Section 3. Spectral effects on plant growth: Protected ornamentals

3.0. INTRODUCTION

Many different plant species and varieties are commercially grown within the protected ornamental sector. Although morphology and flowering requirements differ considerably across this diverse range of plants, in the majority of cases crops must remain compact and healthy but must also be in bloom at the point of sale. Achieving this goal can be challenging, especially as many crops are only grown during the winter/spring months when natural light levels are low. Many ornamental crops are routinely treated with plant growth regulators to help retain a compact form. However, ongoing challenges are resulting in a gradual reduction in the number and diversity of PGRs that are available. Finding alternative solutions to maintain plant quality will provide growers with additional methods for maintaining plant quality, helping protect the industry from the potential loss of PGRs. In this section, we will examine the potential for using light treatments to control plant morphology and also how light treatments can be used to induce flowering.

Species examined include

Petunia

Pansy

Pelargonium

Begonia

Chrysanthemum

3.1. PETUNIA

The petunia results were performed during year 1 and year 2 of the project. The key findings of this work are summarised here. For more detail see the year 1 and year 2 reports.

3.1.1. Methods

Petunia (*Petunia hybrida,* Mirage Blue F1, CN Seeds) were used for all trials. Seed were sown in one inch cells and placed under the different light treatments. Plants were transplanted into six-packs filled with Levington M2 substrate when the plug plants were of sufficient size.

Light treatments

Year 1 light treatments. The effects of red:blue ratios were investigated using six light treatments with 0%, 11%, 15% 33% 58% and 100% blue light (Appendix: Light treatments, Table 1). The influence of far-red treatments were examined using light treatments containing a standard red blue treatment (11% blue) provided by Philips production modules and four intensities of far-red light (0, 15, 20 and 40 µmol m^{-2} s^{-1}) provided by Philips FR research modules (Appendix: Light treatments, Table 2).

Year 2 light treatments. The influence of light intensity on growth and development was examined using four different light intensities (100, 180, 280 and 360 µmol m^{-2} s^{-1}) of red:blue light (11% blue) provided by Philip production models (Appendix: Light treatments, Table 3). The influence of red, blue and far-red treatments were examined using eight treatments. These treatments comprised two red:blue ratios (30% blue and 60% blue) with four far-red intensities (~0, ~10, ~20, ~30 µmol m^{-2} s^{-1}; Appendix: Light treatments, Table 4).

3.1.2. Results

Influence of light intensity on growth and development

Petunia plug plants were grown under four different light intensities (Figure 3.3) for 26 days. Plant size was observed to increase as the light intensity increased from 100 to 280 µmol m^{-2} s^{-1}. At the highest light intensity (360 µmol m^{-2} s^{-1}) the morphology became more compact. These more compact plants had more robust, thicker feeling leaves with darker pigmentation, a morphology associated with high light environments. The soil plugs were observed to be increasingly robust as the light intensity increased indicating that root growth increased with intensity. After 26 days the plug plants were transplanted to six-packs after

which they grew rapidly (Figure 3.1). The growth rates correlated with light intensity and after 35 days (from sowing) the plants from the 360 µmol m^{-2} s^{-1} light treatment possessed open flowers. The numbers of flower buds as well as the number of open flowers were tracked between day 35 and day 57 (Figure 3.2). Open flowers were observed in the 280 µmol m^{-2} s^{-1} treatment after 38 days and after 46 days in the 200 µmol m^{-2} s^{-1} treatments. No open flowers were observed in the 100 µmol m^{-2} s^{-1} treatment, though the first flower buds were visible at 58 days. Number of flower buds and numbers of open flowers increased as more light was supplied to the plants.

Figure 3.1. Petunia plants grown under different light intensities for 35 days (5th November 2015) nine days after transplantation to six-packs. Numbers indicate the total PAR photon irradiance measured in µmol m^{-2} s^{-1}.

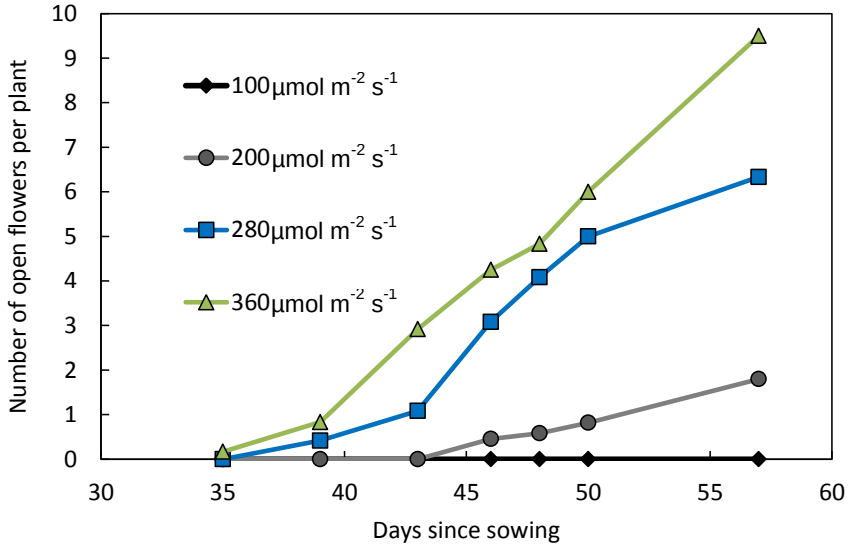

Figure 3.2. Influence of light intensity on the time course of petunia flower production when grown under four different photon irradiances.

