Canadian Journal of Plant Science

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Journal:	<i>Canadian Journal of Plant Science</i>
Manuscript ID	CJPS-2021-0022.R2
Manuscript Type:	Article
Date Submitted by the Author:	19-Jul-2021
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Is the invited manuscript for consideration in a Special Issue?_:	Canadian Horticulture Special Issue
Keywords:	canopy width, optimal light recipe, quality index, stem diameter, tri-chromatic light

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Growth and morphological responses of gerbera seedlings to narrow-band lights with different light spectral combinations as sole-source lighting in a controlled environment

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Abstract

To optimize light-emitting diode (LED) spectral recipes for gerbera (*Gerbera jamesonii*) seedling propagation, seed germination and seedling morphology, biomass, flowering, and storage quality were observed in four cultivars, 'Midi Dark Purple', 'Majorette Red Dark Eye', 'Maxi Pink', and 'Maxi White', under six spectrum treatments: (1) FL, cool white fluorescent light; (2) RB, a photon flux ratio of 85% red and 15% blue (RB-LED); (3) RB + UVB, RB-LED combined with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B; (4) RB + UVA, RB-LED combined with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A; (5) RB + G, a photon flux ratio of 60% red, 15% blue, and 25% green; (6) RB + FR, RB-LED combined with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red. For all treatments, the photosynthetic photon flux density was $165 \mu\text{mol m}^{-2} \text{s}^{-1}$ under a 16-h photoperiod. Seedling growth and morphology were similar under FL and RB for all cultivars, except for a wider canopy of 'Majorette Red Dark Eye' under RB. Each of the tri-chromatic light treatments (i.e., RB + UVB, RB + UVA, RB + G or RB + FR) showed similar effects as RB, except for thicker 'Maxi Pink' stems under RB + FR. Furthermore, the quality index, an integrated evaluation of seedling quality, was similar under all the treatments for each cultivar. Given similar seedling quality and the advantages of LEDs, RB-LED can potentially replace FL for controlled-environment gerbera seedling production, but the tri-chromatic lights tested in this study appear to be unnecessary.

Key words: canopy width; LED; optimal light recipe; quality index; stem diameter; tri-chromatic light

Introduction

Commercial seedlings have been produced increasingly in controlled-environment facilities using electrical light for sole-source lighting (SSL) (Lopez and Runkle 2017). Cool white fluorescent light (FL) has traditionally been used as SSL in controlled-environment seedling production (Gómez et al. 2019). 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 (Morrow 2008).

LED lighting with red (R, 600–700 nm) and blue (B, 400–500 nm) spectral combinations (i.e., RB-LED) have been commonly used for horticultural crop production (Randall and Lopez 2015; Kong et al. 2018). Although the ideal R:B photon flux ratio in horticultural RB-LED lighting can vary with plant species, a ratio of 85% R and 15% B has been commonly and successfully used for a wide range of plant species, including gerbera (Randall and Lopez 2014; Llewellyn et al. 2019). RB-LED, compared to FL, enlarged leaf area of chili pepper (*Capsicum annuum*), kale (*Brassica napus*) and arugula (*Eruca sativa* L.), and increased fresh weight (FW) and dry weight (DW) of chili pepper and lettuce (*Lactuca sativa* L.) (Johkan et al. 2010; Gangadhar et al. 2012; Lee et al. 2016; Ying et al. 2020a). However, in other studies, RB-LED and FL have shown to have similar effects on seedling growth in cucumber (*Cucumis sativus*), tomato (*Solanum lycopersicum*), impatiens (*Impatiens walleriana*), salvia (*Salvia splendens*) and petunia (*Petunia × hybrida*) (Wollaeger and Runkle 2014; Hernández et al. 2016). It appears that the effects of RB-LED relative to FL on plant growth vary with plant species. However, there is a lack of related research on gerbera seedlings.

Plants sense and respond to a broad range of light spectra from ultraviolet (UV, 100–400 nm) to far-red (FR, 700–800 nm), although R and B wavelengths are the most important spectral

qualities for plant biomass accumulation (McCree 1972). Some promotive effects on seedling growth have been observed under tri-chromatic light (i.e., three spectral qualities). For example, including FR along 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). Also, under FR along with RB-LED, pansy (*Viola × wittrockiana*) transplants flowered 7 d earlier than RB (Craver et al. 2018), and the promoted flowering of snapdragon by RB + FR was apparently saturated by $\geq 16 \mu\text{mol m}^{-2} \text{s}^{-1}$ of FR (Park and Runkle 2017). Combining spectra from green (G, 500–600 nm) ($\approx 22\text{--}25\%$ of total PPFD) with RB-LED 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, whether RB + FR or RB + G relative to RB has a similar promotion effect as the above species is unknown for gerbera seedlings under LED as SSL.

