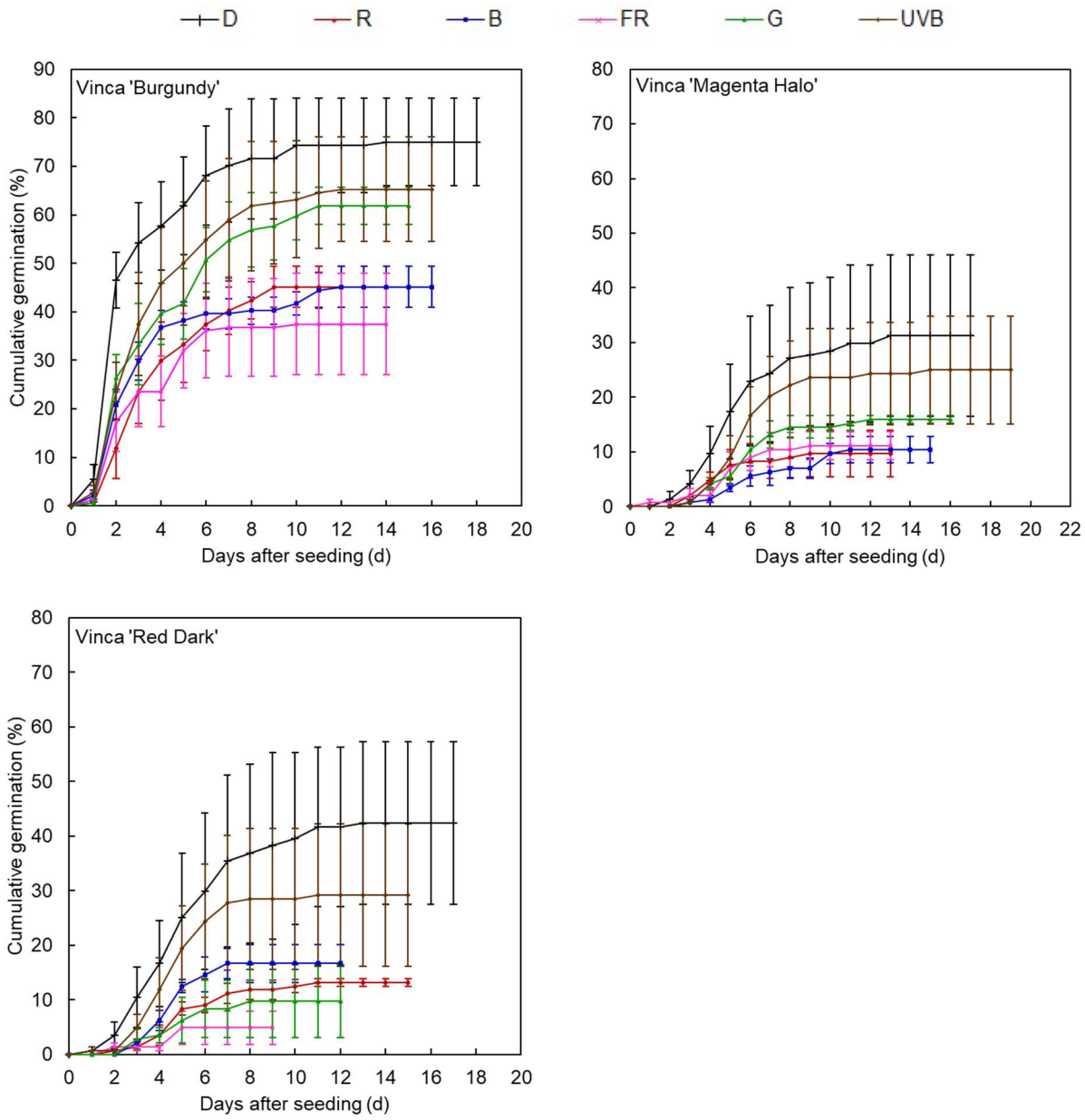

Figure 2. 7. Temporal variation of cumulative seed germination (%) of vinca genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light.

2.3.2 Final germination percentage

Light treatments affected final germination percentage for nearly all the tested species except petunia, but the effect of the light treatments varied with different cultivars within the same species (Fig. 2.8). In begonia ‘Apricot Shade’, R, G, and UVB led to higher final germination percentage than FR by 62%, 58%, and 63%, respectively, and D and B showed no difference relative to R, G, FR and UVB, but in ‘Nonstop Red’, there was no difference among the treatments. In echinacea ‘Lakota Santa Fe’, G led to higher final germination percentage than B and FR by 25% and 45%, respectively, and D, R, and UVB showed no difference relative to G or B light, but in ‘PowWow Wild Berry’, there was no difference among the treatments. For gerbera ‘Maxi Pink’, R, G and UVB led to higher final germination percentage than FR by 40%, 38%, and 51%, respectively, and D and B showed no difference relative to R, G, FR and UVB. In gerbera ‘Maxi White’, D and UVB led to higher final germination percentage than FR by 28% and 26%, respectively, and R, B, and G showed no difference relative to any of the light treatments. In gerbera ‘Midi Dark Purple’, R led to higher final germination percentage than FR by 32%, respectively, and D, B, G, and UVB showed no difference relative to R and FR, but in ‘Majorette Red’, there was no difference among the treatments. For both vinca ‘Burgundy’ and ‘Red Dark’, D led to a higher final germination percentage than FR by 38%, and R, B, G and UVB showed no difference relative to D and FR, but in ‘Magenta Halo’, there was no difference among the treatments. For the above genotypes affected by light, all the light quality treatments except for FR showed a similar effect as D on final germination percentage. Among the light quality treatments (not including D), final germination percentage was the lowest under FR.

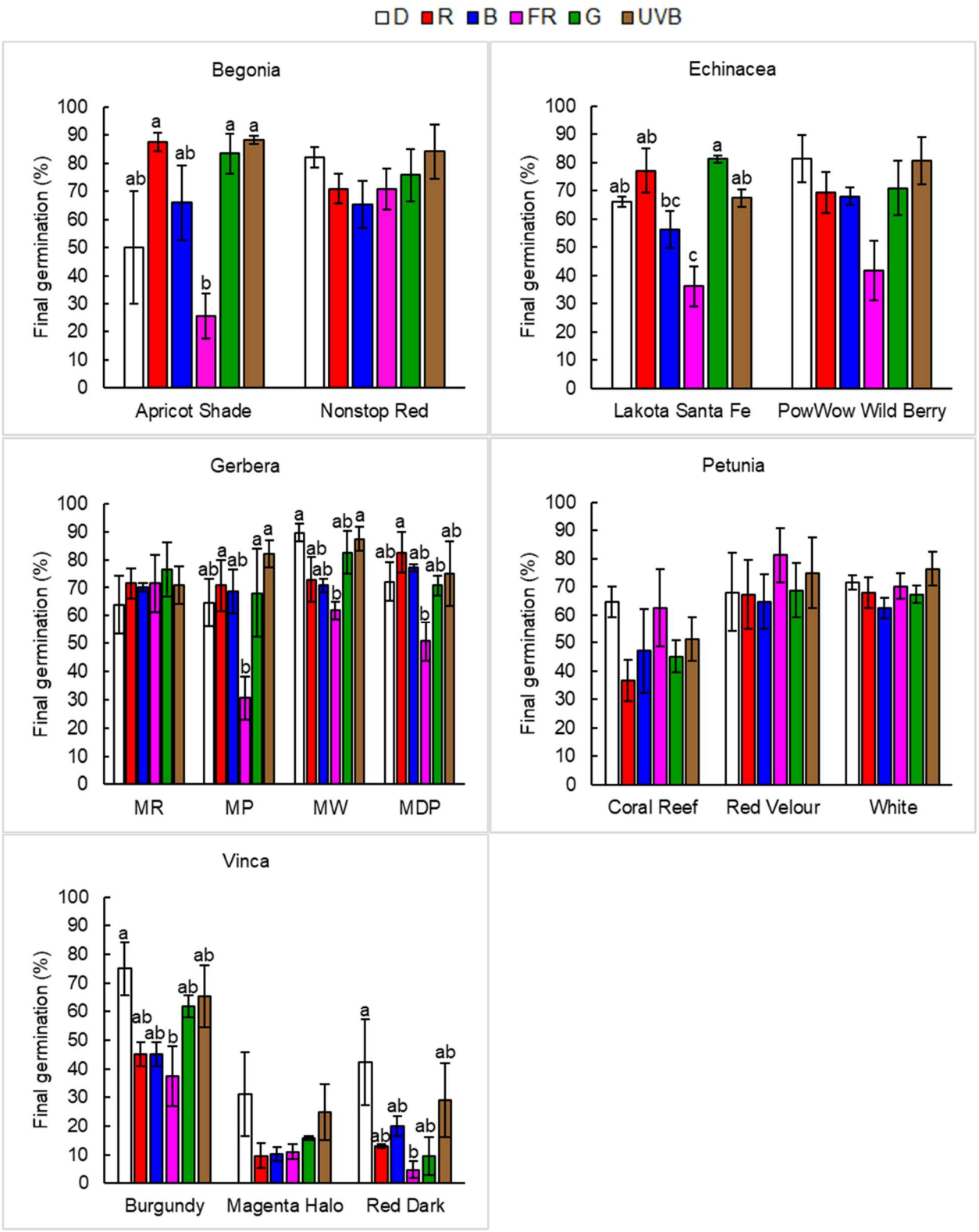

Figure 2. 8. Final germination percentage (%) of seeds in 14 ornamental plants genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue,

FR = far-red, G = green, and UVB = UVB light. Within the same genotype, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test. For gerbera, MR = 'Majorette Red', MP = 'Maxi Pink', MW = 'Maxi White', and MDP = 'Midi Dark Purple'.

2.3.3 Germination onset time

Light treatments did not affect germination onset time for nearly all the tested species except gerbera (Fig. 2.9). For gerbera, the effect of light treatments varied with different genotypes: the light treatments affected onset time in 'Maxi Pink', 'Maxi White', and 'Midi Dark Purple', but not in 'Majorette Red'. For the three affected gerbera genotypes, a similar effect under D was observed for nearly all the light treatments except FR, which delayed germination onset compared with D by 1–1.5 d. Among the five light quality treatments, germination onset time was the shortest under G for 'Maxi White', under R, G, or UVB for 'Maxi Pink', and under R, B, G, or UVB for 'Midi Dark Purple'. For the above genotypes affected by light, all the light quality treatments except for FR showed a similar effect as D on germination onset time. Among the light quality treatments (not including D), germination onset time was longer under FR.

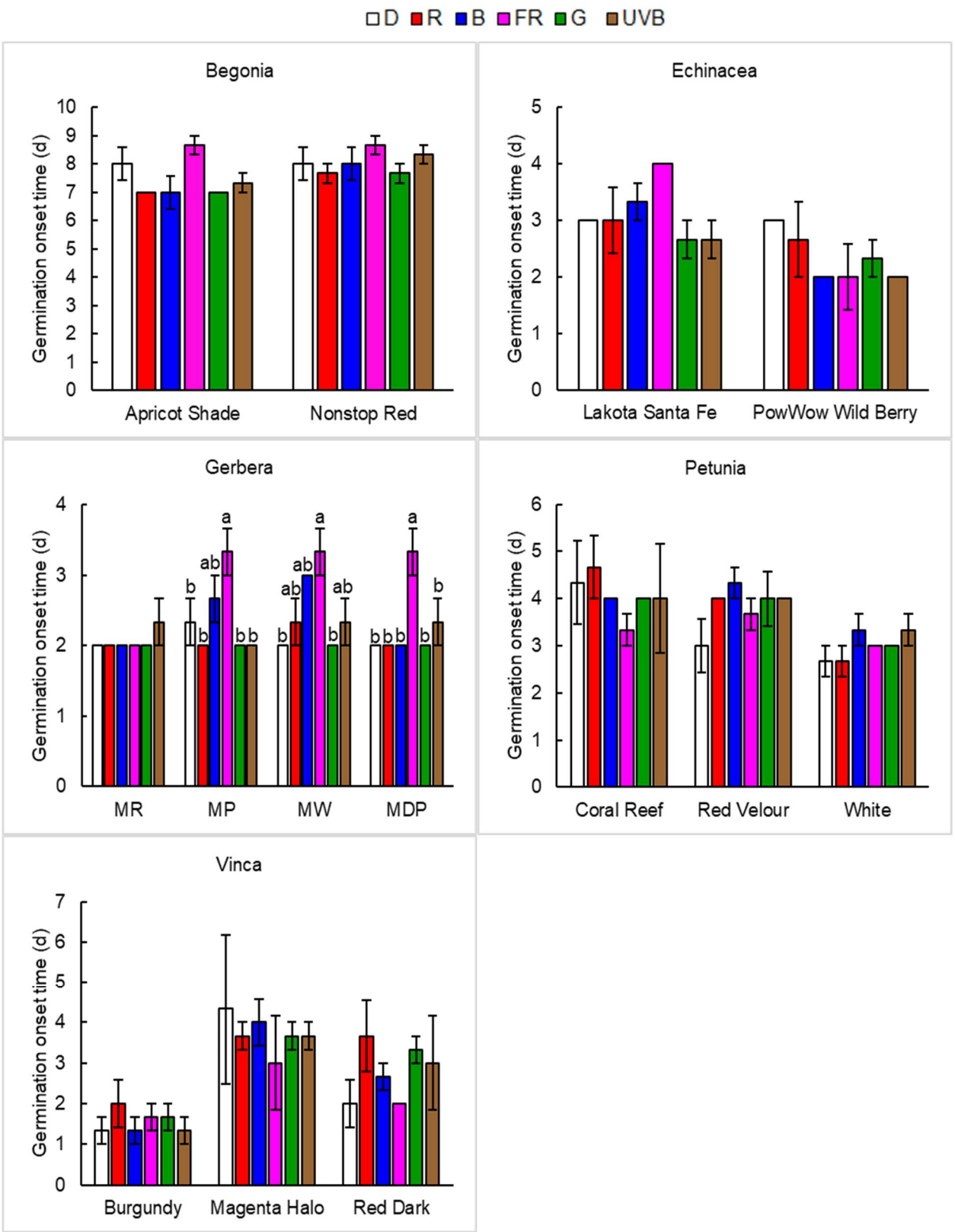
D R B FR G UVB
Begonia
Germination onset time (d)
Apricot Shade
Nonstop Red
Echinacea
Lakota Santa Fe
PowWow Wild Berry
Gerbera
MR
MP
MW
MDP
Petunia
Coral Reef
Red Velour
White
Vinca
Burgundy
Magenta Halo
Red Dark

Figure 2. 9. Germination onset time (days from the sowing date to the first day of observed seed germination) of seeds in 14 ornamental plant genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light. Within the same genotype, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test. For gerbera, MR = 'Majorette Red', MP = 'Maxi Pink', MW = 'Maxi White', and MDP = 'Midi Dark Purple'. For genotypes that have no error bars for some treatments, the onset time (d) was the same for all three time replicates and there is no SE to present.

2.3.4 Germination time spread

Light treatments affected germination time spread in petunia only, although the effect varied with its different cultivars (Fig. 2.10). For petunia 'Red Velour', seed germination had a shorter time spread under G than UVB by around 6 d, and all the light quality treatments showed no difference relative to D. However, for the other two petunia cultivars, 'Coral Reef' and 'White', there were no differences among all the light treatments. For the above genotype affected by light, all the light quality treatments showed a similar effect as D on germination time spread. Among the light quality treatments (not including D), germination time spread was shorter under G.

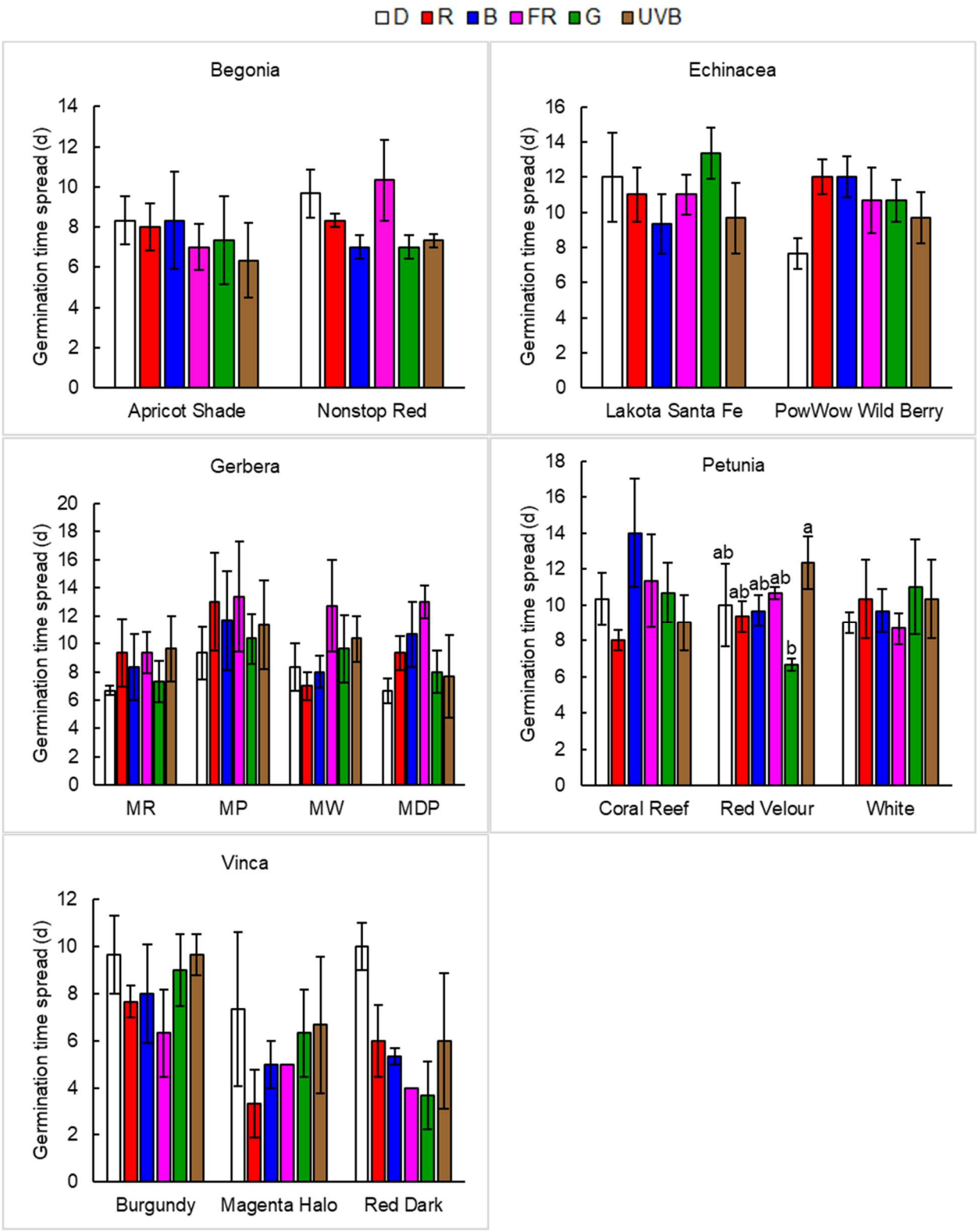

Figure 2. 10. Germination time spread (time from the first day of observed seed germination to the day germination percentage became stable, i.e., the first of the five days) of seeds in 14

ornamental plant genotypes under different light treatments. Data are mean ± standard error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light. Within the same genotype, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test. For gerbera, MR = 'Majorette Red', MP = 'Maxi Pink', MW = 'Maxi White', and MDP = 'Midi Dark Purple'.