As well as producing the most flowers, plants grown under the greatest light intensities also produced larger flowers that opened more rapidly than those from the lower light intensities. To gain a more detailed assessment of the plant growth rate and morphology destructive samples of the plants were collected on day 43. Plant mass increased up to 280 µmol m^{-2} s^{-1} but remained similar as the intensity increased further (Figure 3.3A). This may because biomass accumulation slows once the plants begin to flower. As the plants from the highest intensity began flowering first the slower growing plants mass accumulation could have caught up. Number of side branches was unaffected by intensity (Figure 3.3B). Leaf length was similar in all the treatments though a small decrease was observed as intensity increased (Figure 3.3C). Leaf width was observed to increase as light intensity increased from 100 to 280 µmol m^{-2} s^{-1} but to decrease as the intensity increased further (Figure 3.3D). Internode length decreased progressively as intensity increased and leaf mass area (Figure 3.3A; LMA; an estimate of leaf thickness) increased progressively as more light was provided (Figure 3.3F). The results reported in this section demonstrate the benefits of increasing light intensity on the speed of growth and flowering as well as plant quality of petunias. Adding more light to a system, however, requires greater investment in lamps and electricity. With this in mind how efficiently does this system convert electrical energy in to saleable plant material, how much energy is consumed in the process and do shorter production times save energy? Using the data from Figure 3.2 we estimated the number of days it took to produce petunia plants with two flowers (Figure 3.4A). The 100 µmol m^{-2} s^{-1} treatment produced no flowers and so is excluded from this analysis. The time taken to produce two flowers decreases from 58 days to 41 days (17 days or 30% quicker) as the intensity increased from 200 µmol m^{-2} s^{-1} to 360 µmol m^{-2} s^{-1}. By combining the time required and the energy inputs for crop production total energy inputs were determined Figure 3.4B. The energy consumption was observed to increase with light intensity and the 360 µmol m^{-2} s^{-1} treatment consumed 41% more energy than the 200 µmol m^{-2} s^{-1} treatment.