Solar radiation has a small amount of UVA (320–400 nm) and UVB (280–320 nm) (Neugart and Schreiner 2018). The average UVA proportion in solar radiation is around 7% of photosynthetically active radiation (PAR, 400–700 nm) (Mah 2019), and is at least 10 times higher than UVB (Verdaguer et al. 2017). Previous studies have indicated that excluding either UVA or UVB from solar radiation 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 2012; Lazzeri et al. 2012). Possibly, adding a low-level (similar to the proportions of solar radiation) of UVA (e.g., $\approx 7\%$ of total PPFD) or UVB (e.g., $\approx 0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$) to RB-LED

may improve seedling quality (e.g., compact plant morphology 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 (Andreasen et al. 2014). A daily light integral (DLI) of 10–12 mol m⁻² d⁻¹ (i.e., 175 to 210 µmol m⁻² s⁻¹ with a 16-h photoperiod) has been recommended for production of high-quality ornamental seedlings in 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 grown in a greenhouse (Randall and Lopez 2015). Possibly, a DLI closer to the lower limit of the recommended level (e.g., 9.5 mol m⁻² d⁻¹; i.e., ≈165 µmol m⁻² s⁻¹ with a 16-h photoperiod) could be enough for controlled-environment production of gerbera seedlings using SSL.

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

Materials and Methods

Plant materials and growing conditions

The experiment was conducted on four gerbera cultivars: *G. jamesonii* ‘Midi Dark Purple’, ‘Majorette Red Dark Eye’ (hereafter ‘Majorette Red’), ‘Maxi Pink’, and ‘Maxi White’, with two replicates over time in a 29 m² walk-in growth chamber at the University of Guelph, Guelph, ON, Canada. All four cultivars are commercially grown as potted plants, and are commonly propagated by seeds. ‘Majorette Red’ seeds were obtained from Sakata Seed America Inc. (Morgan Hill, CA, USA) and seeds of the other three cultivars were obtained from Florist Holland (De Kwakel, The Netherlands). All seeds were uncoated. 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 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 treatment, the seeds sown in the outer two rows were used as guard rows. After seeding, the trays were sub-irrigated with tap water (pH = 7.9, EC ≈ 0.9 dS m⁻¹) until more than 50% of seeds in each tray had germinated. Then, the trays were sub-irrigated with a nutrient solution described in Kong et al. (2018). 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 average (± standard deviation (SD)) air temperature and RH during the experiment were 22.3 ± 1.0 °C and 67.4 ± 3.0 %, respectively.

Experimental design and treatments

The experiment was conducted as a randomized complete block design (RCBD) with one factor (spectrum treatment) and two blocks (or time replicates) for each cultivar. The six spectrum treatments included: (1) FL: cool white fluorescent light as control; (2) RB: a

combination of red and blue LEDs with a photon flux ratio of 85% red and 15% blue (RB-LED); (3) RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; (4) RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; (5) RB + G: a photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; and (6) RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. For each spectrum treatment, the light intensities of different spectral components are presented in Table 1. 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, and their locations were re-randomized between replications.

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 spectra were provided by LED fixtures (LX601C; Heliospectra AB, Gothenburg, Sweden). The RB + UVB and RB + UVA lights were provided by LX601C LED fixtures 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 treatments had a targeted PPFD of $\approx 165 \mu\text{mol m}^{-2} \text{s}^{-1}$ on a 16-h photoperiod to achieve a DLI of $\approx 9.5 \text{ mol m}^{-2} \text{d}^{-1}$. The R, B, G and FR spectra from the LX601C fixtures were set to their target intensities using 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, number of bulbs, and lamp height, respectively. The height of the

fixtures from the top of the trays was ≈ 150 cm for the cool white fluorescent lamp, ≈ 70 cm for the LX601C LED fixtures, and ≈ 65 cm for the UVB and UVA fixtures.

To check light uniformity, light intensity and spectrum were measured over a 16-point grid and a centre point under the fixtures at plant-level within the treatment area in each compartment for each replicate using a radiometrically-calibrated spectrometer (UV/Vis Flame-S-XR; Ocean Optics, Inc., Dunedin, FL, USA) coupled to a CC3 cosine corrector with a $1.9 \text{ m} \times 400 \text{ }\mu\text{m}$ optical fibre. For the spectrum treatments, the light spectral distributions and phytochrome photostationary state (PPS) values are presented in Fig. 1. The PPS values for each spectrum treatment were calculated using the protocol (Mah et al. 2019) developed by our lab according to Sager et al. (1988).