2.3.5 Germination speed

Light treatments affected germination speed for nearly all the tested species except petunia, but the effect of the light treatments varied with different cultivars within the same species (Fig. 2.11). In begonia 'Apricot Shade', compared with D, germination speed was higher under R, G and UVB, not different under B, and lower under FR, but in 'Nonstop Red', all the light quality treatments showed no difference from D, despite higher germination speed under R, G, and UVB than FR. In echinacea 'Lakota Santa Fe', germination speed was higher under D, R, B, G and UVB than FR, but in 'PowWow Wild Berry', there was no difference among the treatments. In gerbera 'Maxi White', D led to higher germination speed than FR, and R, B, G and UVB showed no difference relative to FR and D. In gerbera 'Midi Dark Purple', R and UVB led to higher final germination speed than B and FR, D and G showed no difference relative to R and UVB and to B, and B showed no difference relative to FR. For both gerbera 'Majorette Red' and 'Maxi Pink', there were no differences among the treatments on germination speed. In vinca 'Burgundy', D led to higher germination speed than R, G, and UVB, and B and FR showed no difference relative to other treatments, but in 'Magenta Halo' and 'Red Dark', there were no differences among the treatments. For the above genotypes affected by light, in most cases all the light quality treatments except for FR showed a similar effect as D on germination speed. Among the light quality treatments (not including D), germination speed generally was lowest under FR.

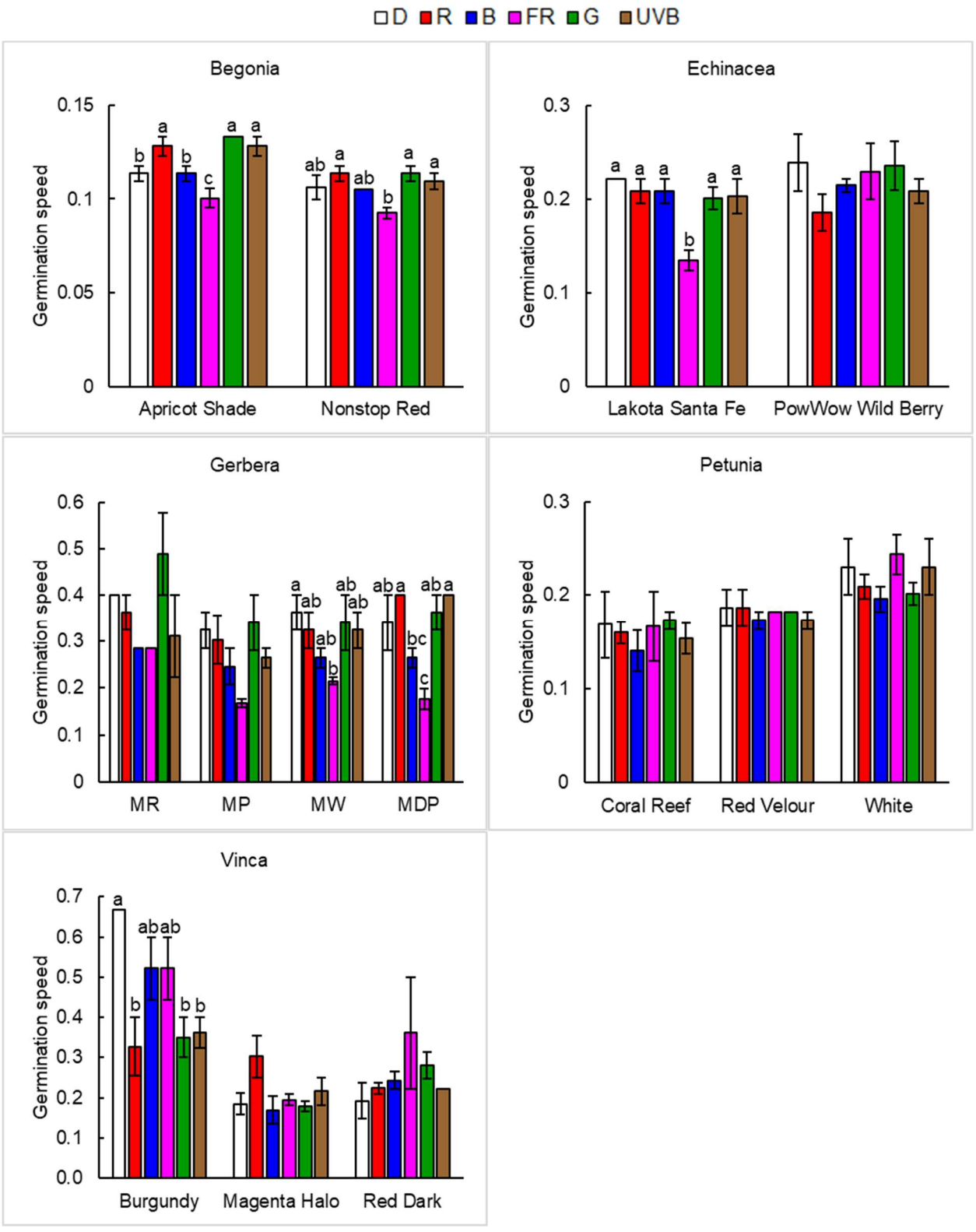

Figure 2. 11. Germination speed (calculated as the inverse of median seed germination; 1/t50) of seeds in 14 ornamental plant genotypes under different light treatments. Data are mean ± standard

error (SE) (n = 3). D = dark, R = red, B = blue, FR = far-red, G = green, and UVB = UVB light. Within the same genotype, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test. For gerbera, MR = 'Majorette Red', MP = 'Maxi Pink', MW = 'Maxi White', and MDP = 'Midi Dark Purple'. For genotypes that have no error bars for some treatments, the t50 (d) and as a result, speed, were the same for all three time replicates and there is no SE to present.

2.4 Discussion

For the tested species (even for begonia and gerbera as light-requiring species for germination), the narrow-band monochromatic light treatments generally did not promote seed germination compared with darkness, based on both cumulative germination variation and four germination parameters. In particular, B light was similar to darkness on all the germination parameters and all the tested species. Similar results were observed with soybean (*Glycine max*) (Hawley, 2013), chickpea (*Cicer arietinum*) (Vasilean et al., 2018), and 18 vegetable genotypes (Kong and Zheng, 2018) where lighting treatments did not promote seed germination compared to darkness. From a commercial standpoint, this is good knowledge for growers looking to save on lighting costs as these genotypes germinated well in the dark. The indifferent germination response to light treatments relative to darkness may be due to a cold storage (around 4°C) of the seeds before seeding. Low temperatures can reduce the light requirement for seed germination by breaking seed dormancy in many species (Hartmann et al., 2002b; Pons, 2014). A threshold level of P_{fr}, physiologically active phytochrome, is required for seed dormancy breaking, although phytochrome may be pre-existent in the seeds as low-level P_{fr}, which originates from before ripening of the seed (Pons, 2014). Natural light can increase the level of P_{fr} in seeds to reach the

threshold level, and low temperature can lower the threshold level, and reduce the rate of reversing P_{fr} in dry seeds to physiologically inactive phytochrome, P_r, under darkness (Pons, 2014). Consequently, seed germination in darkness increased after a low-temperature exposure in many plant species (Pons, 2014). Therefore, the unintentional low-temperature treatment on the seed germination response to monochromatic light needs further study on the plant genotypes tested in the present study.

In many cases, FR vs. darkness negatively affected seed germination (especially for begonia, echinacea, and gerbera), which was demonstrated by lower final germination percentage, longer germination onset time, and slower germination speed in some plant genotypes. A FR-rich light environment is indicative of a shade signal, and the inhibitory seed germination could be considered a shade-avoidance response in plants, despite an argument on this opinion, since the environmental conditions that a seed germinates in are what the new seedling experiences after germination (Goggin and Steadman, 2012). FR light has also inhibited germination of some vegetables such as tomato (*Solanum lycopersicum*), lettuce (*Lactuca sativa*), pepper (*Capsicum annuum*), and kale (*Brassica oleracea*) compared to darkness (Hawley, 2013). The light response of seed germination in the present study can be considered a long duration exposure response, rather than a short duration one, since the light exposure lasted for several days, not for less than one hour (Pons, 2014). For this response type, FR light has been shown to be the most effective for inhibiting germination (Demotes-Mainard et al., 2016; Pons, 2014).

Among the tested narrow-band monochromatic lights, generally R, G, and UVB were the most promotive, and FR was the most inhibitory for seed germination in the tested species except for vinca, a light-inhibited species (Carta et al., 2017). Phytochrome is the main photoreceptor involved in the light responses of seeds, and a P_{fr}/P_r ratio higher than the threshold level can promote gibberellic acid and repress abscisic acid biosynthesis, allowing for the induction of seed germination (Demotes-Mainard et al., 2016; Shinomura et al., 1996). For phytochrome, absorption of R light increases the ratio of P_{fr}/P_r due to photoconversion to P_{fr}; however, absorption of FR light reduces the ratio of P_{fr}/P_r due to photoconversion to P_r (Demotes-Mainard et al., 2016). This may explain the seed germination response difference between R and FR light in the present study. The effectiveness of G light on seed germination might be related to the presence of a G light photoreceptor, which was speculated to reduce and remove inhibition of dormancy release in seeds of annual ryegrass (*Lolium rigidum*) under narrow-band lights with wavelengths ranging between 510 and 550 nm (Goggin and Steadman, 2012). Despite the effectiveness on seed germination, UVB had a lower intensity (0.5 vs. 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$) than other light treatments in the present study, since it is currently believed that plants are able to perceive low-level (0.1–1 $\mu mol \cdot m^{-2} \cdot s^{-1}$) UVB as a signal, without deleterious effects (Dotto and Casati, 2017). UVB light has also been reported to cause the seed coating to breakdown allowing germination to occur (Noble, 2002). Also, phytochrome, as the main plant photoreceptor involved in seed germination, likely mediates the germination responses to a broad spectrum of light, including UVB and G light, as it can absorb these wavelengths in addition to R or FR (Demotes-Mainard et al., 2016; Shinomura et al., 1996).

Despite the above general trend under the tested narrow-band monochromatic lights, it is difficult to find the universally optimal light conditions for ornamental seed germination, since the germination response to light varied with plant genotypes and germination parameters, partly supporting our hypothesis. For example, under R, G, and UVB compared to darkness, germination speed was promoted for begonia 'Apricot Shade', a light-requiring genotype, but was inhibited for vinca 'Burgundy', a light-inhibited genotype. In addition to germination speed, another three parameters describe the germination response to light treatments from different angles. Final germination percentage indicates the germination capacity; onset time reflects whether germination starts early or late; time spread, indirectly via germination speed, indicates the germination synchrony (Hartmann et al., 2002b; Ranal and De Santana, 2006). However, the contrasting effects of R, G, and UVB compared to darkness on the two types of plant genotypes were not observed in the above three parameters, but only in germination speed. Possibly, to evaluate the species' sensitivity in germination response to light, germination speed appears to be the most useful parameter, and R, G, and UVB were the most promotive monochromatic light qualities.

Natural sunlight has a broad spectrum (Smith et al., 2017), and seed germination has been suggested to respond to more than only one wavelength of light, since in addition to phytochrome, other photoreceptors are also involved in the seed germination process (Goggin and Steadman, 2012). Although, R, G, and UVB were found to be the most promotive narrow-band monochromatic light qualities for light-requiring species in the present study (e.g., begonia or gerbera), the optimal light spectral combination is still unclear for seed germination. Possibly,

a combination of R, G, and UVB could be choice for these species. However, the optimal proportion for each component in the combination of R, G, and UVB still needs further research.

In summary, for the tested species, compared with darkness, the seed germination response was generally indifferent to narrow-band monochromatic light except for FR light. In many cases, FR negatively affected seed germination, which was demonstrated by lower final germination percentage, delayed germination onset time, and decreased germination speed in some plant genotypes. Germination speed was promoted for begonia 'Apricot Shade', a light-requiring genotype and inhibited for vinca 'Burgundy', a light-inhibited genotype under R, G, and UVB compared to darkness, suggesting that germination speed may be the most sensitive in response to light among the four germination parameters. In terms of evaluation on all the four germination parameters and the temporal variation of cumulative germination, generally R, G, or UVB appeared to be the most promotive among the tested narrow-band monochromatic lights, followed by B, and FR was the most inhibitory for seed germination in the tested ornamental species. Germinating in darkness for the first few days, depending on species' onset time, would be recommended. If using light, a combination of R, G, and UVB would be recommended as the optimal light conditions for seed germination in these species, although the optimal proportion for each component of the light spectral combination needs further research.

CHAPTER THREE

GROWTH AND MORPHOLOGICAL RESPONSES OF GERBERA SEEDLINGS TO NARROW-BAND LIGHTS WITH DIFFERENT LIGHT SPECTRAL COMBINATIONS AS SOLE-SOURCE LIGHTING IN A CONTROLLED ENVIRONMENT

Abstract

Narrow-band light, such as light-emitting diodes (LEDs), has been increasingly used as sole-source lighting to produce seedlings in controlled environments year-round. However, the optimal light recipe for production of high-quality gerbera seedlings is unclear. To investigate seedling responses to different light recipes, four gerbera (*Gerbera jamesonii*) cultivars, 'Midi Dark Purple', 'Majorette Red Dark Eye', 'Maxi Pink', and 'Maxi White', were grown under six light treatments: (1) FL, cool white fluorescent light, as control; (2) RB, LED combination of 85% red and 15% blue; (3) RB + UVB, RB mixed with 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet B sourced from narrow-band fluorescent light; (4) RB + UVA, LED combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; (5) RB + G, LED combination of 60% red, 15% blue, and 25% green; (6) RB + FR, LED combination of RB and 17.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far-red. All light treatments had a photosynthetic photon flux density (PPFD) of 165 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and a 16-h photoperiod. For the tested four cultivars under RB, compared with FL, plant growth and morphology did not change except for a wider canopy of 'Majorette Red Dark Eye'. Compared with RB, tri-chromatic light treatments (i.e., RB + UVB, RB + UVA, RB + G or RB + FR) showed similar effects on seedling growth and morphology except for a thicker stem of 'Maxi Pink' under RB + FR. However, quality index, an integrated evaluation of seedling quality, was not different among all the light treatments for all the tested cultivars. In terms of seedling quality evaluation, RB-LED

can potentially replace FL, and the tri-chromatic lights tested in this study appear to be unnecessary for controlled-environment production of gerbera seedlings.

3.1 Introduction

Commercial seedlings have been increasingly produced in controlled-environment facilities using electrical light for sole-source lighting (SSL) (Gibson et al., 2020; Lopez and Runkle, 2017). This indoor environment allows for consistent year-round production of seedlings even when outdoor climate conditions (i.e., temperature and light) are unfavourable (Craver et al., 2018; Gibson et al., 2020; Gómez et al., 2019). Cool white fluorescent light (FL) has traditionally been used as SSL in controlled-environment seedling production (Gerovac et al., 2016; Gómez et al., 2019; Kubota et al., 2012). Growers are increasingly using light-emitting diodes (LEDs) as SSL due to their many advantages over traditional light sources such as adjustable light spectral quality which allows growers to optimize light recipes based on production goals (Morrow, 2008; Mitchell and Stutte, 2017).

LED lighting with a red (R) and blue (B) light combination (i.e., RB-LED light) has been commonly used for horticultural crop production (Hogewoning et al., 2010; Kong and Zheng, 2019; Kong et al., 2018b; Naznin et al., 2016; Randall and Lopez, 2015; Ying et al., 2020a), since R and B are absorbed most efficiently by plants (Huché-Thélier et al., 2016). Although the ideal R:B ratio in commercial RB-LED light can vary with plant species, a mixture of 85% R and 15% B has been commonly and successfully used for a wide range of plant species, including gerbera (Llewellyn et al., 2019; Randall and Lopez, 2014). RB-LED, compared to FL, enlarged leaf area of chili pepper (*Capsicum annuum*), hybrid moth orchid (*Phaelenopsis* × *Doritis*), kale

(*Brassica napus*) and arugula (*Eruca sativa* L.), and increased fresh weight (FW) and dry weight (DW) of chili pepper, lettuce (*Lactuca sativa* L.), vanilla (*Vanilla planifolia*) and hybrid moth orchid (Bello-Bello et al., 2016; Gangadhar et al., 2012; Johkan et al., 2010; Lee et al., 2016; Shin et al., 2008; Ying et al., 2020b). However, in other studies, RB-LED relative to FL has not shown to be better for seedling growth in cucumber (*Cucmis sativus*), tomato (*Solanum lycopersicum*), impatiens (*Impatiens walleriana*), salvia (*Salvia splendens*) and petunia (*Petunia × hybrida)* (Hernández et al., 2016; Wollaeger and Runkle, 2014). It appears that effects of RB-LED relative to FL on plant growth vary with plant species. However, there is a lack of related study on gerbera seedlings.

Plants sense and respond to a broad range of light spectra from ultraviolet (UV) to far-red (FR), although R and B lights are the most important wavelengths for plant biomass accumulation by affecting photosynthesis and photomorphogenesis (McCree, 1972). Some promotion effects on seedling growth have been observed under tri-chromatic light. For example, including FR with RB-LED increased aboveground FW, DW and leaf area of lettuce (Lee et al., 2016), and total leaf area and shoot DW of geranium (*Pelargonium × hortorum*) and snapdragon (*Antirrhinum majus*) seedlings (Park and Runkle, 2017), as well as cotyledon area of some microgreens (Ying et al., 2020b). Also, after including FR with RB-LED, pansy (*Viola × wittrockiana*) transplants flowered 7 days earlier (Craver et al., 2018), and the promoted flowering of snapdragon by RB + FR was apparently saturated by ≥16 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR (Park and Runkle, 2017). Besides FR, combining G (≈22–25% of total PPFD) with RB-LED generally increased shoot biomass, or leaf area of tomato, petunia, impatiens, and salvia (Wollaeger and Runkle, 2014), and promoted leaf expansion and increased shoot FW of lettuce and kale (Meng

et al., 2019). However, it is unknown for gerbera seedlings under LED as SSL, whether RB + FR or RB + G relative to RB has also a similar promotion effect as the above species.