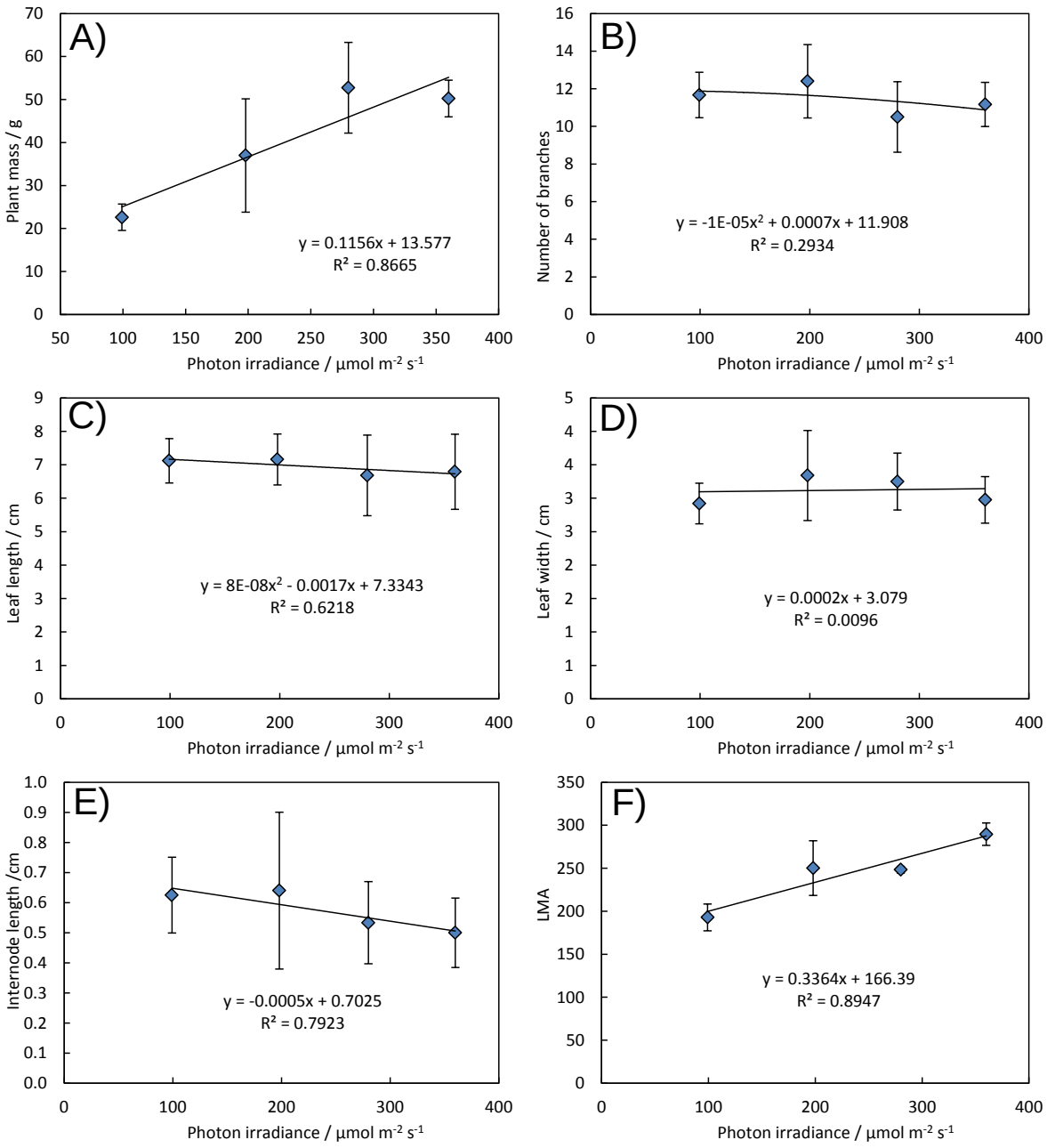

Figure 3.3. The influence of light intensity on Petunia plant mass and morphology after 43 days of growth. **A)** Mean plant mass. **B)** Mean number of side branches. The mean leaf length **C)** and width **D)** of the leaf below the first flower (the last vegetative leaf). **E)** Mean length of the internode below the last vegetative leaf. **F)** The mean leaf mass area (LMA) of the last vegetative leaf.