Growth and morphology measurements

Seed germination was recorded when a seed had visible radicle emergence, and cumulative germination percentages were calculated daily for each cultivar under each spectrum treatment until $\approx 90\%$ seed germination. For each cultivar, once at least 50% of the seedlings under each spectrum treatment had four fully expanded true leaves (≈ 5 weeks after sowing), the seedlings of the cultivar from all spectrum treatments were harvested for morphological observations and biomass determination. Ten plants of each cultivar from each spectrum treatment were randomly selected for the harvest. Canopy height and width were measured with a ruler, and the fully expanded true leaves were counted for each harvested plant. 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). The plants were then cut at substrate level, 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. (2020b) in replicate one. In the second replicate, the total leaf area was measured using a Li-Cor 3100C leaf area meter (Li-Cor Inc., Lincoln, NE, USA) and the longest petiole length was measured with a ruler. Both leaf area measurement methods were calibrated 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 of the harvested plants were then washed to remove substrate and dried at 90°C to constant weight to determine DW. Leaf mass per unit area (LMA), leaf/total DW, stem/total DW, root/shoot dry mass (R:S) ratio, and quality index (QI) were calculated using eqs. 1 to 5, respectively.

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

$$(2) \% \text{ Leaf DW} = \text{leaf DW (g)} / \text{total plant DW (g)} \times 100\%$$

$$(3) \% \text{ Stem DW} = \text{stem DW (g)} / \text{total plant DW (g)} \times 100\%$$

$$(4) \text{ R:S ratio} = \text{root DW (g)} / \text{aerial (i.e., shoot) DW (g)}$$

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

After harvest, six remaining plants of each treatment $\times$ cultivar combination with similar size were randomly selected to test post-spectrum treatment flowering responses. These plants were transplanted into 8.5 cm $\times$ 8.5 cm $\times$ 10 cm pots containing Sunshine Mix #1 substrate (Sun Gro Horticulture, Agawam, MA, USA) and 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 of each treatment $\times$ cultivar combination were randomly sampled to measure canopy height and CCI in order to investigate the seedling quality changes under the simulated storage and transport conditions.

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 $\pm$ standard error (SE). For each cultivar, separations of means for different spectrum treatments were performed using Tukey's HSD test at the statistical significance level of $P < 0.05$.

Results

Seed germination

There were no spectrum treatment effects on seed germination for any cultivar (Fig. 2) with cumulative germination percentages of $94.9 \pm 1.1\%$ for 'Majorette Red', $96.0 \pm 1.1\%$ for 'Maxi Pink', $96.3 \pm 1.0\%$ for 'Maxi White' and $97.8 \pm 0.8\%$ for 'Midi Dark Purple'.

Canopy morphology

For all cultivars, canopy height was not different under RB compared to FL, or under each of the four tri-chromatic light treatments (i.e., RB + UVB/UVA/G/FR) compared to RB (Fig. 3A).

The canopy width of 'Majorette Red' was 12% larger under RB compared to FL (Fig. 3B), but for this cultivar, there was no difference in canopy width under each of the four tri-chromatic light treatments compared to RB. The canopy widths were not affected by the spectrum treatments for the other three cultivars.

Stem morphology

There were only spectrum treatment effects on stem diameter of 'Maxi Pink' (Fig. 4A), which had 14% thicker stems under RB + FR compared to RB, but stem thickness was not different under RB compared to FL, or under the other three tri-chromatic light treatments (i.e., RB + UVB/UVA/G) compared to RB. There were no spectrum treatment effects on stem length for all cultivars (Fig. 4B), which was 0.4 ± 0.02 cm for 'Majorette Red', 0.4 ± 0.02 cm for 'Maxi Pink', 0.4 ± 0.02 cm for 'Maxi White', and 0.4 ± 0.01 cm for 'Midi Dark Purple'.

Leaf morphology

For all cultivars, total leaf area was not different under RB compared to FL, or under each of the four tri-chromatic light treatments (i.e., RB + UVB/UVA/G/FR) compared to RB (Fig. 5A). There were no spectrum treatment effects on CCI, the longest petiole length, or LMA for all cultivars (Fig. 5B-D). For 'Majorette Red', 'Maxi Pink', 'Maxi White' and 'Midi Dark Purple', the CCI values were 33.6 ± 1.0 , 37.1 ± 1.3 , 27.5 ± 0.7 and 37.7 ± 0.8 , respectively, the longest petiole lengths were 2.3 ± 0.1 , 2.6 ± 0.1 , 1.7 ± 0.1 and 2.2 ± 0.1 cm, respectively, and the LMA values were 3.3 ± 0.1 , 3.5 ± 0.1 , 3.1 ± 0.1 and 3.6 ± 0.1 mg cm⁻², respectively.