Solar radiation also comprises a small amount of UVA (320–400 nm) and UVB (280–320 nm) (Huché-Thélier et al., 2016; Neugart and Schreiner, 2018). The average UVA level in sunlight is around 7% of photosynthetically active radiation (PAR) (Mah, 2019), and in a natural environment, plants are exposed to at least 10 times as much UVA than UVB (normally below 1 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in sunlight) (Verdaguer et al., 2017). However, there is a lack of knowledge on the effects of including UVA or UVB with RB-LED on seedling growth and development. Previous studies have indicated that excluding either UVA or UVB from solar light compromised plant compactness due to losing the inhibitory effect of UVA or UVB on elongation growth, and reduced stress tolerance due to decreased biosynthesis of plant secondary metabolites after filtering out UVA or UVB (Kataria and Guruprasad, 2012a, 2012b, 2015; Lazzeri et al., 2012). Possibly, including a low-level (similar to the percentage of sunlight) of UVA (e.g., ≈7% of total PPFD) or UVB (e.g., ≈0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$) with RB-LED may improve seedling quality (e.g., compact plants or stress tolerance) in controlled-environment production using SSL.

Gerbera (*Gerbera jamesonii* Bolus ex. Hooker f.) is one of the most commercially important ornamental plants globally, both as a cut flower and potted plant, in a wide range of flower colours (Andreasen et al., 2014; Pawłowska et al., 2018; Singh et al., 2014). In 2019, potted gerbera plants accounted for approximately 3.4 million plants sold in Canada (Statistics Canada, 2020b). An optimal daily light integral (DLI) of 10–12 $mol \cdot m^{-2} \cdot d^{-1}$ (i.e., 175 to 210 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with a 16-h photoperiod) is recommended for production of high-quality

ornamental seedlings inside the greenhouse (Randall and Lopez, 2014). Plants grown in growth chambers using electrical light as SSL have shown to be more compact and of better quality than those in a greenhouse (Randall and Lopez, 2015). It is possible that a DLI closer to the lower limit of the optimal level (e.g., 9.5 $mol \cdot m^{-2} \cdot d^{-1}$; i.e., ≈165 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with a 16-h photoperiod) is enough for controlled-environment production of gerbera seedlings using SSL.

Under SSL at a PPFD of 165 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with a photoperiod of 16-h, it was hypothesized that for gerbera seedlings (1) RB-LED light, compared to FL, does not affect plant quality negatively at least for some cultivars; (2) combining FR or G with RB-LED light can promote plant growth, and including FR can induce earlier flower initiation after transplanting; and (3) combining UVA or UVB with RB-LED light can improve some quality traits. The objective of the present study was to investigate the effects of various light recipes on the growth and morphology of gerbera seedlings in a controlled environment using SSL by testing the above hypotheses.

3.2 Materials and Methods

3.2.1 Plant materials and growing conditions

The experiment was conducted on four gerbera cultivars, including *G. jamesonii* 'Midi Dark Purple', 'Majorette Red Dark Eye' (hereafter 'Majorette Red'), 'Maxi Pink', and 'Maxi White', with two temporal replications in a 29 m^2 walk-in growth chamber at the University of Guelph, Guelph, ON, Canada. 'Majorette Red' seeds were from Sakata Seed America Inc. (Morgan Hill, CA, USA) and the other three cultivars were from Florist Holland (De Kwakel, The Netherlands). Seeds were sown uncovered (one seed per cell) in 105-cell (7 × 15 cell) trays

containing Sunshine Mix #5 substrate (Sun Gro Horticulture, Agawam, MA, USA). For each replication, there were two sown trays placed together under each light treatment. Each tray contained two cultivars, and each cultivar occupied three rows of cells in one tray (i.e., 45 cells total). For the two trays under each light treatment, the seeds sown in the outer two rows were used as guards. After seeding, the trays were sub-irrigated with tap water (pH = 7.9, EC ≈0.9 $dS \cdot m^{-1}$) until more than 50% of seeds in each tray had germinated. Then, the trays were subsequently sub-irrigated with a nutrient solution described in Kong et al. (2019a). The target air temperature (˚C) and relative humidity (RH; %) were set at 22˚C and 65%, respectively, and controlled by a computer system (Argus Controls Systems Ltd., Surrey, BC, Canada). Based on the data recorded every 5 minutes by data loggers (Onset HOBO U12-013; Onset Computer Corporation, Bourne, MA, USA), the actual average values of air temperature and RH during the light treatment period were 22.3 ± 0.7 ˚C and 67.4 ± 2.1 %, respectively.

3.2.2 Experimental design and treatments

The experiment used a randomized complete block design (RCBD) with one factor (light treatment) and two blocks (or time replicates) for each cultivar. The six light treatments included: (1) FL, cool white fluorescent light as control; (2) RB, combination of 85% red and 15% blue; (3) RB + UVB, combination of RB and 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of UVB; (4) RB + UVA, combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of UVA; (5) RB + G, combination of 60% red + 15% blue + 25% green; and (6) RB + FR, combination of RB and 17.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far-red. For each light treatment, the light intensities of different wavelength components and light spectral distribution are presented in Table 3.1 and Fig. 3.1, respectively. The six treatments were randomly allocated to six compartments inside the chamber, which were separated from each

other by opaque white curtains to prevent neighbouring light effects. The light treatments were replicated over time by changing the positions of light treatments within the six compartments.

Table 3. 1. Light intensity of different wavelength components and total photosynthetic photon flux density (PPFD) of the different light treatments.

Light treatments	Light intensity ($\mu mol \cdot m^{-2} \cdot s^{-1}$)						Total PPFD[y] ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
	R (600–700 nm)	B (400–500 nm)	UVB (280–320 nm)	UVA (320–400 nm)	G (500–600 nm)	FR (700–800 nm)	
FL	41.5 ± 2.2[z]	31.0 ± 2.3	0.5 ± 0.01	2.2 ± 0.1	90.5 ± 0.2	4.3 ± 0.02	162.5 ± 0.3
RB	141.5 ± 0.5	25.1 ± 0.2	–	–	–	–	167.1 ± 0.6
RB + UVB	139.2 ± 0.3	24.7 ± 0.02	0.5 ± 0.1	–	–	–	164.3 ± 0.3
RB + UVA	141.6 ± 0.1	25.1 ± 0.1	–	9.6 ± 0.3	–	–	167.2 ± 0.05
RB + G	98.9 ± 0.5	24.2 ± 0.2	–	–	41.5 ± 0.5	–	164.3 ± 1.2
RB + FR	140.6 ± 1.3	25.1 ± 0.4	–	–	–	17.3 ± 0.5	166.2 ± 1.6

[z]Values were averaged over a 16-point grid and a centre point under the light fixtures measured before each replicate then subsequently averaged to get one value for each treatment. Data are presented as mean ± SE (n = 2).

[y]photosynthetic photon flux density; 400–700 nm. For the six light treatments, FL = cool white fluorescent light; RB = 85% red and 15% blue LED; RB + UVB = RB-LED and 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet B sourced from narrow-band fluorescent light; RB + UVA = LED combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; RB + G = LED combination of 60% red + 15% blue + 25% green; RB + FR = LED combination of RB and 17.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far-red.

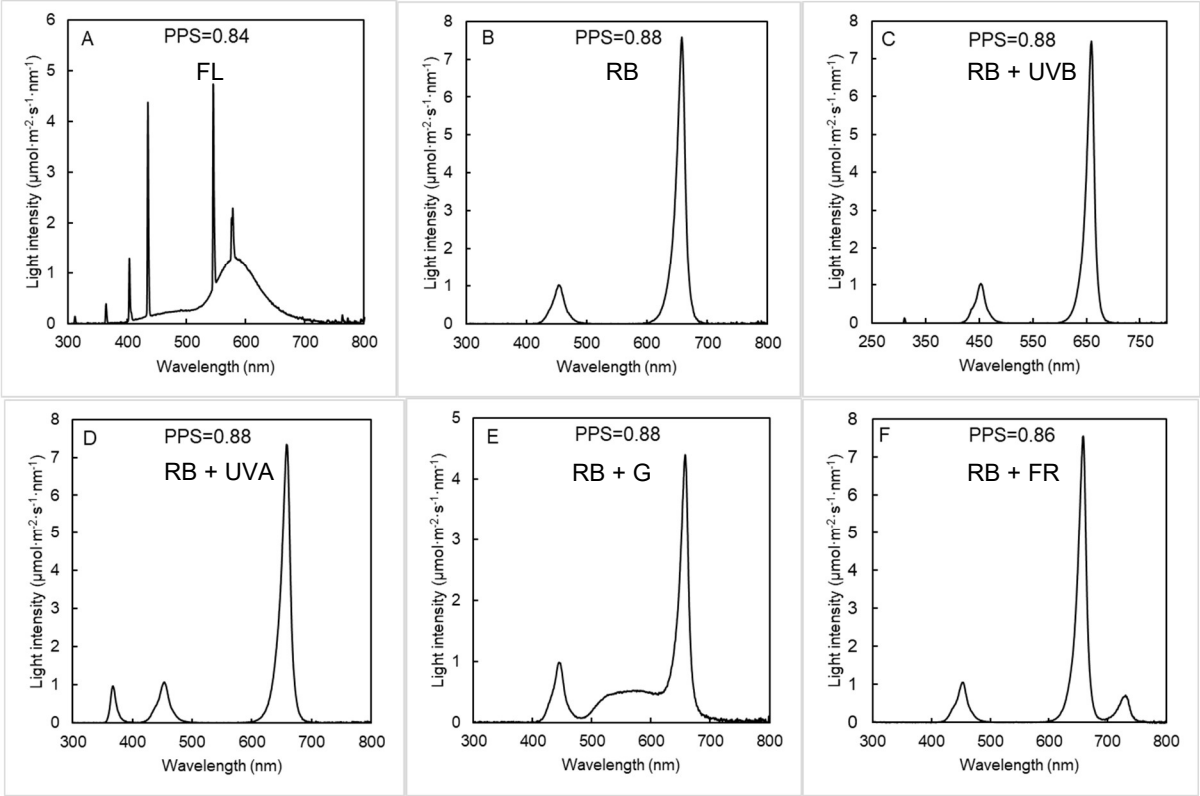

Figure 3. 1. The spectral distributions of six light treatments, A) FL, B) RB, C) RB + UVB, D) RB + UVA, E) RB + G, and F) RB + FR. For the six light treatments, FL = cool white fluorescent light; RB = 85% red and 15% blue LED; RB + UVB = RB-LED and 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet B sourced from narrow-band fluorescent light; RB + UVA = LED combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; RB + G = LED combination of 60% red + 15% blue + 25% green; RB + FR = LED combination of RB and 17.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far-red. The average PPFD of each treatment was ≈165 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 $h \cdot d^{-1}$, providing a daily light integral (DLI) of ≈9.5 $mol \cdot m^{-2} \cdot d^{-1}$. PPS = phytochrome photostationary state, which is the estimated phytochrome photoequilibrium according to the method by Sager et al. (1988).

The FL light was provided by a cool white fluorescent lamp (F96T12/CW/VHO; Osram Sylvania Ltd., Markham, ON, Canada). The RB, RB + G and RB + FR lights were provided by LED lighting system (LX601C; Heliospectra AB, Gothenburg, Sweden). The RB + UVB and

RB + UVA lights were provided by LX601C LED lamps in combination with a narrow-band UVB light (PL-L-36W; Philips, Solarc Systems Inc., Minesing, ON, Canada) and multiple UVA LED bulbs (HZT-1101B-1130B; Shenzhen Huazhitai Technology Co., Ltd., Shenzhen, China), respectively.

All six treatments were targeted at a PPFD of ≈165 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on a 16-h photoperiod (9:00 AM–1:00 AM) to achieve a DLI of ≈9.5 $mol \cdot m^{-2} \cdot d^{-1}$. The intensities of R, B, G and FR lights from the LED lighting system were set to their target intensities using a computer program, System Assistant 2.0.1 (Heliospectra AB, Gothenburg, Sweden). The target intensities of UVB, UVA, and FL lights were achieved by adjusting layers of neutral-density mesh, bulb numbers, and lamp height, respectively.

Light spectra and intensities were set up and verified using a USB2000+UV-vis spectrometer (Ocean Optics, Inc., Dunedin, FL, USA). The height of the fixtures from the top of the trays was ≈150 cm for the cool white fluorescent lamps, ≈70 cm for the LX601C LED lamps, and ≈65 cm for the UVB lamp and UVA bulbs fixtures.

3.2.3 Growth and morphology measurements

Seed germination was defined as visible radicle emergence, and cumulative germination percentages were calculated daily for each cultivar under each light treatment until ≈90% seed germination. For each replicate and each cultivar, once at least 50% of the seedlings under each light treatment had four fully expanded true leaves (≈5 weeks after sowing), the seedlings of the cultivar from all the light treatments were harvested for morphological observations and biomass determination. Ten plants of each cultivar from each light treatment and each time replicate were

randomly selected for the harvest. For each sampled plant, before harvesting, canopy height and width were measured with a ruler, and the fully expanded true leaves of each sampled plant were counted. Then, chlorophyll content index (CCI) for each fully expanded true leaf was measured using a CCM-200 Chlorophyll Concentration Meter (Opti-Sciences Inc., Hudson, NH, USA). After the pre-harvesting measurements, the plants were cut at the base above the substrate, and the aerial parts were separated into stems and leaves (with petioles). Stem length and diameter were determined using a ruler and digital caliper, respectively. Total leaf area and longest petiole length were determined from scanned images following the method by Ying et al. (2020c) in replicate one. In replicate two, the total leaf area was measured using a Li-Cor 3100C leaf area meter (Li-Cor Inc., Lincoln, NE, USA) and the longest petioles were measured with a ruler. For both replicates, each method was calibrated, respectively, before leaf area measurements. The separated aerial plant parts were then put in paper bags and dried at 90˚C till they reached a constant weight to determine dry weight (DW). Roots were then washed to remove substrate and dried at the same conditions as aerial plant parts to determine DW. Leaf mass unit area (LMA), leaf/total DW, stem/total DW, root/shoot dry mass ratio (R:S), and quality index (QI) were calculated using equations (1)–(5), respectively.

(1) LMA ($mg \cdot cm^{-2}$) = true leaves DW (mg) / total true leaf area (cm^2)

(2) Leaf/total DW (%) = leaf DW (g) / total DW (g) × 100%

(3) Stem/total DW (%) = stem DW (g) / total DW (g) × 100%

(4) R:S ratio = root DW (g) / aerial (i.e., shoot) DW (g)

(5) QI = total DW (g) × {R:S ratio + [stem length (cm) / stem diameter (mm)]}(Currey et al., 2013)

After harvest, six remaining plants of each replicate with similar size from each cultivar and each light treatment were randomly selected to test flowering response. These plants were transplanted into 8.5 × 8.5 × 10 cm pots containing Sunshine Mix #1 substrate (Sun Gro Horticulture, Agawam, MA, USA). The transplants were then placed in a chamber using FL as SSL under the same conditions as mentioned above to investigate the date of appearance of the first visible flower bud (>1 cm diameter) for each plant.

After transplanting, the remaining seedlings were placed in a dark room (23.3 ± 1.0 ˚C air temperature, and 41.0 ± 2.8 % RH) for one week. Then, 5–6 plants were randomly sampled to measure canopy height and CCI in order to investigate the seedling quality changes under the mimicked storage and transport conditions.

3.2.4 Statistical analysis

Data were subjected to analysis of variance using SAS statistical software (University Edition; SAS Institute, Cary, NC, USA) and were presented as means ± SE (standard error). For each cultivar, separations of means for different light treatments were performed using Tukey's HSD test at a significance level of 0.05. Residuals were tested for normality using the Shapiro-Wilk test and the data was transformed using a lognormal distribution to achieve a normal distribution before performing the analysis if necessary.

3.3 Results

3.3.1 Seed germination

Seed germination did not differ among all the light treatments for each cultivar. The mean values of cumulative germination percentage were 94.9 ± 1.1% for ‘Majorette Red’, 96.0 ± 1.1% for ‘Maxi Pink’, 96.3 ± 1.0% for ‘Maxi White’ and 97.8 ± 0.8% for ‘Midi Dark Purple’.

3.3.2 Canopy morphology

The canopy height of ‘Majorette Red’ was affected by light treatments (Fig. 3.2A). For ‘Majorette Red’, although canopy height was not different under RB compared to FL or under RB compared to the four tri-chromatic light treatments (i.e., RB + UVB/UVA/G/FR), canopy was taller under RB + FR compared to RB + UVA. The canopy width of ‘Majorette Red’ was also affected by light treatments (Fig. 3.2B). For ‘Majorette Red’, canopy width was larger under RB compared to FL, and there was no difference in canopy width under each of the four tri-chromatic light treatments compared to RB, but seedlings under RB + UVB had larger canopy width compared to RB + UVA and RB + G. The canopy height and width were not affected for the other three cultivars.