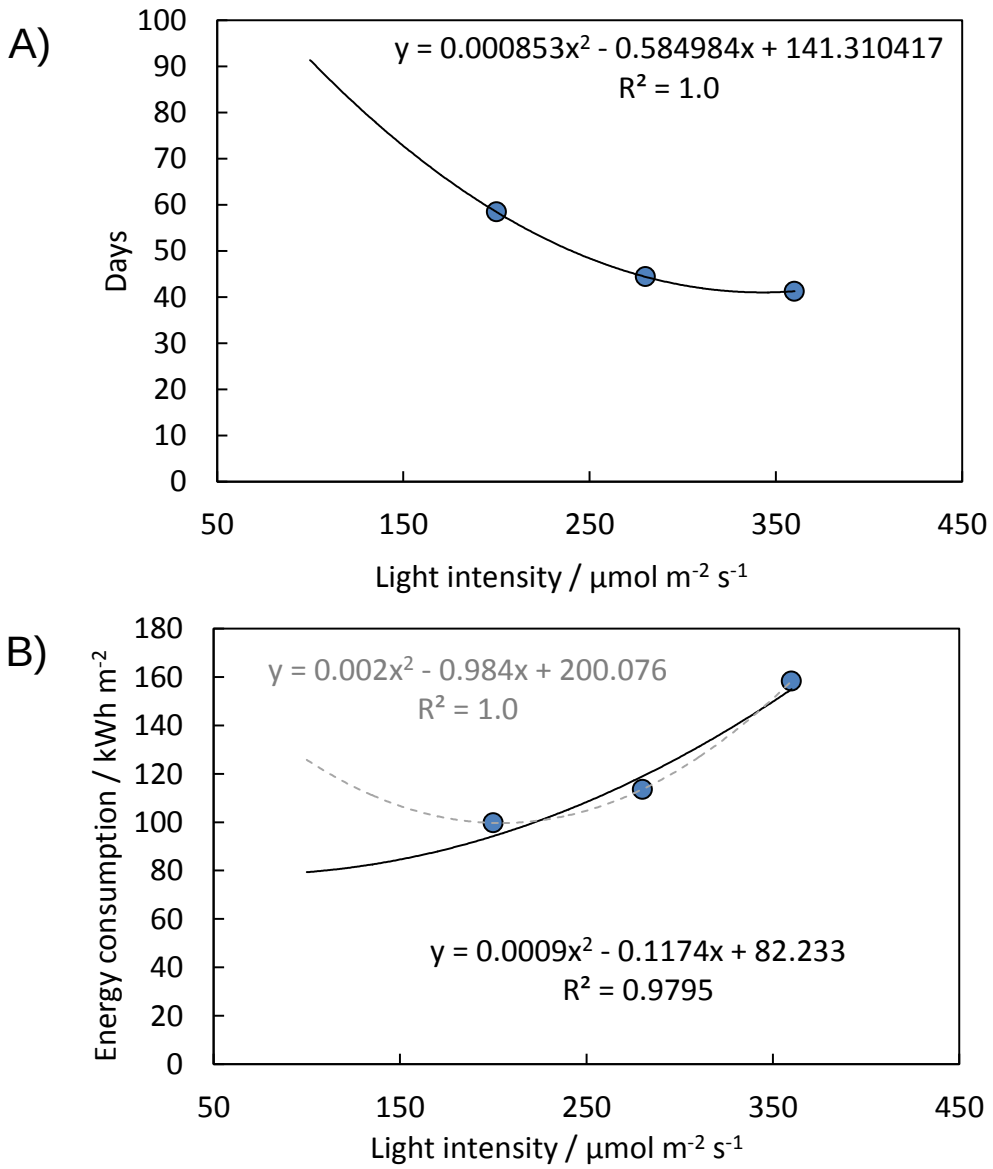

Figure 3.4. The influence of photon irradiance on **A)** duration required and **B)** electrical energy required to produce petunia plants with 2 flowers. Solid line in A) represents a best fit polynomial regression. The grey dashed line in B) represents a best fit polynomial regression while the solid line shows the relationship calculated using the regression line from A).

The influence of red:blue ratio on petunia

The petunia plants germinated and grew rapidly and produced good quality plug plants 3.5 weeks after sowing. The plug plants produced under the 100% blue light treatment had the largest leaves but, overall, these plants were the lowest quality as they had long petioles. The most compact plants were produced under the 58% blue light treatment. The fastest growing and best quality plants were produced under the 11 and 15% blue light treatments. The plant size was strongly influenced by light treatment at all stages of growth after potting

on (Figure 3.5). Plants grown under 100% blue light produced larger leaves and consistently longer internodes than those in the lower blue percentage treatments that also contained red light (Figure 3.6). Total shoot mass was, however, lowest for the plants grown under 100% blue and greatest under the 11% blue light. This indicates that the large

Figure 3.5. Images of the petunia plants grown under four different red blue light environments after 42 days of growth (23rd February 2015).

increase in plant height was associated with significant changes in biomass partitioning. The most compact plants were observed in the 58% blue treatment. Branch number was found to be greatest in the 11% light treatment and correlated with shoot biomass. The large differences in plant morphology were combined with large differences in flowering rates between the different light treatments. Flowering occurred earliest and most intensely in plants grown under 100% blue light (Figure 3.7). Plants from the 11% blue light treatments were the second most vigorously flowering and plants from the 58% blue light treatment produced the fewest flowers. In order to assess if the differences in flowering could be described by the different growth rates of the plants from the different treatments, the total number of flowers was divided by the total shoot mass (Figure 3.7B). For the plants grown under light treatments ranging between 11 and 58% blue light, flowers were produced at a similar rate with one flower occurring for every 0.5-1 g of fresh weight. In the 100% blue light treatment, flower production per mass of plant was greatly increased, with