Biomass accumulation and allocation

There were no spectrum treatment effects on biomass accumulation and allocation for all cultivars (Fig. 6). For 'Majorette Red', 'Maxi Pink', 'Maxi White' and 'Midi Dark Purple', the total DW was 0.21 ± 0.01 , 0.24 ± 0.01 , 0.18 ± 0.003 and 0.17 ± 0.01 g, respectively, the percent leaf DW was $71.8 \pm 0.4\%$, $74.6 \pm 0.5\%$, $73.1 \pm 0.7\%$ and $74.4 \pm 0.6\%$, respectively, the percent stem DW was $9.2 \pm 0.3\%$, $9.6 \pm 0.3\%$, $11.0 \pm 0.3\%$ and $9.1 \pm 0.5\%$, respectively, and the R:S ratios were 0.23 ± 0.01 , 0.19 ± 0.01 , 0.20 ± 0.01 and 0.17 ± 0.004 , respectively.

Quality index

There were no spectrum treatment effects on the QI for all cultivars (Fig. 7), with QI values of 62.8 ± 2.0 for 'Majorette Red', 67.2 ± 2.2 for 'Maxi Pink', 52.0 ± 1.2 for 'Maxi White' and 49.1 ± 1.7 for 'Midi Dark Purple'.

Storage quality of seedlings

At the end of the simulated storage period, there were no spectrum treatment effects for any cultivar on plant height and CCI of upper and lower true leaves (Fig. 8A-C), with post-storage plant heights of 6.8 ± 0.2 , 7.4 ± 0.1 , 6.7 ± 0.3 and 7.0 ± 0.2 cm, upper true leaves' CCI values of 20.0 ± 0.8 , 20.6 ± 1.4 , 17.2 ± 1.0 and 23.6 ± 1.5 , and lower true leaves' CCI values of 19.8 ± 0.9 , 20.2 ± 0.7 , 16.4 ± 0.9 and 22.0 ± 2.1 , for 'Majorette Red', 'Maxi Pink', 'Maxi White' and 'Midi Dark Purple', respectively.

Flowering time

There were no spectrum treatment effects on post-transplant flower initiation time (i.e., days from transplanting to the first visible bud) for any of the four cultivars (Fig. 8D), with flower initiation times of 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'.

Discussion

The effects of the RB-LED treatment were similar to FL, except for a larger canopy width of 'Majorette Red'. This confirmed the first hypothesis that RB-LED, compared to FL, did not reduce seedling quality at least for some gerbera cultivars. Possibly, in 'Majorette Red', 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 a 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 $\approx 210 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Mah et al. 2018) and in lettuce at $\approx 100 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Johkan et al. 2010). The above plant species along with gerbera ‘Majorette Red’ may be highly sensitive to a decreased B level.

G in combination with R and B can increase whole plant photosynthesis due to deeper penetration of G into the leaf canopy (Kim et al. 2004). 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 (Wollaeger and Runkle 2014; Meng et al. 2019). However, no promotion effects were observed under RB + G relative to RB for any of the plant traits in all the cultivars in the present study. The smaller leaf canopy of gerbera seedlings in the present study compared with other studies might 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 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. However, subsequent flowering of the transplants was not promoted by including FR along with RB 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). In addition to the varying sensitivity in response to FR among different plant species, R:FR ratio was also 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 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.

In the present study, including UVA or UVB along with RB-LED did not affect any of the metrics (including storage quality) measured in gerbera seedlings for all the cultivars relative to RB. 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. Adding UVB to RB-W (white)-LED light (PPFD of $\approx 185 \mu\text{mol m}^{-2} \text{s}^{-1}$ for 16 h d⁻¹) for 4 h d⁻¹ for 6 d caused compact plants by inhibiting elongation growth in lettuce (Lee et al. 2014). Including UVA (3% of PFD) to RB-G-LED combination (PPFD of $30 \mu\text{mol m}^{-2} \text{s}^{-1}$ for 16 h d⁻¹) improved storage quality of broccoli (*Brassica oleracea* var. *italica* Plenck) transplants (Wojciechowska et al. 2020). The difference between our study and the above studies might result from different background lighting, UVA or UVB levels, or plant species.