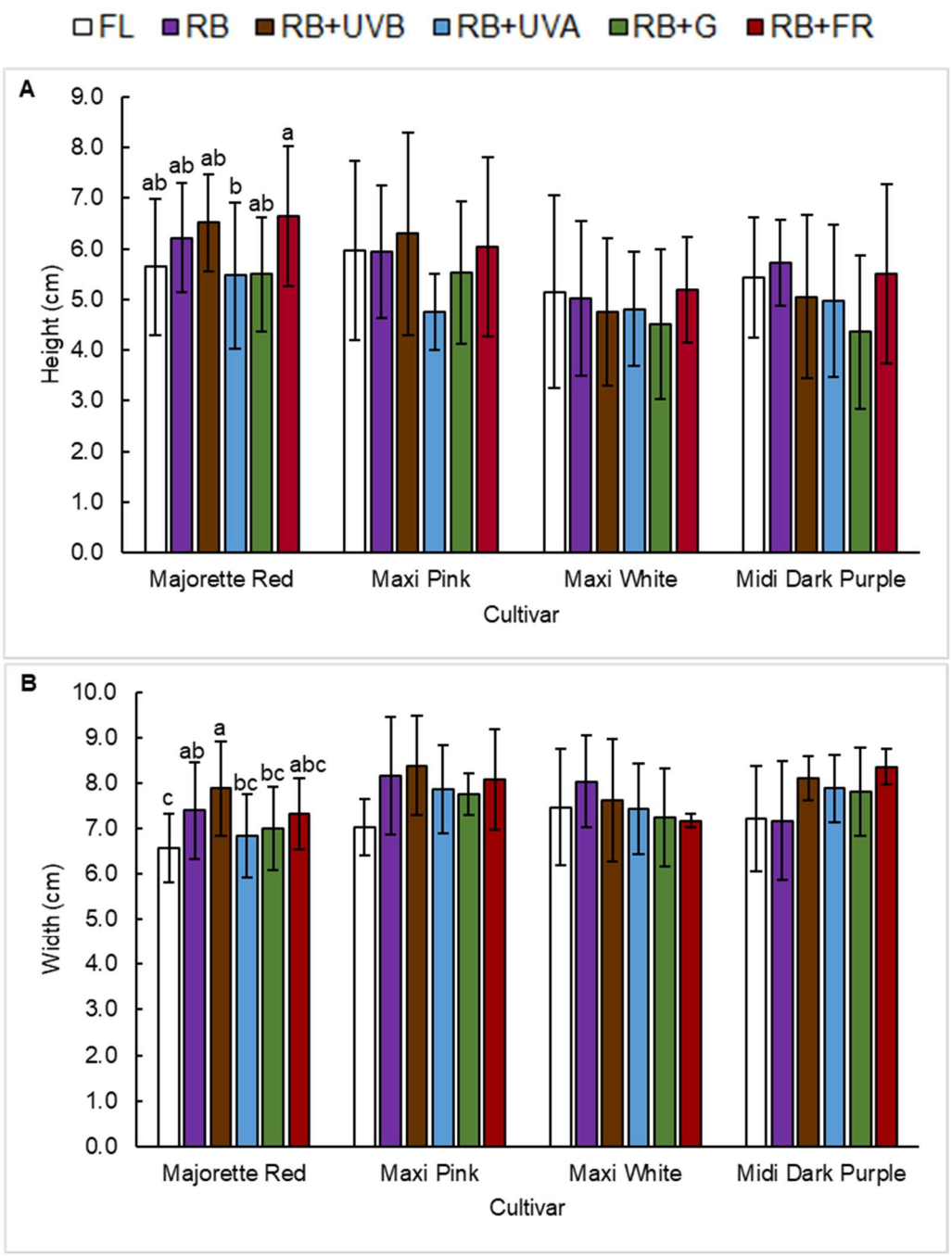

Figure 3. 2. Plant canopy morphology under different light treatments of four gerbera cultivars. Data are mean ± standard error (SE) (n = 2). For the six light treatments, FL = cool white fluorescent light; RB = 85% red and 15% blue LED; RB + UVB = RB-LED and 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet B sourced from narrow-band fluorescent light; RB + UVA = LED combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; RB + G = LED combination of 60% red + 15% blue +

25% green; RB + FR = LED combination of RB and 17.3 µmol·m^{-2}·s^{-1} of far-red. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

3.3.3 Stem morphology

Light treatments did not affect stem diameter for nearly all cultivars, except for 'Maxi Pink' (Fig. 3.3), where stem was thicker under RB + FR compared to RB. Light treatments did not affect stem length in all cultivars and the mean stem length was 0.4 cm for all four cultivars.

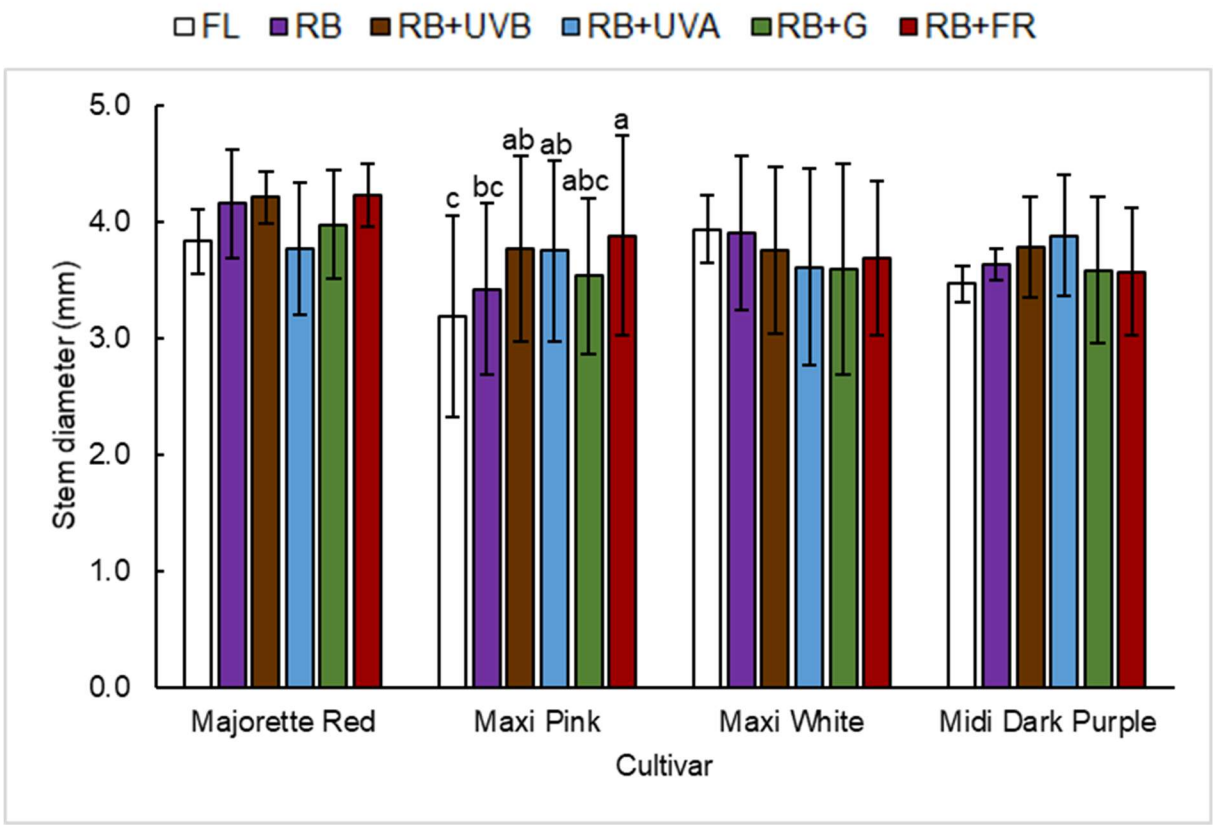

Figure 3. 3. Stem diameter (mm) under different light treatments of four gerbera cultivars. Data are mean ± standard error (SE) (n = 2). For the six light treatments, FL = cool white fluorescent light; RB = 85% red and 15% blue LED; RB + UVB = RB-LED and 0.5 µmol·m^{-2}·s^{-1} of ultraviolet B sourced from narrow-band fluorescent light; RB + UVA = LED combination of RB and 9.6

$\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; RB + G = LED combination of 60% red + 15% blue + 25% green; RB + FR = LED combination of RB and 17.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far-red. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

3.3.4 Leaf morphology

Light treatments did not affect total leaf area for nearly all cultivars, except 'Majorette Red' (Fig. 3.4). For 'Majorette Red', although total leaf area was not different under RB compared to FL, or under RB compared to the four tri-chromatic light treatments, total leaf area was greater under RB + UVB compared to RB + UVA. Light treatments did not affect CCI, the longest petiole length, or LMA in all cultivars. For 'Majorette Red', 'Maxi Pink', 'Maxi White' and 'Midi Dark Purple', the mean CCI values were 33.6 ± 1.0, 37.1 ± 1.3, 27.5 ± 0.7 and 37.7 ± 0.8, respectively, and the mean values of the longest petiole length were 2.3 ± 0.1, 2.6 ± 0.1, 1.7 ± 0.1 and 2.2 ± 0.1 cm, respectively, and the mean LMA values were 3.3 ± 0.1, 3.5 ± 0.1, 3.1 ± 0.1 and 3.6 ± 0.1 $mg \cdot cm^{-2}$, respectively.

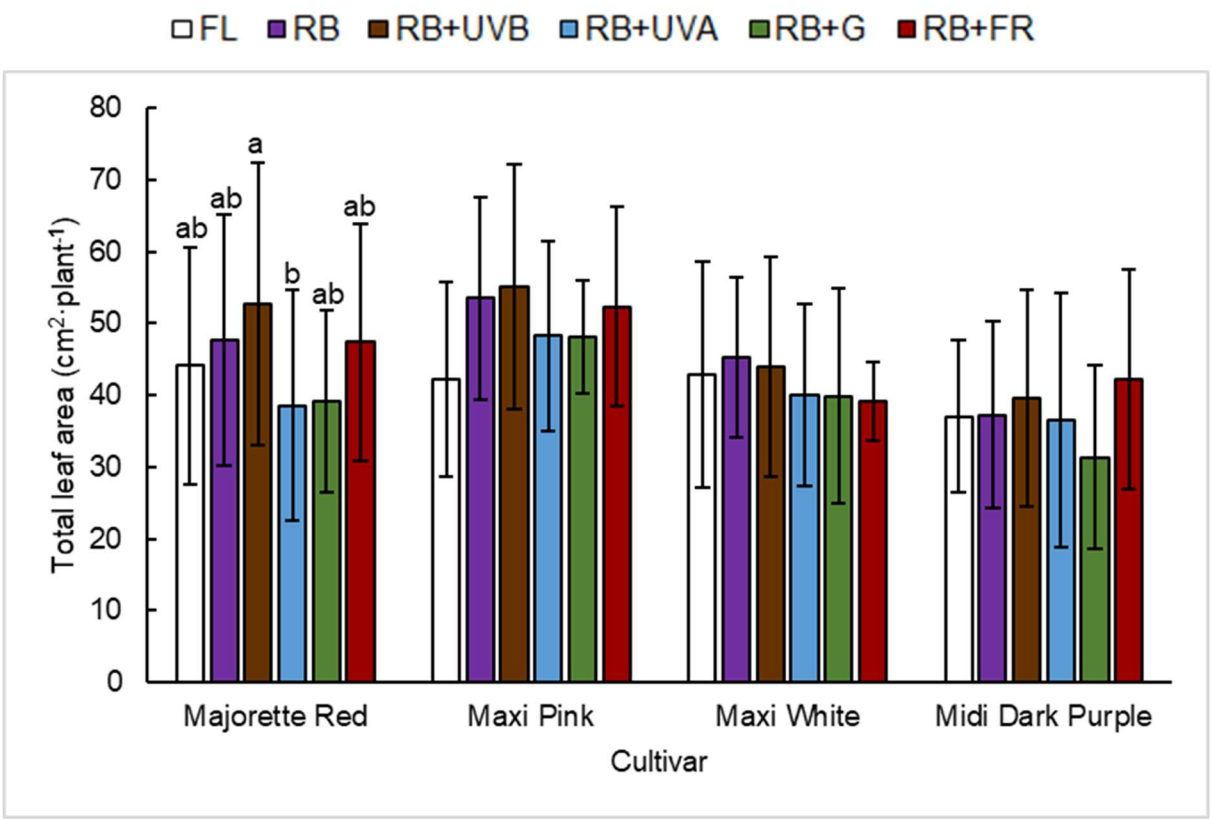

Figure 3. 4. Leaf area ($cm^2 \cdot plant^{-1}$) under different light treatments of four gerbera cultivars. Data are mean ± standard error (SE) (n = 2). For the six light treatments, FL = cool white fluorescent light; RB = 85% red and 15% blue LED; RB + UVB = RB-LED and 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet B sourced from narrow-band fluorescent light; RB + UVA = LED combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; RB + G = LED combination of 60% red + 15% blue + 25% green; RB + FR = LED combination of RB and 17.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far-red. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

3.3.5 Biomass accumulation and allocation

In all four tested cultivars, biomass accumulation and allocation were not affected by light treatments. For 'Majorette Red', 'Maxi Pink', 'Maxi White' and 'Midi Dark Purple', the mean values of total DW were 0.21 ± 0.01, 0.24 ± 0.01, 0.18 ± 0.003 and 0.17 ± 0.01 g,

respectively, and the mean percentages of leaf/total DW were 71.8 ± 0.4%, 74.6 ± 0.5%, 73.1 ± 0.7% and 74.4 ± 0.6%, respectively, and the mean percentages of stem/total DW were 9.2 ± 0.3%, 9.6 ± 0.3%, 11.0 ± 0.3% and 9.1 ± 0.5%, respectively, and the mean R:S ratio values were 0.23 ± 0.01, 0.19 ± 0.01, 0.20 ± 0.01 and 0.17 ± 0.004, respectively.

3.3.6 Quality index

In all four tested cultivars, the quality index was not affected by light treatments (Fig. 3.5).

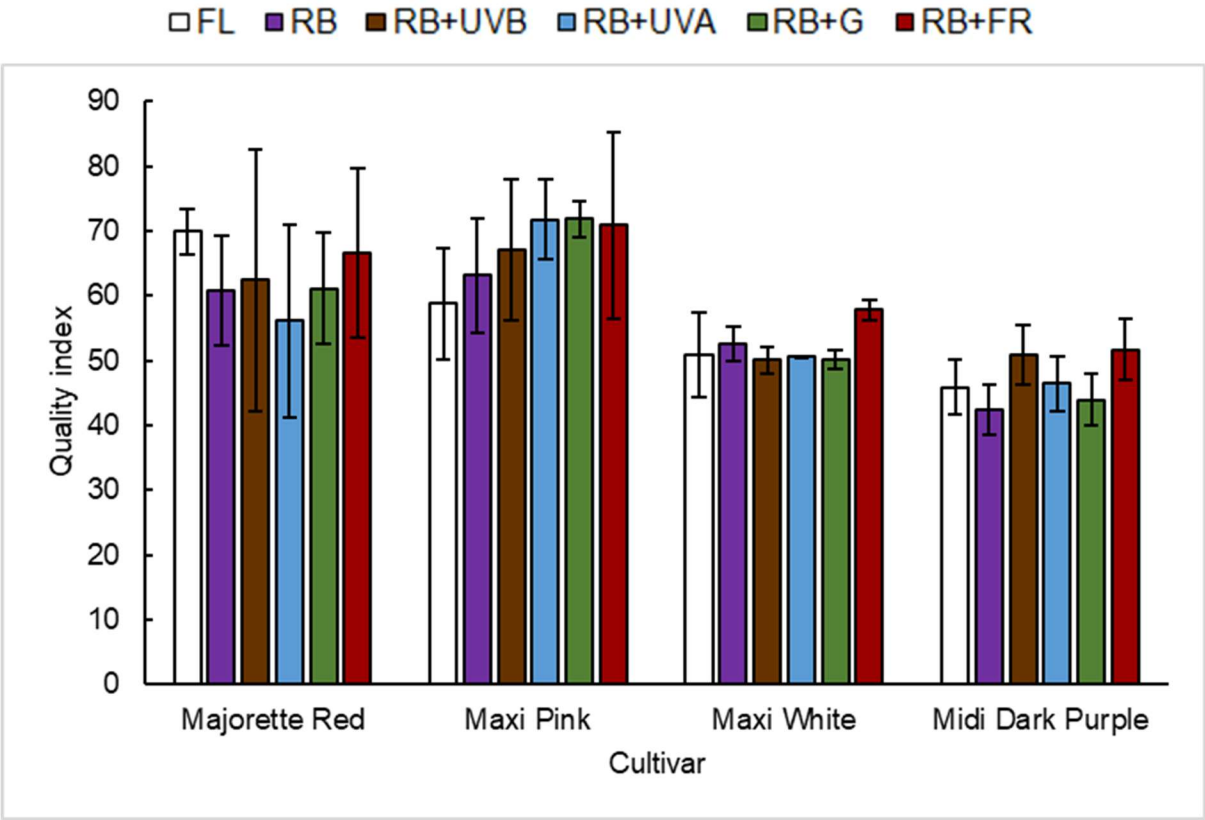

Figure 3. 5. Quality index under different light treatments of four gerbera cultivars. Data are mean ± standard error (SE) (n = 2). For the six light treatments, FL = cool white fluorescent light; RB = 85% red and 15% blue LED; RB + UVB = RB-LED and 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet B sourced from narrow-band fluorescent light; RB + UVA = LED combination of RB and 9.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet A; RB + G = LED combination of 60% red + 15% blue + 25% green; RB + FR =

LED combination of RB and 17.3 μmol·m^{-2}·s^{-1} of far-red. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

3.3.7 Storage quality of seedlings

In all four cultivars, at the end of storage, plant height and CCI of upper and lower true leaves were not affected by light treatments. For 'Majorette Red', 'Maxi Pink', 'Maxi White' and 'Midi Dark Purple', the mean values of plant height were 6.8 ± 0.2, 7.4 ± 0.1, 6.7 ± 0.3 and 7.0 ± 0.2 cm, respectively, and the mean CCI values of upper true leaves were 20.0 ± 0.8, 20.6 ± 1.4, 17.2 ± 1.0 and 23.6 ± 1.5, respectively, and the mean CCI values of lower true leaves were 19.8 ± 0.9, 20.2 ± 0.7, 16.4 ± 0.9 and 22.0 ± 2.1, respectively.

3.3.8 Flowering time

Light treatments did not affect subsequent flower initiation time, i.e., days from transplanting to the first visible bud, of the transplants for each of the four cultivars. The mean values of flower initiation time were 36.5 ± 1.5 d for 'Majorette Red', 52.6 ± 2.4 d for 'Maxi Pink', 47.8 ± 1.3 d for 'Maxi White', and 38.5 ± 1.8 d for 'Midi Dark Purple'.

3.4 Discussion

For the tested gerbera cultivars, RB-LED generally showed a similar effect as FL on the metrics measured, except canopy width of 'Majorette Red'. This confirmed the first hypothesis that RB-LED light, compared to FL, does not negatively affect seedling quality at least for some gerbera cultivars. For the light-affected cultivar, 'Majorette Red' seedlings grown under RB-LED had a wider canopy compared to FL despite no differences in other traits. Possibly, in this

cultivar, RB-LED compared to FL promoted elongation growth of the lower fully expanded leaves (e.g., increased blade length/width ratio, which however was not measured). In the present study, RB-LED relative to FL had a lower B percentage (15% vs. 19%), which may promote plant elongation for some plant genotypes sensitive to decreased B level (Hernández et al., 2016). Similar promotion effects on plant canopy by RB relative to FL have also been found in marigold, geranium, petunia, and calibrachoa at ≈210 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Mah et al., 2018) and in lettuce at ≈140 (Park et al., 2012) and 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Johkan et al., 2010). The above plant species along with gerbera 'Majorette Red' may be very sensitive to a decreased B level.