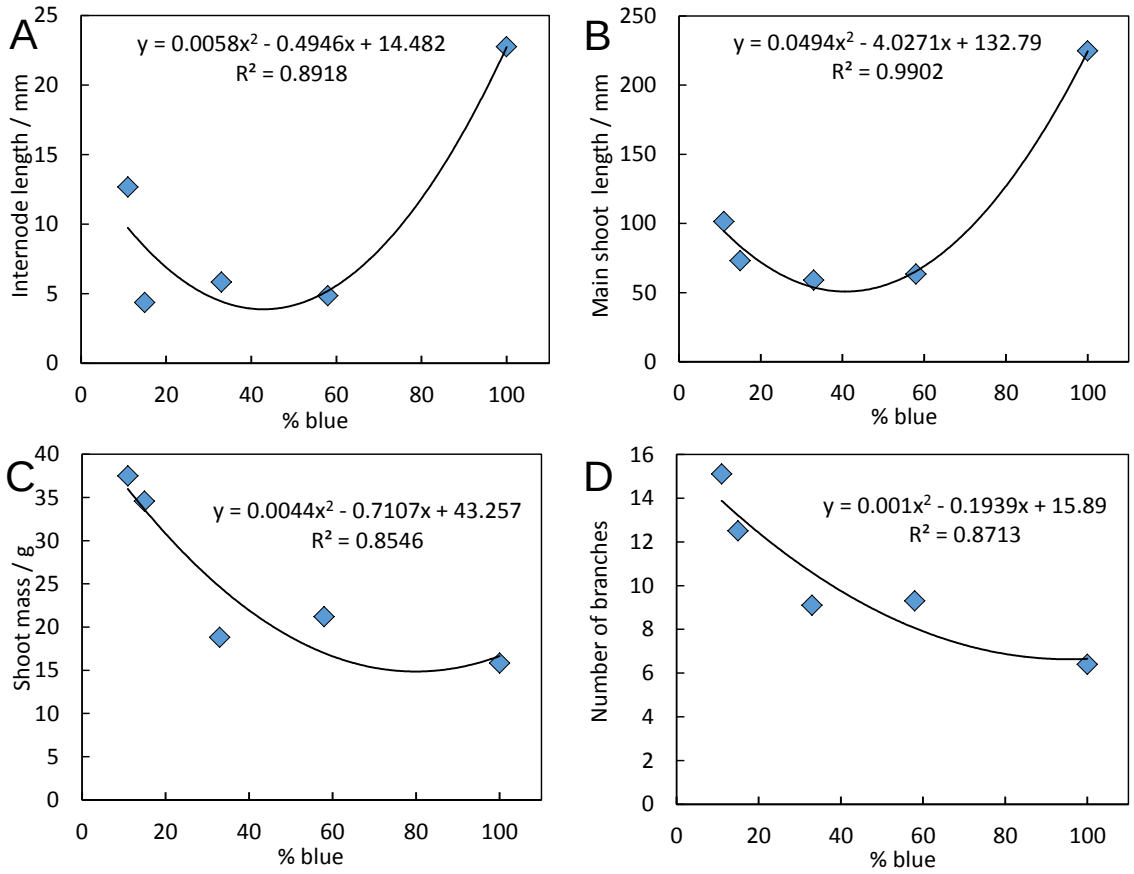

Figure 3.6. The influence of blue light percentage on the **A)** internode lengths, **B)** main shoot length, **C)** the fresh shoot mass and **D)** the number of side branches of petunia plants grown under different red blue light treatments.

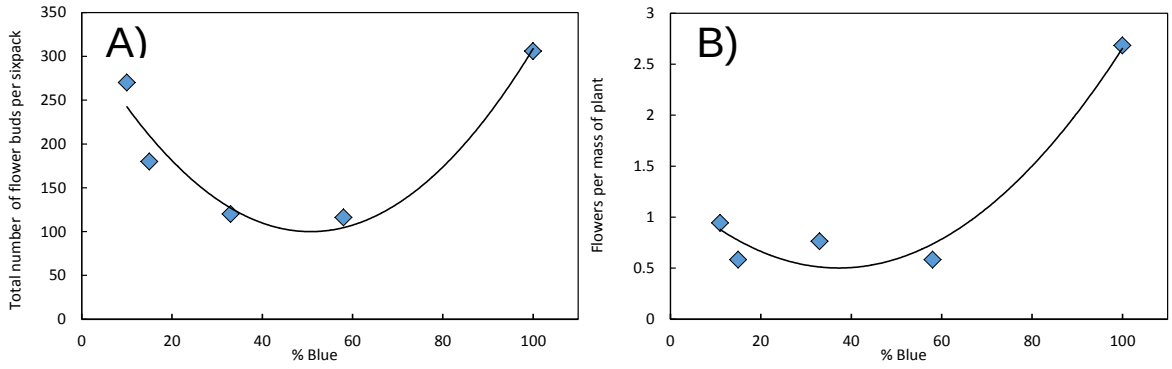

Figure 3.7. The relationship between blue light percentage and **A)** total numbers of flowers and **B)** number of flowers per gram of fresh weight for petunia plants grown under the different light treatments.

greater than 2.5 flowers occurring for every gram of plant tissue. This indicates a large increase in investment towards flowers in plants grown with no red light.

The influence of far-red on petunia

The petunia plug plants were similar in size in the four far-red treatments, though the plants in the no far-red treatment had shorter petioles and the leaves were held nearer to the substrate. The plants in the treatment with the highest far-red photon irradiance were slightly weaker plants than those in the other treatments. Once potted up, the differences between the treatments increased as the plants grew (Figure 3.8). Internode and main stem lengths increased linearly with increasing far-red intensity (Figure 3.9 A&B). Far-red intensity had little influence on shoot mass (Figure 3.9C). The number of side branches decreased rapidly in response to increasing far-red treatments, resulting in a leggy appearance (Figure 3.9D). The plants in the no far-red treatment remained compact and produced many branches, but flowering was delayed by two weeks in comparison to the other treatments. In the far-red light treatment plants, total flower bud production occurred earlier and more intensely but the transition of bud to flowers was also promoted. In contrast to the influence of far-red on internode lengths, flowering was not observed to increase linearly in response to far-red light. Instead, far-red intensities of 15 µmol m^{-2} s^{-1} were sufficient to induce a maximum number of flowers (Figure 3.10). However, when the number of flowers produced per fresh mass of plant was determined, flower number was found to increase linearly with far-red intensity.