Characteristics of a high-quality seedling include a compact canopy, thick stem, strong roots, and high biomass (Randall and Lopez 2014). In this case, a composite of multiple traits is necessary to depict seedling quality. The QI is a useful tool to evaluate seedling quality as it integrates multiple morphological parameters such as stem length (or plant height), stem diameter, and plant biomass (Currey et al. 2013). In the present study, there were no spectrum treatment effects on the QI for any gerbera cultivar. This would suggest that RB-LED can potentially replace FL as SSL for growing gerbera seedlings in controlled environments if only considering the effects on seedling quality. However, in practical production, the currently higher initial investment on LED technologies 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 (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 a third spectrum 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 should be noted that plants under RB-LED can appear purple, making it difficult for growers to monitor colour changes (i.e., disease or nutrient deficiency) in plants (Smith et al. 2017). Including G with RB-LED makes it easier for growers to observe the plants and to detect the signs of diseases (Mitchell and Stutte 2017).

In summary, for the four gerbera cultivars grown inside a controlled environment using SSL at a PPFD of $\approx 165 \mu\text{mol m}^{-2} \text{s}^{-1}$ and a 16-h photoperiod, the seedlings under RB-LED relative to FL had similar plant morphology except for an increased canopy width of '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 thicker 'Maxi Pink' stems under RB + FR. There were no spectrum treatment effects on the QI, an integrated quality index of transplants for all four cultivars. It appears that RB-LED can potentially replace FL as SSL for controlled-environment production of gerbera seedlings, and tri-chromatic lights used in this study may be unnecessary, if only considering seedling quality.

Acknowledgements

This project is part of the Accelerating Green Plant Innovation for Environmental and Economic Benefit Cluster and is funded by the Canadian Ornamental Horticulture Alliance (COHA-

ACHO) and by the Government of Canada under the Canadian Agricultural Partnership's AgriScience Program. We thank Plusrite Hortscience for their financial support, Heliospectra AB for providing LED light fixtures, and Sakata Seed America Inc. and Bayview Flowers Ltd. for providing seeds and advice. Thanks to Michelle Edwards for her help with statistical analysis and Dave Llewellyn for his excellent technical support and informative discussions during the study.

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Table 1. Light intensity of different spectral components and total photosynthetic photon flux density (PPFD) of the different spectrum treatments.

Spectrum treatment	Light intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$)						PPFD (400– 700 nm) ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
	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	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

Note: Data are presented as mean ± standard error (SE). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with 0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with 9.6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with 17.3 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED.

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

Fig. 2. Cumulative seed germination (%) under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

Fig. 3. Plant canopy morphology under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-

LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

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

Fig. 5. Leaf morphology under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-

red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

Fig. 6. Biomass accumulation and allocation under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

Fig. 7. Quality index under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

Fig. 8. Post-harvest storage quality and flowering of four gerbera cultivars grown under different spectrum treatments. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced

from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

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

59x39mm (300 x 300 DPI)

Fig. 2. Cumulative seed germination (%) under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with 0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with 9.6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with 17.3 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

34x18mm (300 x 300 DPI)

Fig. 3. Plant canopy morphology under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

41x18mm (300 x 300 DPI)

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

41x18mm (300 x 300 DPI)

Fig. 5. Leaf morphology under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

41x35mm (300 x 300 DPI)

Fig. 6. Biomass accumulation and allocation under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

41x35mm (300 x 300 DPI)

Fig. 7. Quality index under different spectrum treatments of four gerbera cultivars. Data are mean $\pm$ standard error ($n = 2$). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with $9.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with $17.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at $P < 0.05$ level according to Tukey's HSD test.

34x18mm (300 x 300 DPI)

Fig. 8. Post-harvest storage quality and flowering of four gerbera cultivars grown under different spectrum treatments. Data are mean $\pm$ standard error (n = 2). For the six spectrum treatments, FL: cool white fluorescent light; RB: photon flux ratio of 85% red and 15% blue sourced from LED (RB-LED); RB + UVB: RB-LED in combination with 0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-B sourced from narrow-band fluorescent light; RB + UVA: RB-LED in combination with 9.6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of ultraviolet-A sourced from LED; RB + G: photon flux ratio of 60% red, 15% blue, and 25% green sourced from LED; RB + FR: RB-LED in combination with 17.3 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red sourced from LED. Within the same cultivar, treatments bearing the different letters are significantly different at P < 0.05 level according to Tukey's HSD test.

41x35mm (300 x 300 DPI)