G in combination with R and B can increase photosynthesis of the whole canopy due to deeper penetration of G into the leaf canopy (Davis and Burns, 2016; Kim et al., 2004b). RBG-LED combinations were reported to promote plant growth and biomass accumulation in some plant species such as tomato and lettuce, compared to RB-LED (Meng et al., 2019; Wollaeger and Runkle, 2014). However, the promotion effects were not observed under RB + G relative to RB-LED for all the plant traits in all the cultivars in the present study. The smaller leaf canopy of gerbera seedlings in the present study compared with that in the previous studies might partly explain the different results. In addition to G, simultaneous delivery of FR with R and B can also increase plant growth and biomass (Park and Runkle, 2016, 2017), at least partly by increasing the quantum yield of photosystem II (Myers, 1971; Zhen and van Iersel, 2017). A similar promotion effect on stem growth (i.e., increased stem diameter) was also obtained in the present study on gerbera 'Maxi Pink' under RB + FR relative to RB-LED. However, subsequent flowering of the transplants was not promoted by including FR with RB-LED for all the cultivars in the present study. This was inconsistent with a previous study on flowering of some

ornamental seedlings by Park and Runkle (2017). Also, R:FR ratio was higher in the present study (8.5:1) compared with the previous study where the lowest R:FR ratio was only 1:1. Nevertheless, a thicker stem under RB + FR relative to RB-LED is an indicator of high-quality seedlings, partly confirming the second hypothesis that seedling growth can be promoted by combining FR or G with RB-LED light.

In the present study, including UVA or UVB with RB-LED did not affect any of the metrics measured in gerbera seedlings for all the cultivars. This disproved the third hypothesis that some quality traits for gerbera seedlings can be improved by combining UVA or UVB with RB-LED. The indifferent plant response to the addition of UVA or UVB in the present study was inconsistent with the results of some previous studies. Including UVA (at a level of around 4–13% of PAR) with RBFR-LED combination (PPFD of 230 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 $h \cdot d^{-1}$) increased shoot FW and DW and leaf area in lettuce (Chen et al., 2019). Adding UVB to RB-W-LED light (PPFD of ≈185 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 $h \cdot d^{-1}$) for 4 $h \cdot d^{-1}$ for 6 d caused compact plants by inhibiting elongation growth in lettuce (Lee et al., 2014). The difference between our study and the above studies might result from different background lighting, UVA or UVB levels, or plant species.

A high-quality seedling has a compact canopy, thick stem, strong roots, and high biomass (Randall and Lopez, 2014). In this case, sometimes using one trait to evaluate seedling quality is not useful. The QI is a useful tool to evaluate seedling quality as it integrates multiple morphological parameters such as plant height, stem length and diameter, and plant biomass (Currey et al., 2013). In the present study, the QI was not different among all the light treatments for any of the tested gerbera cultivars. This would suggest that RB-LED can potentially replace

FL to grow gerbera seedlings in controlled environments as SSL if only considering the effects on seedling quality. However, in practical production, currently, the higher initial investment on LED light fixtures needs to be taken into consideration (Kusuma et al., 2020). Nevertheless, LEDs are increasing in efficiency and decreasing in cost, and, compared to FL, produce less radiant heat and have a longer operating life (Bula et al., 1991; Davis and Burns, 2016; Gómez et al., 2019). For LED lighting, our results would also suggest the tri-chromatic lights used in the present study might be unnecessary for production of gerbera seedlings in controlled environments as SSL if only considering seedling quality. The reason lies in that including the third light wavelength with RB-LED did not improve the integrated quality (i.e., QI) of seedlings, and using just RB-LED in a controlled environment is both cost-efficient and beneficial to the seedlings. However, it is worthwhile to note that plants under RB-LED can appear purple making it difficult for growers to monitor colour changes in plants (Smith et al., 2017). Including G with RB-LED can make the plants easier to view and detect the signs of diseases (Mitchell and Stutte, 2017).

In summary, for the four tested gerbera cultivars grown inside a controlled environment using SSL at a PPFD of ≈165 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and a photoperiod of 16-h, the seedlings under RB-LED relative to FL did not change plant morphology except an increased canopy width for ‘Majorette Red’. The four tri-chromatic light treatments (i.e., combining FR, G, UVA, or UVB with RB-LED) had similar effects as RB-LED on seedling growth and morphology, except for a thicker stem for ‘Maxi Pink’ under RB + FR. Based on the QI, an integrated quality index of transplants, there was no difference among all the light treatments for all the gerbera cultivars. It appears that RB-LED can potentially replace FL and is suitable for controlled-environment

production of gerbera seedlings as SSL, and tri-chromatic lights used in this study may be unnecessary, if only considering seedling quality.

CHAPTER FOUR

DYNAMIC VERSUS CONCURRENT LIGHTING WITH RED AND BLUE LIGHT-EMITTING DIODES AS THE SOLE LIGHT SOURCE CAN POTENTIALLY IMPROVE CAMPANULA STOCK PLANT MORPHOLOGY FOR CUTTING PRODUCTION

Abstract

Campanula stock plants which are too short present difficulty in machine-harvesting of cuttings. The objectives of this study were to 1) investigate whether short-term 24-h dynamic red and blue lighting can promote elongation growth without inducing flowering, and 2) to explore how to apply a dynamic lighting strategy to modify stock plant morphology of campanula (*Campanula portenschlagiana* 'PGM Get MEE®') to improve cutting quality and rooting in a controlled environment. Two sole-source lighting treatments were used: Concurrent lighting (CL) with red (85%) and blue (15%) LEDs (RB) at 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was set as the control while dynamic lighting (DL) with red (170 $\mu mol \cdot m^{-2} \cdot s^{-1}$), blue (30 $\mu mol \cdot m^{-2} \cdot s^{-1}$), and RB (100 $\mu mol \cdot m^{-2} \cdot s^{-1}$) LEDs sequentially at three different lighting stages, respectively, was used as a potential new lighting strategy. At final harvest, the side branches under DL compared to CL were longer, but even though the 24-h experiment (Expt. 1) only lasted for 5 weeks, there were flowers in both treatments. A second experiment (Expt. 2) was conducted with the same cultivar and experimental conditions, but with lighting treatments at a shorter photoperiod (10-h), to explore how to apply a dynamic lighting strategy to modify campanula stock plant morphology to improve cutting quality and rooting. In both experiments, side branch number under DL was greater compared to CL at the end of the first lighting stage. Stock plants under DL were taller from the second lighting stage on to final harvest compared to CL and met the target height for

machine-harvest in both experiments. At final harvest, the side branches under DL compared to CL were more upright in Expt. 2. In Expt. 2, dry biomass of side branches with one branch order, and leaf chlorophyll content were greater under CL compared to DL at final harvest; however, harvested cutting quality and rooting were unaffected. Therefore, with a mix of photoperiods, the dynamic lighting strategy can potentially benefit controlled-environment production of campanula cuttings.

4.1 Introduction

Campanulas (*Campanula* spp.) are commercially important ornamental plants with bell-shaped flowers ranging in colour from deep purple and blue to white (Frello et al., 2002; Seglie et al., 2012; Sriskandarajah et al., 2001). For this species, many commercial growers prefer to use cuttings for propagation since this method can maintain stock plant quality and decrease propagation time compared to seed propagation (Christiaens et al., 2016). Machine-harvesting has the potential to replace manual harvest to reduce labour costs and improve efficiency (Adegbola et al., 2019). However, campanula stock plants that are too short or compact present a challenge for implementing machine-harvest of cuttings, and the minimal height of campanula stock plants needs to reach a target of ≈7.5 cm (Commercial greenhouse grower, personal communication). In addition to plant height, ideal stock plants also need to have many thick side branches without flower buds (Dole and Gibson, 2006; Moe, 1976; Nissim-Levi et al., 2014). Plant growth regulating-chemicals have been used to promote plant elongation in the past, but this method has been restricted due to increased safety and environmental concerns (Bergstrand, 2017). In recent years, light quality has been used as an alternative for modifying plant

morphology for production purpose, especially in controlled environments (Clifford et al., 2004; Islam et al., 2012; Mah et al., 2018; Moe et al., 1991).

Controlled environment facilities equipped with electrical light as sole-source lighting (SSL) have been increasingly used for commercial plant production (Mitchell and Stutte, 2017). However, there is a lack of information on their use for the production and maintenance of stock plants for cutting production. Light-emitting diodes (LEDs) are replacing traditional light sources (e.g., high-pressure sodium and fluorescent lights) for controlled environment plant production as SSL due to their many advantages such as easily adjustable light spectral quality (Massa et al., 2008; Mitchell and Stutte, 2017; Zheng, 2016). Currently, LED lighting with a red (R) and blue (B) light combination (RB-LED) is popular for horticultural crop production (Davis and Burns, 2016), as these wavelengths are readily absorbed and utilized for photosynthesis (McCree, 1972). For RB-LED light, a common R:B ratio of ≈85:15 has been used for bedding plants (Randall and Lopez, 2014), as well as potted campanulas (Ouzounis et al., 2014, 2018). In controlled environments, under RB-LED lighting as SSL, plants display a compact canopy, thick shoots and dark-coloured leaves (Kim and Hwang, 2019; Randall and Lopez, 2014, 2015), possibly because R and B trigger high activity of both phytochrome and cryptochrome (Casal and Mazzella, 1998; Demotes-Mainard et al., 2016). If machine-harvest of cuttings is intended, then using RB-LED may not be suitable for growing campanula stock plants for cutting production.

Our recent studies in controlled environments with SSL indicate that pure monochromatic R and B LED light at moderate levels (e.g., 20–200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) can cause

contrasting morphological responses, at least due to their different phytochrome photostationary state (PPS), which is much higher (0.89 vs. 0.49) for R than B (Kong et al., 2018a, 2019b). For many species, monochromatic B LED light can increase stem elongation, induce earlier flowering, and reduce side branching off the main stem, by promoting a shade-avoidance response (Kong et al., 2018a, 2019a). By contrast, monochromatic R LED light can inhibit stem elongation, delay plant flowering, and increase branching, by preventing shade-avoidance response (Kong and Zheng, 2020; Kong et al., 2018a). In addition to spectral quality (e.g., R and B), light intensity can also affect plant morphology (Johnson et al., 2020; Jones-Baumgardt et al., 2019). For most species, increasing light intensity leads to a shorter and thicker stem, increased side branching, and darker leaf colour (Craver et al., 2018; Gerovac et al., 2016; Kong and Zheng, 2019). Taking into account the ideal morphology of campanula stock plants and the results of our previous studies, possibly using high-intensity R LED light could increase side branching while inhibiting flowering, then using low-intensity B LED light could promote side branch elongation, and finally, using moderate-intensity RB-LED light could increase side branch diameter and leaf greenness. This dynamic lighting strategy, with three different lighting stages, may be an effective lighting strategy for campanula cutting production.

For dynamic lighting using R and B LEDs, the previous studies about plant morphological responses have been reported mainly on lettuce (*Lactuca sativa*). Alternating R and B light at 120 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 12-h each (i.e., 24-h lighting) compared to concurrent R and B (RB) at 120 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (i.e., 240 $\mu mol \cdot m^{-2} \cdot s^{-1}$ total) for 12-h or at 60 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (i.e., 120 $\mu mol \cdot m^{-2} \cdot s^{-1}$ total) for 24-h increased FW, DW and stem length of lettuce (Kuno et al., 2017). Ohtake et al. (2018) found that alternating R and B at 120 and 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively, for

12-h each increased plant height and DW of lettuce compared to RB light at 60 and 20 μmol·m^{-2}·s^{-1} (i.e., 80 μmol·m^{-2}·s^{-1} total) for 24-h, respectively. Lettuce grown under alternating 200 μmol·m^{-2}·s^{-1} of R and 100 μmol·m^{-2}·s^{-1} of B for 1, 2, 4 or 8-h either had greater plant elongation and/or biomass production compared to RB for 8- or 16-h (Chen et al., 2017). Shimokawa et al. (2014) found that alternating R at 100 μmol·m^{-2}·s^{-1} and B at 60 μmol·m^{-2}·s^{-1} for 12-h each (i.e., 24-h lighting) increased FW, DW and leaf length and width of lettuce plants compared to RB for 12-h at the same respective intensities. In the above studies, although dynamic compared to concurrent lighting with R and B LEDs promoted growth (e.g., elongation and biomass production) of lettuce plants, the R and B lighting was repeatedly alternated in a daily cycle. This way of alternating light for plant growth is totally different from dynamic lighting with R and B LEDs at three different stages in a production cycle. However, the information related to such a lighting strategy has so far been unavailable especially for growing campanula stock plants in controlled environments.

Our previous studies have shown that monochromatic B LED light can promote plant elongation, and that this response is greater under lower intensity (Johnson et al., 2020; Kong et al., 2018a) and a 24-h photoperiod (Kong et al., 2019b). In a controlled environment system, continuous (24-h) lighting at a low to moderate intensity is a way of producing crops economically and increasing biomass production (Sysoeva et al., 2010). For campanula, many species/cultivars are long-day plants (LDPs) and this photoperiod promotes flowering (Dole and Gibson, 2006; Kjaer et al., 2012). However, previous studies have shown that duration of light exposure and light quality, along with photoperiod, can affect the flowering response in LDPs. In a controlled environment, 24-h SSL of R and RB-LED delayed flowering of two LDPs (Kong et

al., 2018a), since light quality can regulate flowering independent of photoperiod to some degree (Davis and Burns, 2016). Moe (1976) grew stock plants of a long-day campanula species (*Campanula isophylla*) under 12-h natural light supplemented with 12-h fluorescent light (i.e., 24-h total) for 2, 4, 6 and 8 weeks and found that cuttings taken from plants grown under long-days for up to 4 weeks did have rooting success, while cuttings taken from plants after 6 weeks of long-days had visible flower buds and no rooting success.

To examine a dynamic lighting strategy on campanula, not only stock plant morphology (e.g., plant height, side branch number, length and thickness, leaf colour) would need to be observed, but harvested cutting quality (e.g., length, thickness, and rooting) could be important plant traits for evaluation. The reason lies in that the purpose of adjusting stock plant morphology by lighting is to eventually produce a large number of high-quality cuttings in addition to allow machine-harvesting. Based on all the above information, we hypothesized that a dynamic lighting strategy with R and B LEDs compared to concurrent lighting (i.e., RB-LED) can promote growth and morphological traits of campanula stock plants in a controlled environment as SSL. Campanula stock plants were grown under dynamic lighting with R (170 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and B (30 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and RB (100 $\mu mol \cdot m^{-2} \cdot s^{-1}$) LED, using concurrent RB-LED lighting (100 $\mu mol \cdot m^{-2} \cdot s^{-1}$) as a control. The objectives of this study were 1) to investigate whether a short-term dynamic lighting strategy at 24-h can promote campanula stock plant branch elongation without inducing flowering, and 2) to explore how to apply a dynamic lighting strategy to adjust stock plant morphology of campanula to improve cutting quality and rooting in a controlled environment.

4.2 Materials and Methods

4.2.1 Expt. 1. Using short-term 24 h dynamic lighting to promote elongation growth without inducing flowering

4.2.1.1 Plant materials and growing conditions

The experiment was conducted in a 29 m^2 walk-in growth chamber at the University of Guelph, Guelph, ON, Canada from July to August of 2019. Campanula 'PGM Get MEE®' (*Campanula portenschlagiana*) plants (≈6–7 weeks old) were provided as plugs by a local grower (Sunrise Greenhouses Ltd., Vineland Station, ON, Canada). Before lighting treatments, plugs were transplanted into 8.5 × 8.5 × 10 cm pots (1 plant per pot) containing Sunshine Mix #1 substrate (Sun Gro Horticulture, Agawam, MA, USA). Then the potted plants were put into supporting trays (27 × 56 × 5 cm). For each replicate, there was one tray per lighting treatment, which contained eight plants. The plants were sub-irrigated with a nutrient solution described in Kong et al. (2020) every 2–3 days as needed until plant harvesting.

In the chamber, air temperature and relative humidity (RH) was set at ≈21˚C and 75%, respectively. The air temperature and RH were controlled by an Argus control system (Argus Controls Systems Ltd., Surrey, BC, Canada) and recorded every 5 minutes using data loggers (Onset HOBO U12-013; Onset Computer Corporation, Bourne, MA, USA).

4.2.1.2 Experimental design and treatments

Two lighting strategies were adopted for lighting treatments as follows. (1) Concurrent lighting of R and B LEDs (CL). Throughout the whole experimental period, plants were exposed to the same lighting with a combination of 85% R (661 nm) and 15% B (440 nm) LED light

(RB) at a total PPFD of ≈100 μmol·m^{-2}·s^{-1}. (2) Dynamic lighting of R and B LEDs (DL). Plants were grown under different lighting at three stages of the experimental period: R of ≈170 μmol·m^{-2}·s^{-1} for the first lighting stage, B of ≈30 μmol·m^{-2}·s^{-1} for the second lighting stage, and RB of ≈100 μmol·m^{-2}·s^{-1} for the final lighting stage. The treatments for each stage are presented in Fig. 4.1A. The experiment was conducted as a randomized complete block design (RCBD) with one factor (lighting strategy) and three replicates (i.e., blocks). The three blocks were located at three zones of the chamber (Fig. 4.1B). The above two lighting treatments were randomly allocated to two separate compartments within each of the three blocks (i.e., six compartments in total in the chamber). The six compartments in the chamber were divided by opaque white curtains to prevent neighbouring light effects. A photoperiod of 24 h·d^{-1} was used for all lighting treatments in Expt. 1, which ran for 5 weeks where the three lighting stages lasted 2, 2, and 1 weeks, respectively.