The influence of red, blue and far-red treatments on petunia

A series of light treatments were designed to see if the benefits of red: blue treatments (compact plants) could be combined with the benefits of far-red treatments (early flowering). Petunia plants were grown under eight different light treatments. Two blue percentages (30% blue and 60% blue) each with four different amounts of additional far-red light (0, 10, 20 & 35 µmol m^{-2} s^{-1}). The plants grew well under all treatments and were ready for transplantation 26 days after sowing. While all treatments produced good quality plugs there were noticeable differences in plant morphology. Far-red light produced plants with larger leaves. Destructive measurements of the plug plants identified the plants grown under 30% blue light to have higher biomass than those grown under 60% blue light. For the plants grown under 30% blue light an increase in far-red intensity from 0 to 11 µmol m^{-2} s^{-1} increased biomass but further far-red increases reduced biomass. Far-red light had

Figure 3.8. Images of petunia plants at two stages of growth showing **A)** the influence of far-red light on vegetative growth after 42 days growths and **B)** the influence of far-red light on flowering after 52 days growth.

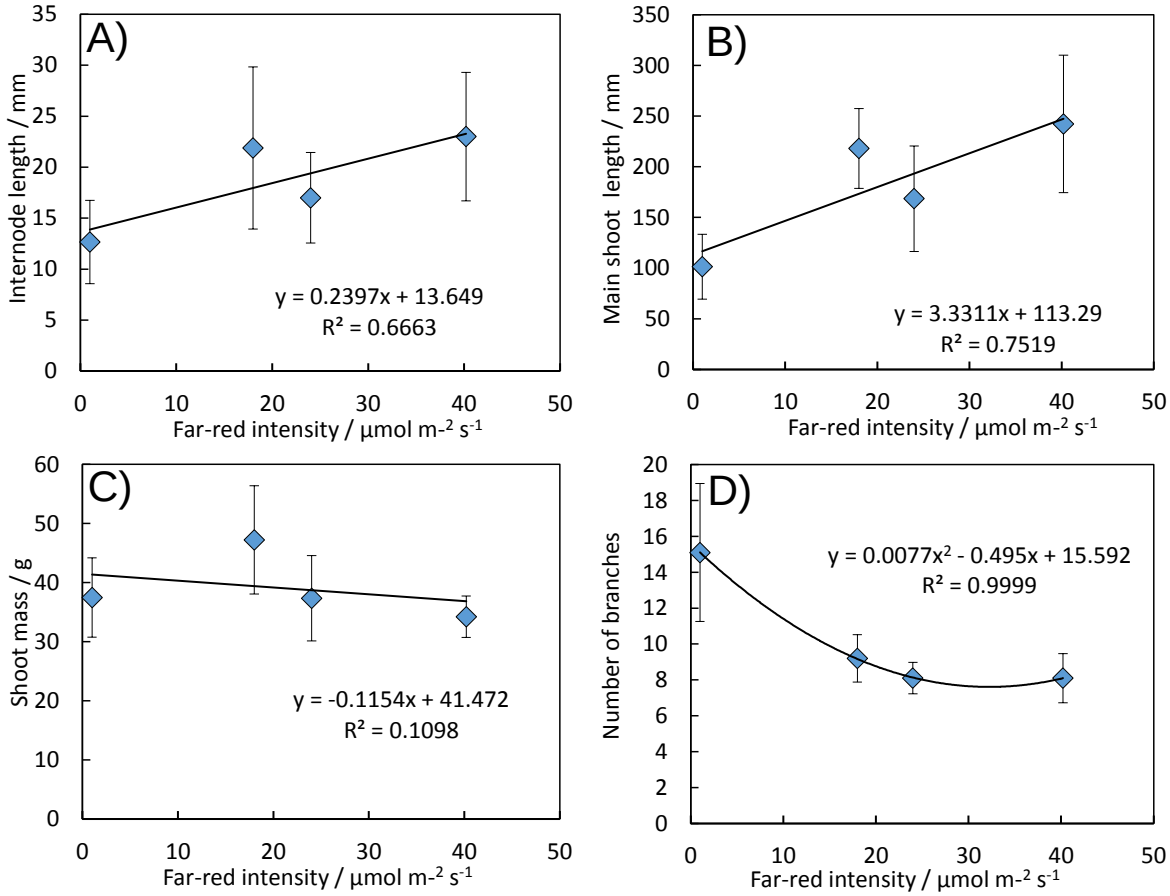

Figure 3.9. The influence of far-red light on the morphology of petunia plants. **A)** Internode length, **B)** length on primary shoot, **C)** total shoot mass, and **D)** the number of side branches per plant.