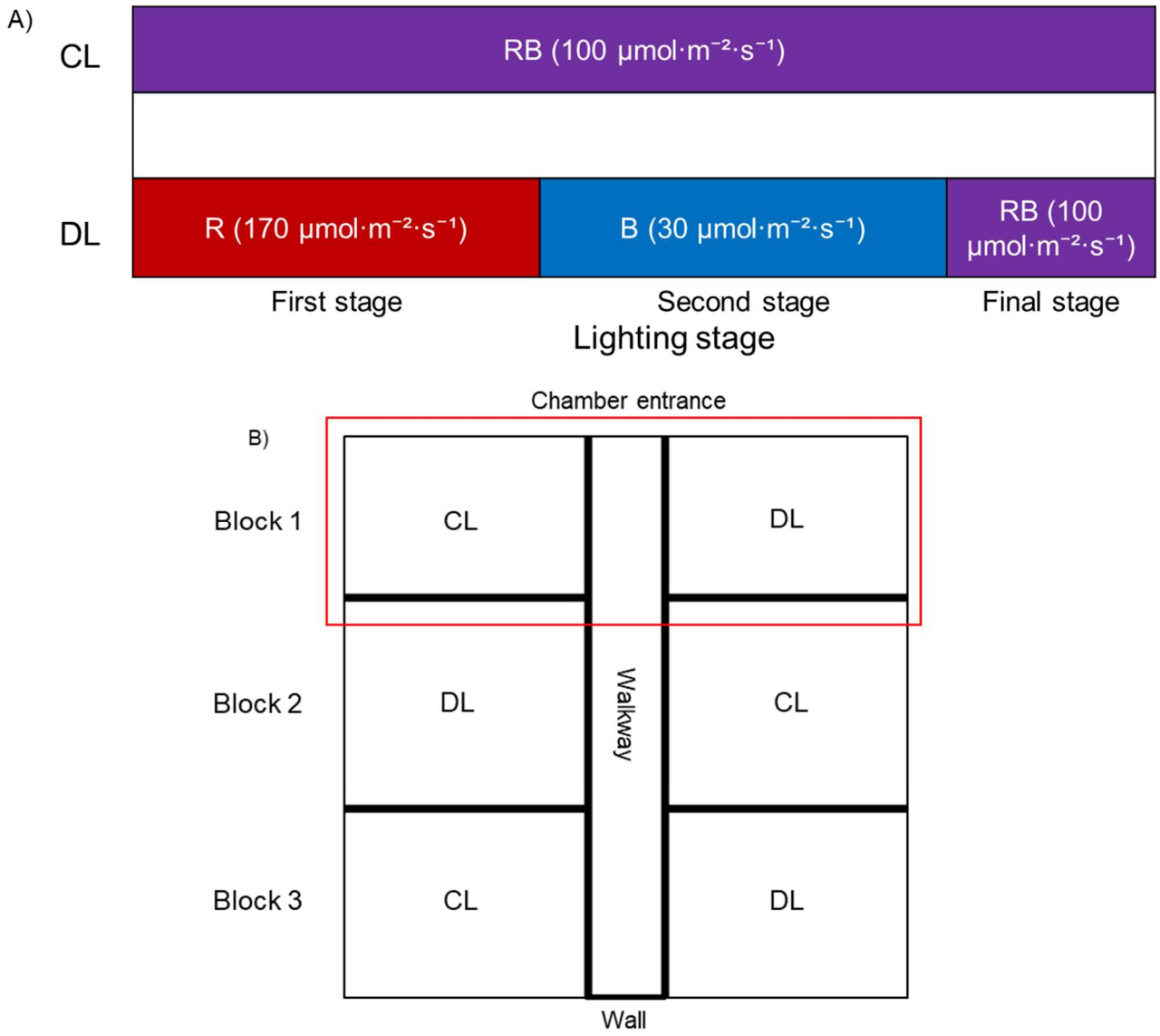

Figure 4. 1. Lighting treatments (A) and experimental design (B) in Expt. 1. For the two lighting treatments, CL was concurrent lighting of red (85%) and blue (15%) LEDs (RB) at 100 µmol·m^{-2}·s^{-1}, and DL was dynamic lighting of red (170 µmol·m^{-2}·s^{-1}), blue (30 µmol·m^{-2}·s^{-1}), and RB (100 µmol·m^{-2}·s^{-1}) LEDs sequentially at three different lighting stages, respectively. A photoperiod of 24 h·d^{-1} was used for both lighting treatments in Expt. 1, which lasted 5 weeks where the three lighting stages of DL were 2, 2, and 1 weeks, respectively. Each block contained both lighting treatments as indicated by the red box.

The LED lighting system was provided by LumiGrow Inc. (ProSeries 325; Emeryville, CA, USA). Light spectra and intensities were set up and verified using a USB2000+UV-vis spectrometer (Ocean Optics, Inc., Dunedin, FL, USA). All LED lighting fixtures were hung at a height of 80 cm above the bench.

4.2.1.3 Growth and morphology measurements

Canopy height from substrate level and width and number of side branches (SB) of each plant were non-destructively measured weekly from the start of light treatments. After 5 weeks, plants were randomly sampled and harvested for morphological observations and biomass determination. For each sampled plant, after measuring canopy height and width, three leaves were randomly selected for measurement of chlorophyll content index (CCI) using a portable CCM-200 Chlorophyll Concentration Meter (Opti-Sciences Inc., Hudson, NH, USA). Then, the plants were cut at the substrate surface and aboveground (i.e., shoot) fresh weight (FW) was measured. Then, all SBs with intact leaves were removed from the main stem. The length of main stem and the heights of the lowest and highest nodes producing SBs on the stem were measured with a ruler. Stem diameter was determined using a digital caliper and stem FW was measured using a scale. The main stems of each harvested plant were then placed in individual paper bags and dried at 90˚C till they reached a constant weight to determine dry weight (DW). After main stem measurements, the number of SBs, or potential cuttings, was counted and the length and diameter were determined for each one using a ruler and digital caliper, respectively. Total SB FW and DW, average SB length, diameter, and FW and DW, and longest SB length and diameter were determined for each plant. All SBs were transferred to paper bags and dried at the same conditions as main stems to determine DW. Shoot DW was determined for each plant

by adding total SB DW and stem DW. In Expt. 1, stock plants from both treatments showed visible flower buds at harvest (5 weeks), so cutting propagation was not tested.

4.2.2 Expt. 2. Using a dynamic lighting strategy to adjust stock plant morphology to improve cutting quality and rooting

A second experiment (Expt. 2) was conducted from October to December of 2019 by applying a dynamic lighting strategy to adjust stock plant morphology of campanula to improve cutting quality and rooting in a controlled environment. Plant materials and growing conditions, experimental design and treatments, and growth and morphology measurements were the same as reported in Expt. 1 unless otherwise stated. In Expt. 2, both lighting treatments used a photoperiod of 10 $h \cdot d^{-1}$ (9:00 AM–7:00 PM) for all three lighting stages, and treatment exposure time was based off the targets reached at the end of each lighting stage in Expt. 1. The three lighting stages of DL lasted 8, 2, and 1 weeks, respectively (Fig. 4.2).

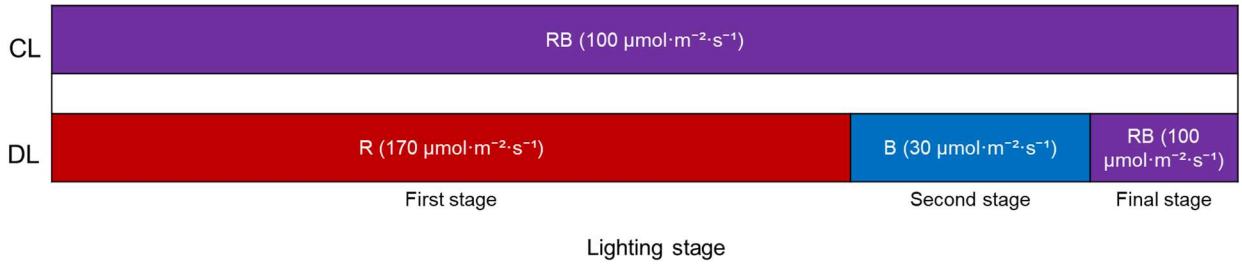

Figure 4. 2. Lighting treatments in Expt. 2. For the two lighting treatments, CL was concurrent lighting of red (85%) and blue (15%) LEDs (RB) at 100 µmol·m^{-2}·s^{-1}, and DL was dynamic lighting of red (170 µmol·m^{-2}·s^{-1}), blue (30 µmol·m^{-2}·s^{-1}), and RB (100 µmol·m^{-2}·s^{-1}) LEDs sequentially at three different lighting stages, respectively. A photoperiod of 10 h·d^{-1} was used for both lighting treatments in Expt. 2, which lasted 11 weeks where the three lighting stages of DL were 8, 2, and 1 weeks, respectively.

After 11 weeks, no flower buds were present under either lighting treatment. In Expt. 2, after the plants were cut at the substrate surface and shoot FW was measured, the inclination angles of SB at the lowest node on the main stem were measured for each plant from the horizontal as a measure of plant elongation (i.e., upward growth). Plants were laid on a white sheet of A4 paper and traced to determine SB inclination angle, and in some cases two SB angles, using a protractor (Fig. 4.3).

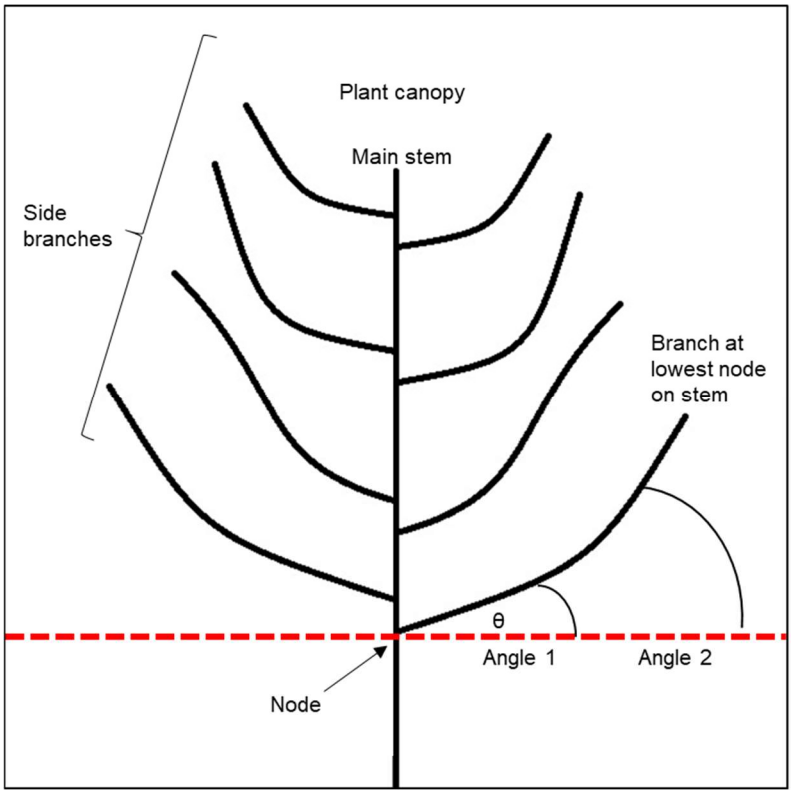

Figure 4. 3. Inclination angles of the lowest side branch (SB) from main stem. Plants' SBs were traced onto a sheet of A4 white paper, and SB angles were measured with a protractor.

In Expt. 2, FW of the longest SB, and the number of SBs with only one branching order and those with more than one branching order were also determined for each plant. The remaining plants from each replicate were destructively harvested following the same protocol as mentioned above. Once all SBs were removed for cutting propagation, three were randomly selected and measured for FW, then put in paper bags and dried at the same conditions mentioned above for DW determination. From the remaining SBs, cuttings were harvested as the shoot tips with 4–5 true leaves for each of them. After measuring cutting length and diameter, the cuttings were stuck in two 50-cell (5 × 10 cell) trays containing Sunshine Mix #5 substrate (Sun Gro Horticulture). For each tray, half of the cells were used for 25 cuttings from each treatment.

The two trays were placed under a clear tent equipped with a misting system in a greenhouse compartment for 3–4 weeks. At the end, the number of rooted cuttings (%), number of rooted cuttings with root branching (%), the average number of roots per cutting, and the longest root length were determined.

4.2.3 Statistical analysis

In each experiment, data were subjected to analysis of variance using SAS statistical software (University Edition; SAS Institute, Cary, NC, USA) and were presented as means ± SE (standard error). Separations of means for different light treatments for each experiment were performed using Tukey's HSD test at a significance level of 0.05, 0.01, or 0.001. Linear regression was used to determine if there were treatments effects between stock plant morphology and lighting treatments for the three lighting stages by comparing 95% confidence intervals of the slope parameters at each lighting stage. Residuals were tested for normality using the Shapiro-Wilk test and the data was transformed using a lognormal distribution to achieve a normal distribution before performing the analysis if necessary.

4.3 Results

4.3.1 Dynamic morphological variation of stock plants

In Expt. 1, canopy height was similar under DL and CL during the first lighting stage, increased under DL relative to CL during the second lighting stage, and had a greater increase under CL relative to DL during the final lighting stage (Fig. 4.4A). In Expt. 2, canopy height had a greater increase under DL relative to CL during the first and second lighting stages but had a greater increase under CL relative to DL during the final lighting stage (Fig. 4.4B). Canopy

width was generally similar between DL and CL in both experiments, except for a greater increase under DL relative to CL during the final lighting stage in Expt. 1 (Fig. 4.4C-D). Under DL relative to CL, the number of first order SBs increased during the first lighting stage and there were no treatment effects during the second lighting stage in both experiments, but there was a greater increase under CL relative to DL during the final lighting stage in Expt. 2 (Fig. 4.4E-F).

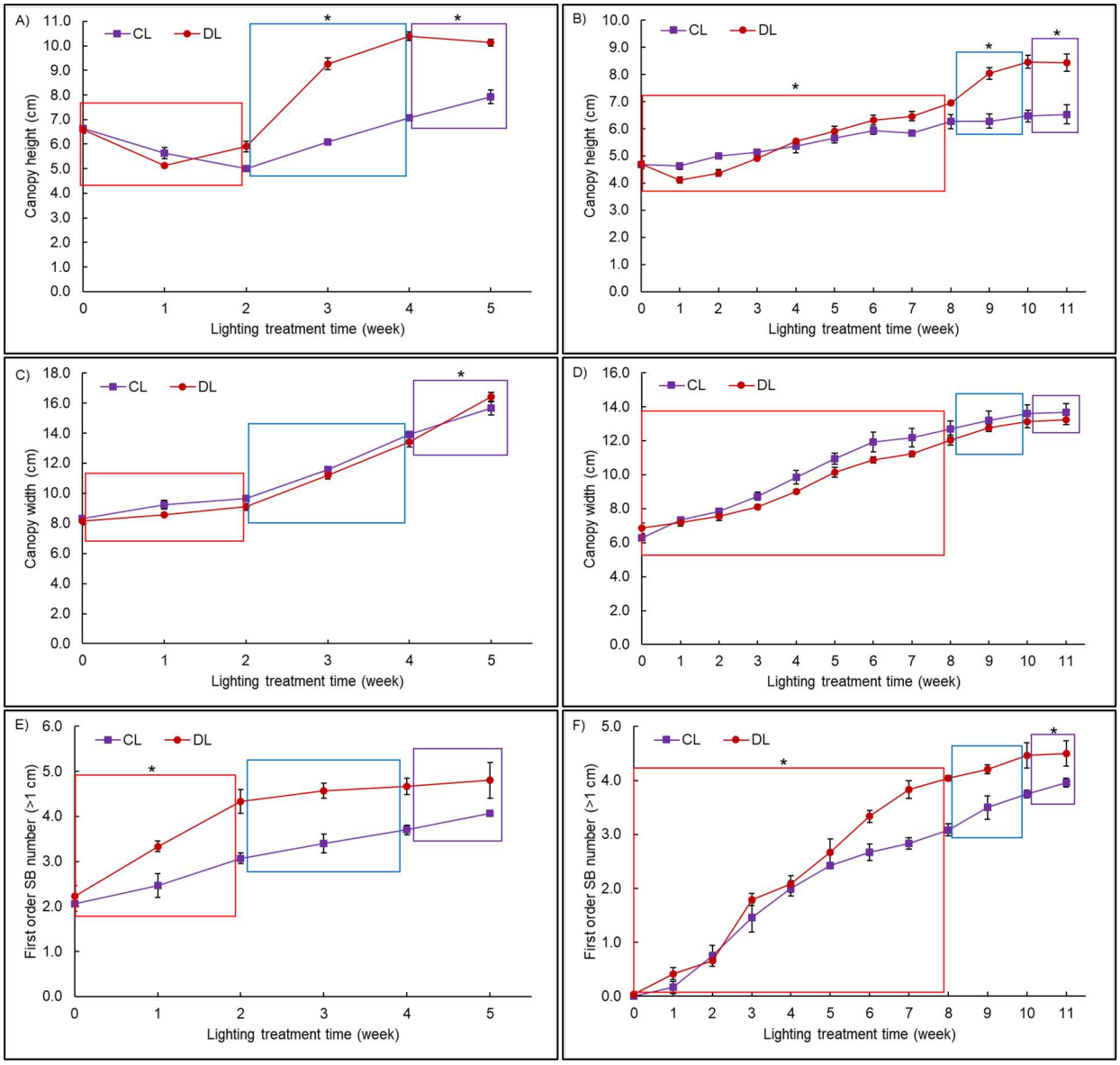

Figure 4. 4. Weekly variation of canopy height and width, and first order side branch (SB) number in stock plants of campanula under two different lighting strategies CL (concurrent red and blue) and DL (dynamic red and blue lighting) in Expt. 1 (A, C, E) and Expt. 2 (B, D, F). Data are mean ± standard error (SE) (n = 3). In each panel, the red, blue and purple boxes indicate the first, second, and final lighting stages, respectively, for the DL treatment. Asterisk (*) indicate that the 95% confidence intervals for the slope of the linear regression lines at the indicated lighting stage did not overlap and treatment effects were present.

4.3.2 Morphology of stock plants at harvesting

In both experiments, canopy height was greater under DL than CL (Fig. 4.5A), and canopy width was greater under DL in Expt. 1 but there was no difference between the two treatments in Expt. 2 (Fig. 4.5B). In both experiments, lighting treatments did not affect main stem length and diameter, and the lowest and highest SB positions on the main stem (Fig. 4.5C-F). In Expt. 2, leaf CCI was higher under CL than DL, but there was no difference between the two treatments in Expt. 1 (Fig. 4.5G). In Expt. 1, both SB length and longest SB length were greater under DL than CL, and there was no difference between the two treatments in Expt. 2 (Fig. 4.5H-I). The number of SBs, SB diameter, and longest SB diameter were not affected by lighting treatments in both experiments (Fig. 4.5J-L). In Expt. 2, both the inclination angles of SB at two locations were greater under DL than CL (Fig. 4.6A-B), but there was no difference in number of SBs with either one branch order nor more than one branch order between the treatments (Fig. 4.6C-D).

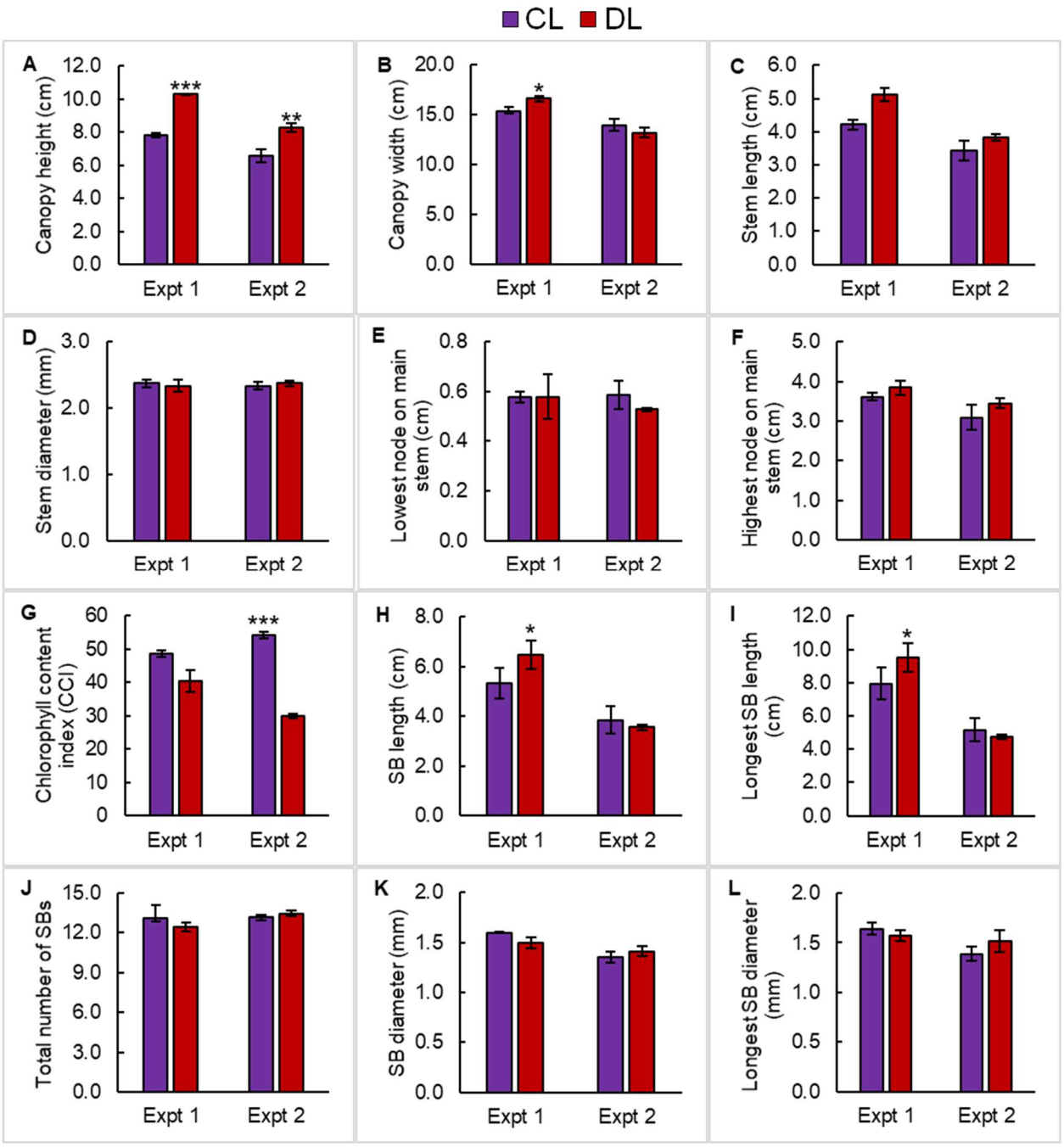

Figure 4. 5. Campanula stock plant morphology under concurrent (CL) or dynamic (DL) lighting strategies. Data are mean ± standard error (SE) (n = 3). Within each experiment, all bars that have no symbol indicate that the two lighting treatments are not significantly different at $P < 0.05$ level, but *, **, or *** indicate a significant difference at $P < 0.05$, 0.01, or 0.001 level, respectively, according to Tukey's HSD test.

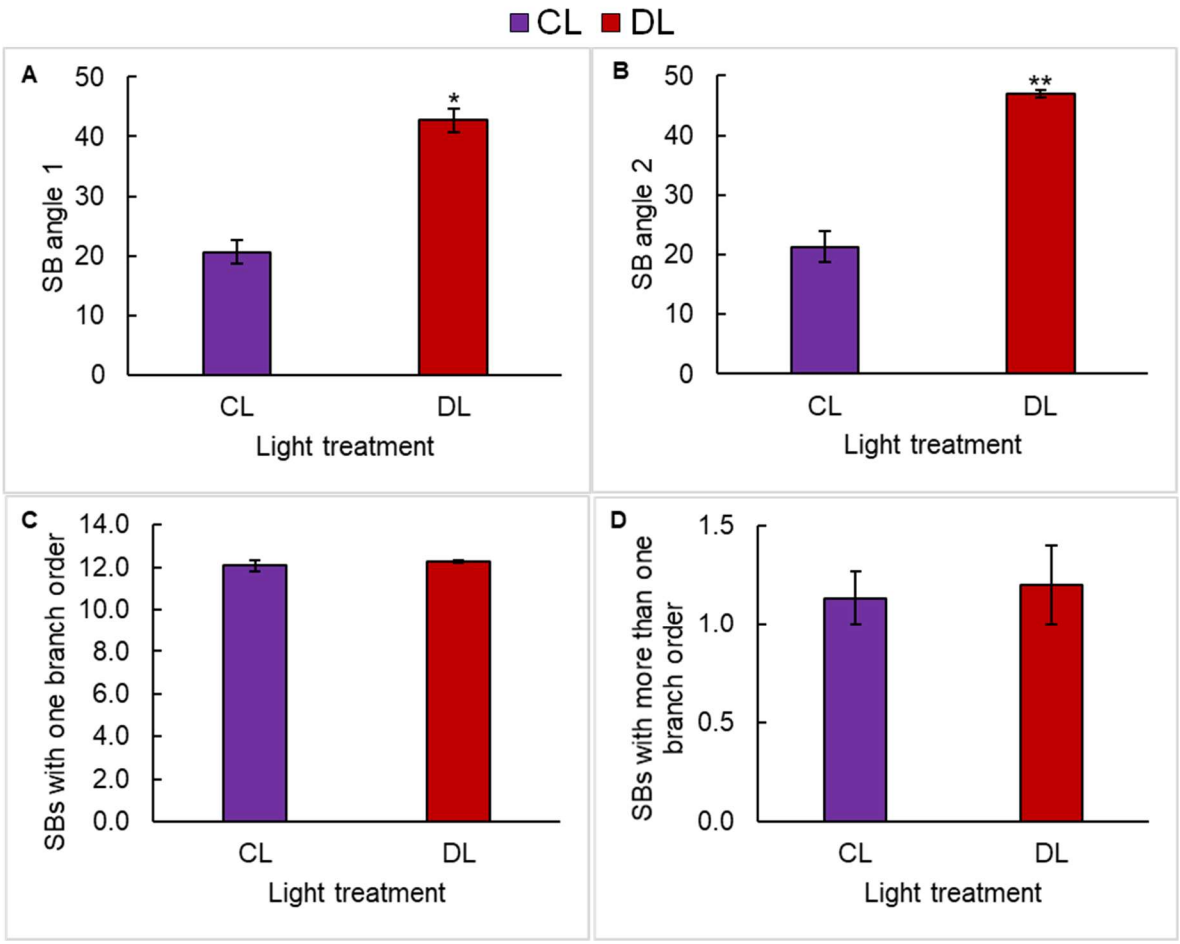

Figure 4. 6. Campanula stock plant morphology under concurrent (CL) or dynamic (DL) lighting strategies in Expt. 2. Data are mean ± standard error (SE) (n = 3). Within each parameter, all bars that have no symbol indicate that the two lighting treatments are not significantly different at $P <$ 0.05 level, but *, **, or *** indicate a significant difference at $P < 0.05$, 0.01, or 0.001 level, respectively, according to Tukey's HSD test.

4.3.3 Final biomass accumulation of stock plants

In Expt. 1, shoot FW was greater under CL than DL, but there was no difference between the two treatments in Expt. 2 (Fig. 4.7A). In both experiments lighting treatments did not affect shoot DW (Fig. 4.7B). Total side branch FW was greater under CL than DL in Expt. 1, but there was no difference between the two treatments in Expt. 2 (Fig. 4.7C). In both experiments,

lighting treatments did not affect total SB DW, FW or DW of main stem and individual SB (Fig. 4.7D-H). In Expt. 2, total DW of SB with one branching order was greater under CL than DL (Fig. 4.8A), but there was no difference between treatments for total DW of SB with more than one branching order or longest SB FW (Fig. 4.8B-C).

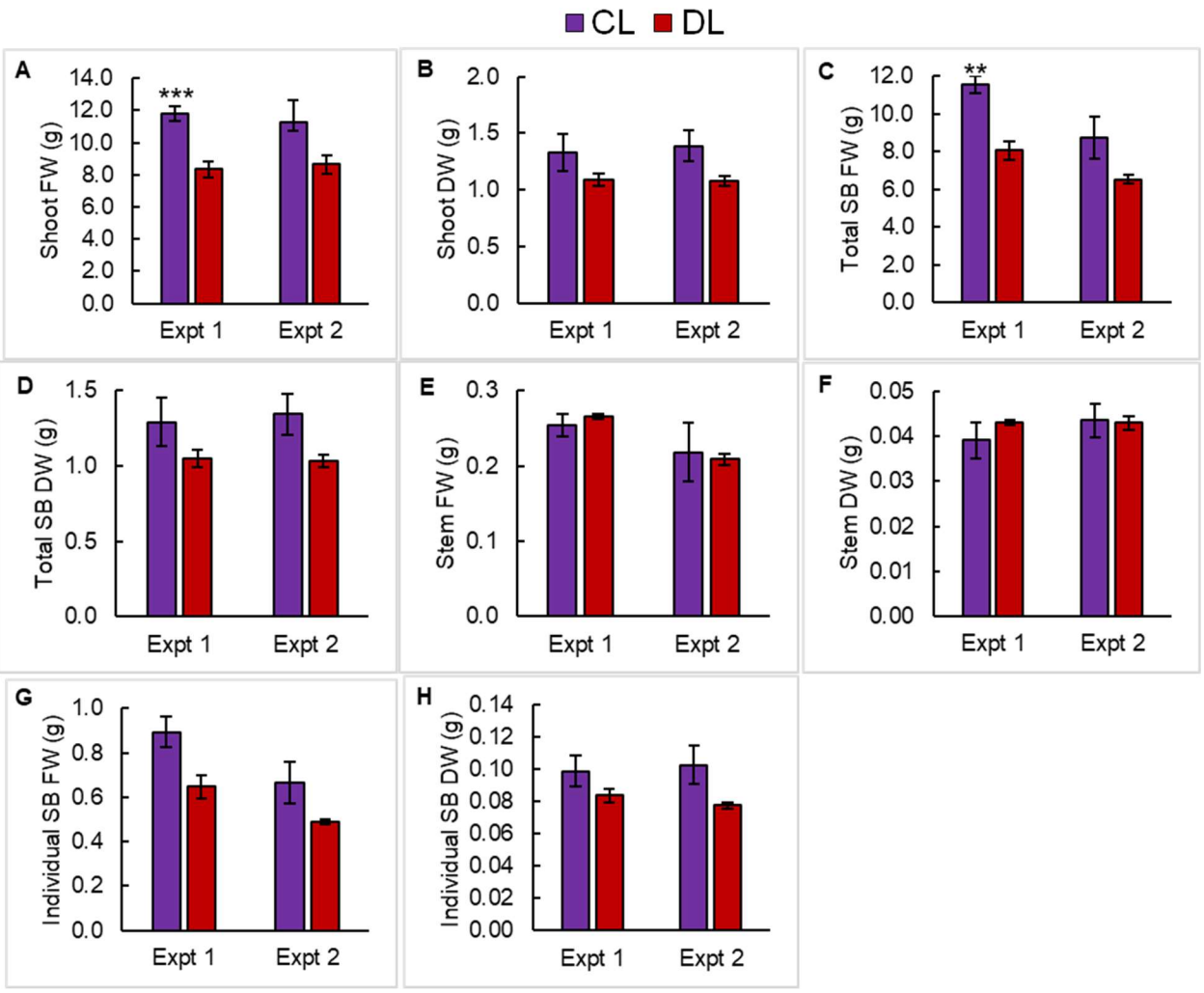

Figure 4. 7. Campanula biomass accumulation under concurrent (CL) or dynamic (DL) lighting strategies. Data are mean ± standard error (SE) (n = 3). Within each experiment, all bars that have no symbol indicate that the two lighting treatments are not significantly different at $P < 0.05$ level, but *, **, or *** indicate a significant difference at $P < 0.05$, 0.01, or 0.001 level, respectively, according to Tukey's HSD test.

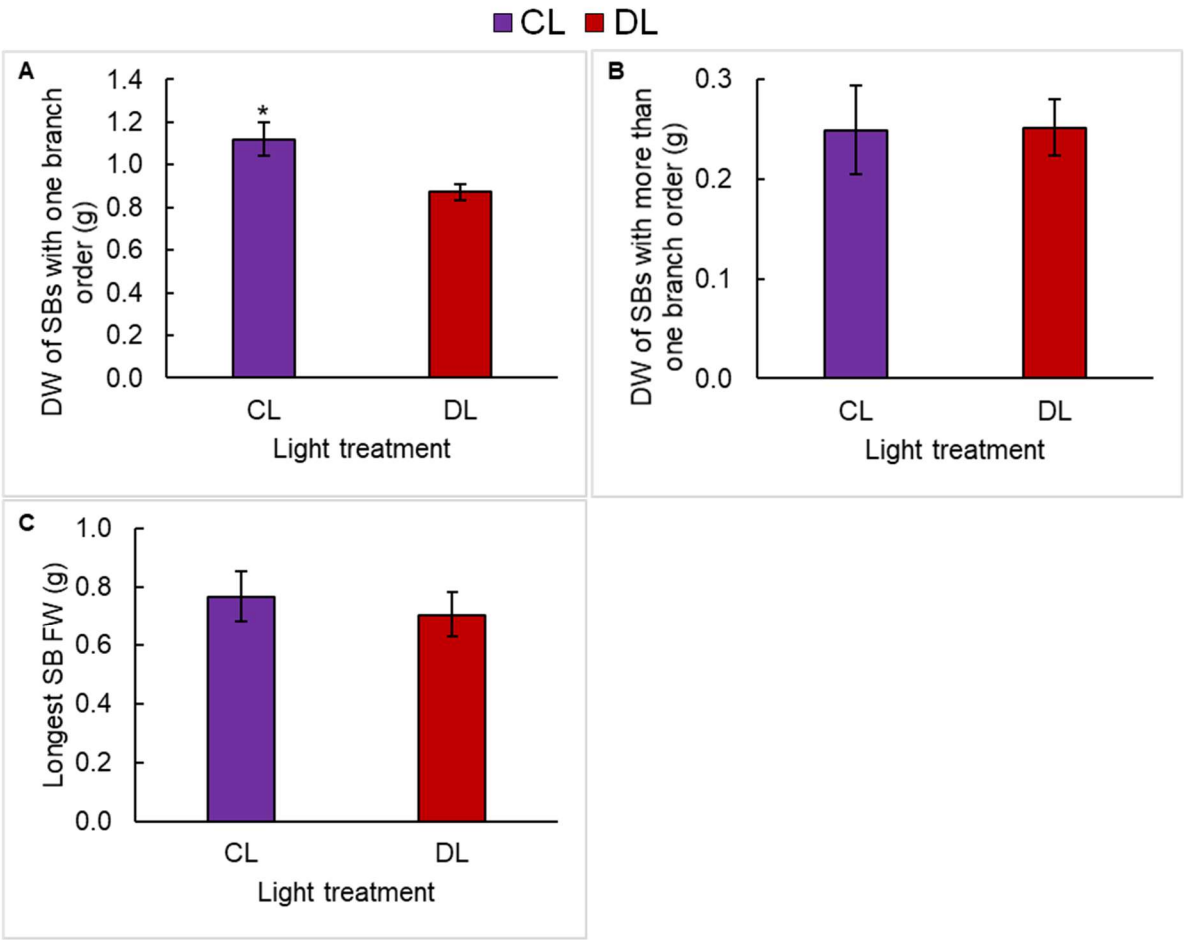

Figure 4. 8. Campanula biomass accumulation under concurrent (CL) or dynamic (DL) lighting strategies in Expt. 2. Data are mean ± standard error (SE) (n = 3). Within each parameter, all bars that have no symbol indicate that the two lighting treatments are not significantly different at $P <$ 0.05 level, but *, **, or *** indicate a significant difference at $P < 0.05$, 0.01, or 0.001 level, respectively, according to Tukey's HSD test.

4.3.4 Morphology, biomass and rooting of harvested cuttings

In Expt. 2, lighting treatments did not affect length, diameter, FW or DW of cuttings (Fig. 4.9A-D), as well as the number of rooted cuttings, number of rooted cuttings with root branching, number of roots per rooted cutting, and the length of the longest root (Fig. 4.10A-D).