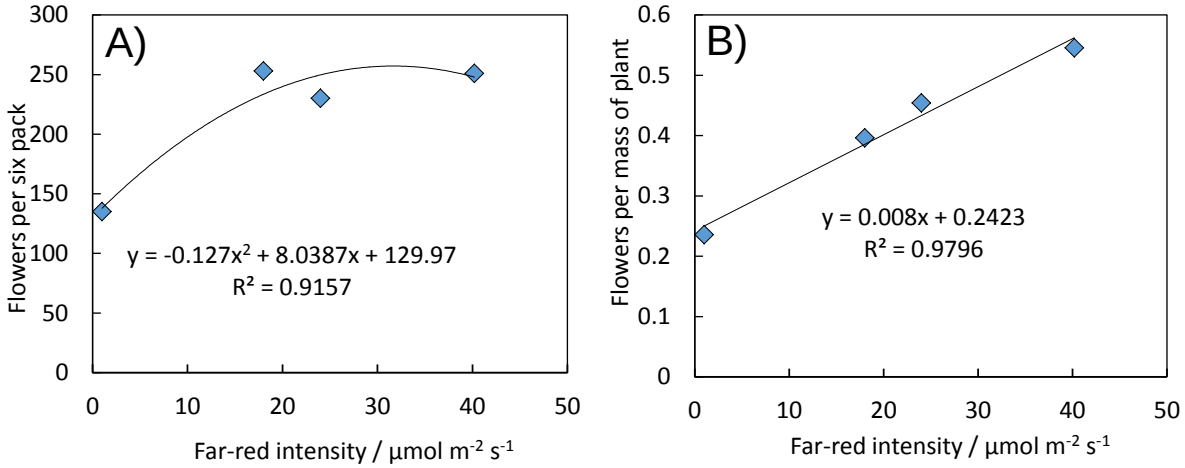

Figure 3.10. The relationships between far-red intensity and **A)** number of flowers per six pack of petunias and **B)** the number of flowers per mass of plant.

little influence of the biomass of plug plants grown under 60% blue light. Far-red light reduced the number of side shoots in plants grown under both 30% and 60% blue light: the 30% blue plants produced slightly more side shoots. Number of leaves per plant was observed to increase as far-red light intensity increased from 0 and 11 µmol m^{-2} s^{-1}, especially under the 60% blue light treatments, but decreased slightly at higher far-red intensities. Leaf lengths were greater under 30% blue than 60% blue light. The increases in leaf length caused by far-red light occurred at lower far-red intensities under the 30% blue treatments than for the 60% blue light treatments. Far-red caused leaf width to decrease slightly in the 30% blue light treatments but to increase slighting under the 60% blue light treatments.

Following transplantation the plants grew rapidly and nine days later the plant morphology was considerably different between the treatments (Figure 3.11). Plants were in full flower by the 13th November 2015 (17 days after transplantation and 43 days after sowing). Plant height and flower production were observed to increase with far-red light. The addition of far-red light had a more pronounced effect in the 60% blue treatments compared to the 30% blue light treatments.

Plant mass was observed to decrease as far-red intensity increased (Figure 3.12). This response was more pronounced at lower far-red intensities in the 60% blue treatment than in the 30% blue light treatment. The number of side branches was greater in the 30% compared to the 60% blue light treatments. For both the 60% and 30% blue treatments, increasing far-red from 0 to 10 µmol m^{-2} s^{-1} resulted in a decrease in side shoots while more far-red, increased the number of side shoots. The length of the last vegetative leaf on the petunias was unaffected by the light quality. Leaf width was observed to increase with far-red light intensity, though for the 30% blue + 36 µmol m^{-2} s^{-1} far-red light treatment leaf width decreased. Internodes increased linearly with far-red light intensity and were similar in length between the 30 and 60% plus far-red treatments. Leaf robustness, assessed in proxy as leaf mass area (LMA), was found to be unaffected by the different light treatments. Flower bud development was also affected by the different light treatments. Total number of flower buds was determined over a 25 day period. Under both the 30% and 60% blue light treatments flower numbers were lowest in the treatments containing no far-red light but were similar in the three treatments containing different amounts of far-red. Slightly more flowers were produced under the 30% blue light treatments probably due to the greater biomass of these plants. Number of open flowers was more strongly influenced by the amount of far-red provided than numbers of flower buds indicating that far-red light also influences flower opening. The most open flowers were produced in the treatments with the most far-red light and the fewest open flowers were observed under the treatments with no

Figure 3.11. Petunia plants grown under the eight red: blue: far-red light treatment. Plants photographed on the 13th November 2015, 47 days after sowing.