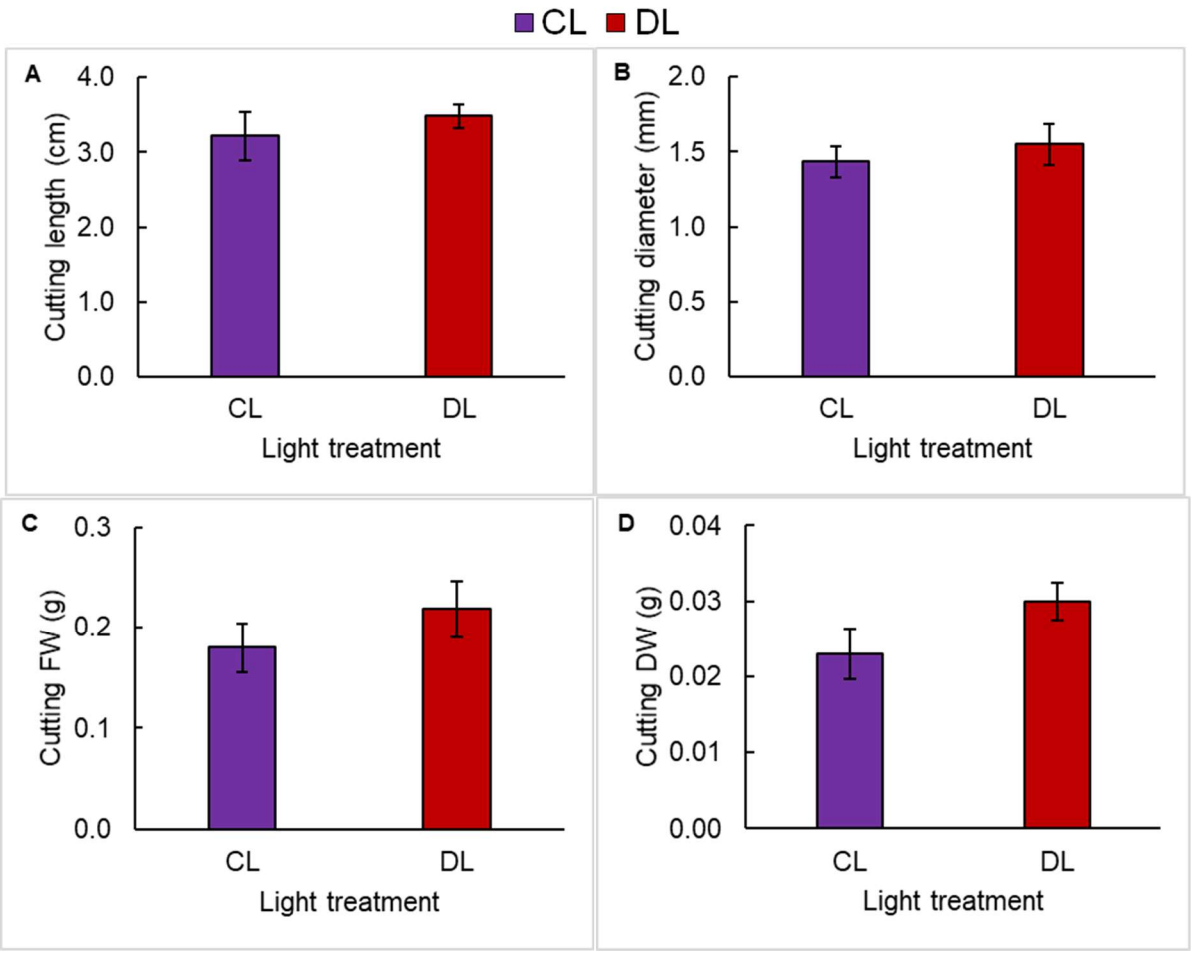

Figure 4. 9. Campanula cutting morphology and biomass accumulation under concurrent (CL) or dynamic (DL) lighting strategies in Expt. 2. Data are mean ± standard error (SE) (n = 3). Within each parameter, all bars that have no symbol indicate that the two lighting treatments are not significantly different at $P < 0.05$ level, but *, **, or *** indicate a significant difference at $P < 0.05$, 0.01, or 0.001 level, respectively, according to Tukey's HSD test.

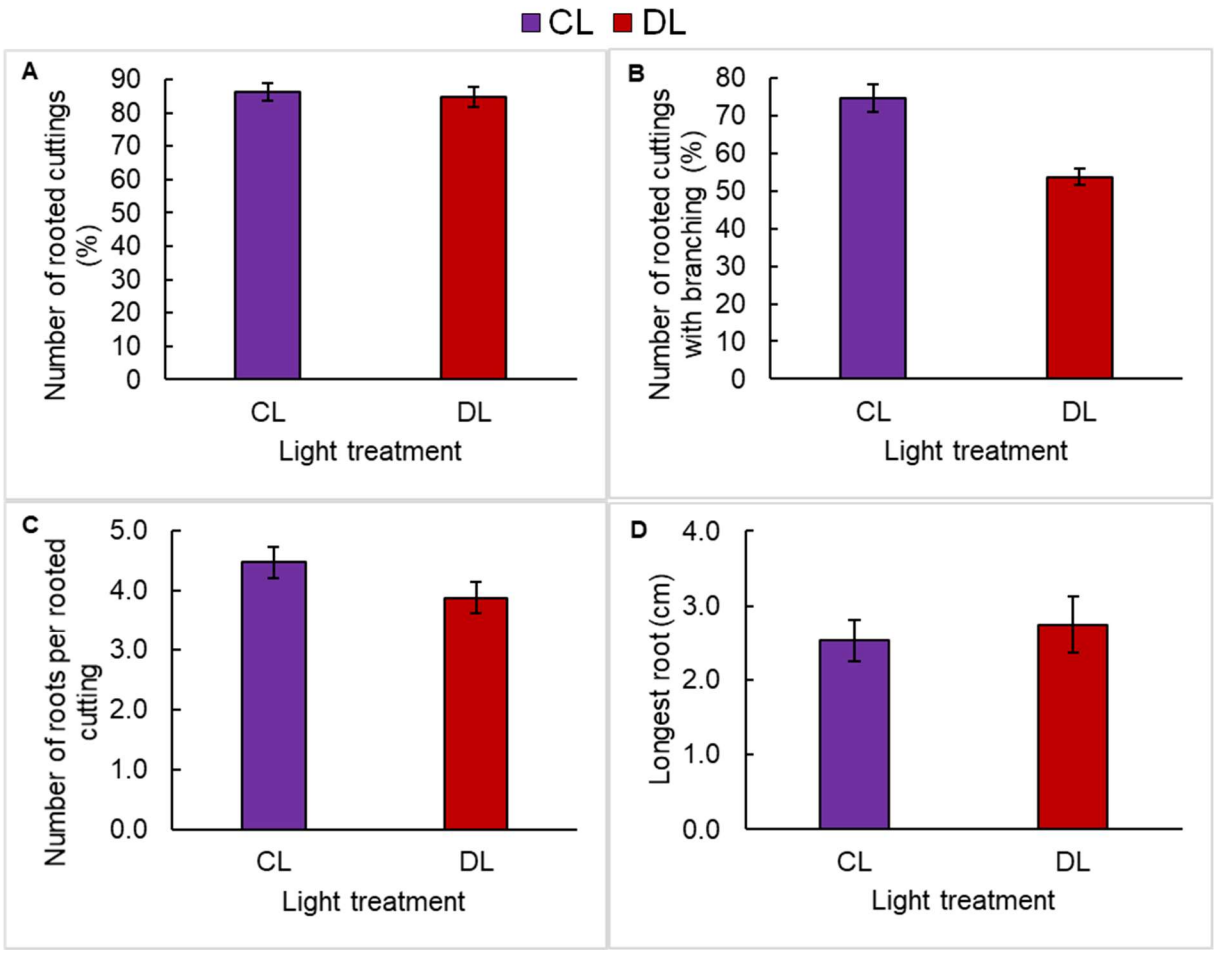

Figure 4. 10. Rooting success and root morphology of campanula cuttings taken from stock plants grown under concurrent (CL) or dynamic (DL) lighting strategies in Expt. 2. Data are mean ± standard error (SE) (n = 3). Within each parameter, all bars that have no symbol indicate that the two lighting treatments are not significantly different at $P < 0.05$ level, but *, **, or *** indicate a significant difference at $P < 0.05$, 0.01, or 0.001 level, respectively, according to Tukey's HSD test.

4.4 Discussion

At the end of the first lighting stage, stock plants under DL produced more SBs than those under CL, despite no difference at final harvest for cuttings. This reached the goal of the

first stage lighting treatment and confirmed that higher-intensity R had a greater promotion effect on side branching than lower-intensity RB. However, it took a longer time (8 vs. 2 weeks) to reach the target of the first stage-lighting in Expt. 2 than in Expt. 1. Possibly, besides light quality, light quantity (or light intensity at the same photoperiod) also plays an important role in regulating branching, especially when associated with a similarly high PPS values (i.e., around 0.89) (Kong et al., 2018a; Leduc et al., 2014; Stutte, 2009). This was also supported by a later catch up of SB number under CL after the second lighting stage, since the intensity of the second stage-lighting was much lower under DL than CL in addition to lower PPS value (0.47 vs. 0.89), which has been confirmed in our previous study on ornamental plants (Kong et al., 2018a).

In both experiments, from the end of the second lighting stage to the final harvest, the stock plants grown under DL remained taller and were >7.5 cm, compared to CL. This indicated that the expected promotion effect on plant height was achieved after lighting with low-intensity B in the second lighting stage. The taller plants under DL did not result from longer main stems, but from longer SBs (Expt. 1) or more upright SBs (i.e., greater inclination angle) (Expt. 2). The promoted elongation and hyponasty of SBs is a typical shade-avoidance response to low-intensity B, which has been observed in previous studies on other plant species (Fukuda et al., 2008; Inoue et al., 2008; Kong et al., 2018a). Despite increased hyponasty, the elongation of SBs promoted by low-intensity B was not observed in Expt. 2. Possibly, the shorter time (i.e., photoperiod) of B lighting in Expt. 2 than in Expt. 1 could explain the results, since the B-promotion effect is positively related to its lighting exposure time such as photoperiod (Kong et al., 2019b).

At the end of the final lighting stage, the stock plants under DL compared to CL had similar SB thickness in both experiments and had similar leaf CCI only in Expt. 1. Based on our measurements at the end of the second lighting stage in Expt. 1, DL compared to CL reduced leaf CCI but had similar SB thickness (data not shown). This indicated that shade-avoidance response induced by low-intensity B during the second lighting stage might have caused obvious negative effects, at least on leaf chlorophyll content, which was also supported by previous studies (Kong et al., 2018a, 2019a; Nhut et al., 2003). However, one-week RB-lighting during the final lighting stage can fully remove the negative effects at a photoperiod of 24-h rather than 10-h. Despite the reduced leaf greenness under DL compared to CL in Expt. 2, the harvested cuttings had similar length and diameter, and subsequent rooting ability. Possibly, for a green cutting with similar stem length and leaf number, stem thickness is more important than leaf chlorophyll content (Cho et al., 2019; Currey et al., 2012; Fischer and Hansen, 1977).

Although DL, compared to CL, increased stock plant height without reducing SB number and thickness or compromising cutting quality, it resulted in some undesirable growth characteristics, such as lower total DW of SB with one branching order and leaf CCI in Expt. 2, rather than in Expt. 1, partly supporting our hypothesis. Possibly, in Expt. 2, a much longer time (8 vs. 2 weeks) of the first stage-lighting with R alone, compared to Expt. 1, might have caused some negative effects on photosynthetic function, which could not be alleviated by later short time of B and RB lighting. Previous studies also indicated that plants grown under long-duration of R alone, compared to RB, have lower net photosynthetic rate and leaf chlorophyll content in some species such as cucumber (*Cucumis sativus*), strawberry (*Fragaria* × *ananassa*), and tomato (*Solanum lycopersicum*) (Hogewoning et al., 2010; Nhut et al., 2003; Zhang et al., 2020).

Aside from higher DW of SBs with one branching order under CL, and despite DL receiving more light (i.e., greater light sum) than CL in Expt. 2, stock plant biomass was generally similar between the two lighting treatments and cutting quality and rooting were similar as well. However, regardless of temporal or spatial combination of R and B lighting, proper R:B ratio is necessary to maintain normal photosynthetic function in plants.

The tested species, *Campanula portenschlagiana*, is a day-neutral plant with regards to flowering response (Whitman and Runkle, 2017) but in Expt. 1, after 5 weeks of 24-h lighting treatment, under both DL and CL, plants showed visible flower buds, which is undesirable for stock plants. The flower buds may affect rooting of cuttings due to a potential nutritional competition between the two strong sinks (i.e., rooting and flowering) (Hutchinson et al., 2012; Moe, 1976; Walters et al., 2019). Although removing flower buds from cuttings is a way to address the problem, it is impractical for large-scale cutting propagation. The flowering response is a complicated physiological process that depends on multiple factors (Runkle et al., 2017). Under a low DLI (e.g., <10 $mol \cdot m^{-2} \cdot d^{-1}$) and a conducive photoperiod (e.g., 16-h), some LDPs had delayed time to visible bud and to first open flower (Owen et al., 2018). Regarding light quality, far-red (FR) light can promote flowering of LDPs (Davis and Burns, 2016), and LDPs, such as *Campanula carpatica*, grown under FR-deficient environments had delayed time to visible bud and flowering, despite a conducive photoperiod (Owen et al., 2018; Runkle and Heins, 2001). In the present study, only R and B lights were used, and our previous study found that 24-h lighting with a high PPS value (i.e., R and RB) delayed flowering in some LDPs such as petunia (*Petunia* × *hybrida*) and calibrachoa (*Calibrachoa* × *hybrida*) (Kong et al., 2018a). However, in Expt. 2 visible flower buds did not appear on stock plants under either DL or CL.

Possibly, for our studied campanula species (*Campanula portenschlagiana*), photoperiod is more important than light quality for flowering.

Considering the undesirable growth characteristic(s) in both Expt. 1 and Expt. 2, it is possible to use different photoperiods at the three lighting stages for DL in the future. In other words, 24-h photoperiod could be applied just for the first stage-lighting treatment, and 10-h photoperiod for the second and final stage lighting treatments. In this case, 24-h R-lighting daily at the first stage would promote faster side branching within two weeks without causing long-term down-regulation of photosynthetic function or promoting flowering. In addition, two-week 10-h B-lighting at the second lighting stage would increase plant height, and one-week 10-h RB-lighting at the final lighting stage would remove the negative effects brought by R or B lighting alone.

In summary, for campanula 'PGM Get MEE®' stock plants grown under SSL, plants showed an increased canopy height under DL compared to CL from the second lighting stage onward under either a 24- or 10-h photoperiod by promoting elongation or hyponasty of SB. Stock plants grown under DL compared to CL had more SBs at the end of the first lighting stage, but had similar number of SBs at the end of the final lighting stage. Also, at the end of the final lighting stage, SB thickness of stock plants was similar under both DL and CL. At a photoperiod of 10-h, although DL reduced leaf CCI and total DW of SB with one branching order in stock plants compared to CL, it did not compromise cutting quality and rooting success. At a photoperiod of 24-h, despite similar growth characteristics, flower buds were visible in stock plants under both DL and CL at the end of the 5-week experiment, which is undesirable in stock

plant production. Using 24-h lighting for DL for only the first lighting stage could potentially address the above problem. Nevertheless, the DL-increased plant height met the expected target and could benefit future machine harvest in a commercial setting.

CHAPTER FIVE
GENERAL DISCUSSION AND CONCLUSIONS

The overall objective of this thesis was to provide recommendations to ornamental growers to improve their plant growth and morphology during the propagation stage by using different light qualities from SSL in an indoor controlled environment. The effects of light quality on seed germination, seedling growth, and stock plant growth and morphology were investigated in three separate growth chamber-studies. The ultimate response to light not only depends on light quality, but also light intensity, photoperiod, and environmental conditions. The results of this thesis demonstrated the potential of improving different aspects of plant propagation by modifying light quality.

In Chapter 2, the effects of different monochromatic light qualities (UVB, B, G, R, and FR) on the seed germination responses of multiple cultivars from five ornamental species was investigated at a low intensity of approximately 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (except for UVB at 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$) under 24-h photoperiod. In general, the seed germination response was not affected by different light qualities and in many cases was similar compared to darkness, although the response varied with plant genotype (i.e., species and cultivar). Considering final germination percentage, germination onset time, germination time spread, and germination speed, R, G, and UVB light appeared to be the most promotive monochromatic lights for seed germination of the tested ornamental plant species, and FR light appeared to be the most inhibitory, demonstrating that modifying light spectral quality can be used to improve plant propagation in a controlled environment.

In Chapter 3, the effects of different light spectral combinations (i.e., recipes) on gerbera seedling growth and quality of four cultivars were evaluated. Six treatments consisting of R and B LED (RB-LED), RB-LED with UVB, UVA, G or FR included, or a cool white FL control were tested under the same PPFD of 165 μmol·m^{-2}·s^{-1} and 16-h photoperiod. Compared to traditionally used FL light, plant growth and morphology were similar under RB-LED, except for a wider canopy of the cultivar 'Majorette Red Dark Eye'. Including a third light spectral quality with RB-LED did not affect plant growth, except for increased stem diameter under RB + FR of 'Maxi Pink' seedlings. The six light treatments used in this study did not have any effect on plant growth and quality of 'Maxi White' or 'Midi Dark Purple', suggesting that the light quality response can be cultivar-specific. The QI, which incorporates characteristics of high-quality plants (i.e., compactness, thick stem, strong roots, and high biomass), was unaffected by light treatments suggesting that just RB-LED is sufficient for controlled-environment propagation of gerbera seedlings and can potentially replace FL light without negatively affecting growth and morphology.

In Chapter 4, a dynamic lighting (DL) strategy was evaluated against concurrent lighting (CL) on campanula stock plant growth and morphology in a growth chamber. The main objective of this study was to produce stock plants with high numbers of cuttings and also cuttings that are long enough and more upright for machine-harvesting. Under short-term 24-h lighting in Expt. 1, although SB elongation and stock plant height were promoted under DL, flower buds were visible in both lighting treatments, suggesting that photoperiod has a greater effect than light quality on flowering for this species. The DL strategy was evaluated in a second experiment with a shorter photoperiod (10-h) to investigate stock plant growth and morphology,

and cutting quality and rooting. The second experiment lasted for a longer duration, and leaf CCI and DW of SBs with one branching order were reduced under DL compared to CL. However, under DL, stock plant height was increased, SBs were more upright, and harvested cutting quality and rooting were unaffected compared to CL in Expt. 2. Therefore, DL with a mix of photoperiods could be used as an effective lighting strategy to modify campanula stock plant morphology for cutting production in a controlled environment.

Overall, the results from Chapter 2, 3, and 4 show the ability and potential of using light quality to improve ornamental plant propagation. However, the results also demonstrate that the responses may be genotype-specific. More research is needed on the response to different light qualities of other commercially important seed-propagated ornamentals. With the indifferent response to light recipes observed in some genotypes in this thesis, growers who are moving to indoor controlled environments, such as multi-level propagation facilities, can group these similar genotypes together for propagation to optimize space and resource use efficiency.

Considering that plant responses to light can be genotype-specific, selecting an “optimal” light quality, or optimal light environment, depends on which parameters are measured and desired (e.g., compactness or elongation). All experiments were conducted in a growth chamber using SSL where other environmental factors (e.g., light intensity, photoperiod, temperature, and RH) were fixed. Changes in these environmental factors, such as either increasing intensity or decreasing photoperiod, could interact with light spectral quality and affect plant growth and morphology, as seen in Chapter 4. This area needs more research and could further benefit controlled-environment ornamental plant propagation.

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