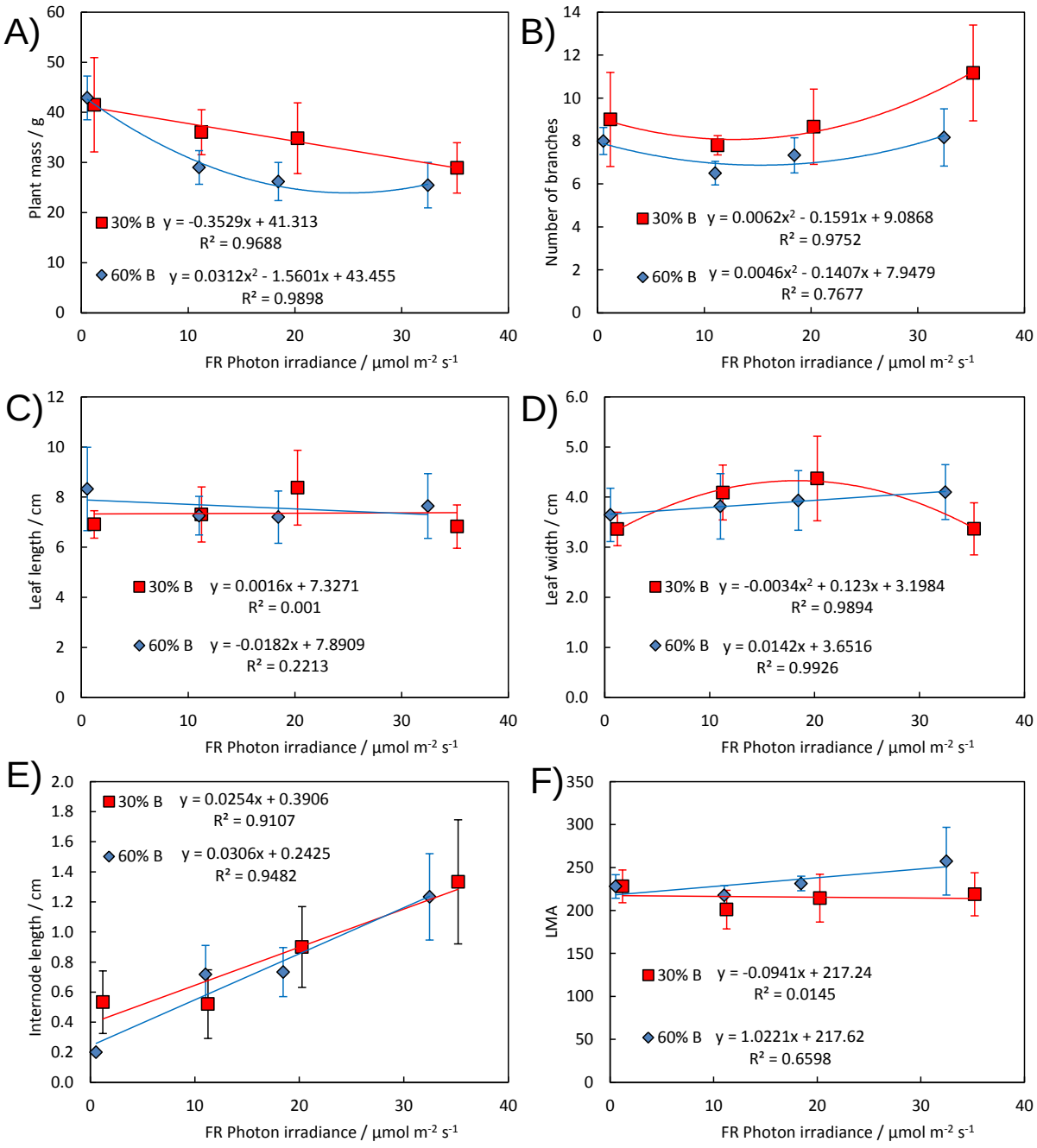

Figure 3.12. The influence of red, blue and far-red light on petunia mass and morphology. Blue symbols and lines represent data from plants grown under 60% blue + 40% red light with different amounts of far-red. Red symbols and lines represent data from plants grown under 30% blue + 70%red light with different amounts of far-red. **A)** Plant mass, **B)** number of branches longer than 1 cm, **C)** length and **D)** width of the last vegetative leaf, **E)** length of the internode below the last vegetative leaf and **F)** leaf mass area (LMA) of the last vegetative leaf.

far-red light. Slightly more open flowers were produced under the 30% blue light treatments compared to the 60% blue treatments.

The rate flower development was assessed in the different treatments to determine the influence of far-red on opening speed (Figure 3.13). Under the 30% blue light treatments far-red light reduced the time it took a flower to open by only about half a day and most of this effect occurred between 0 and 11 µmol m^{-2} s^{-1}. Under the 60% blue treatments flowers opened about one day quicker than those under the 30% blue treatments and the far-red light had a greater influence on opening speed. 35 µmol m^{-2} s^{-1} of far-red light reduced opening speed by 1 day. Flower morphology was also altered by light quality (Figure 3.14). Flower diameter was found to increase with far-red intensity. Flowers from the 30% blue treatment were slightly larger than those from the 60% blue treatment but the influence of far-red light was similar for both sets of blue light treatment. While far-red was found to increase flower size the sepal size was found to decrease as far-red intensity increased.

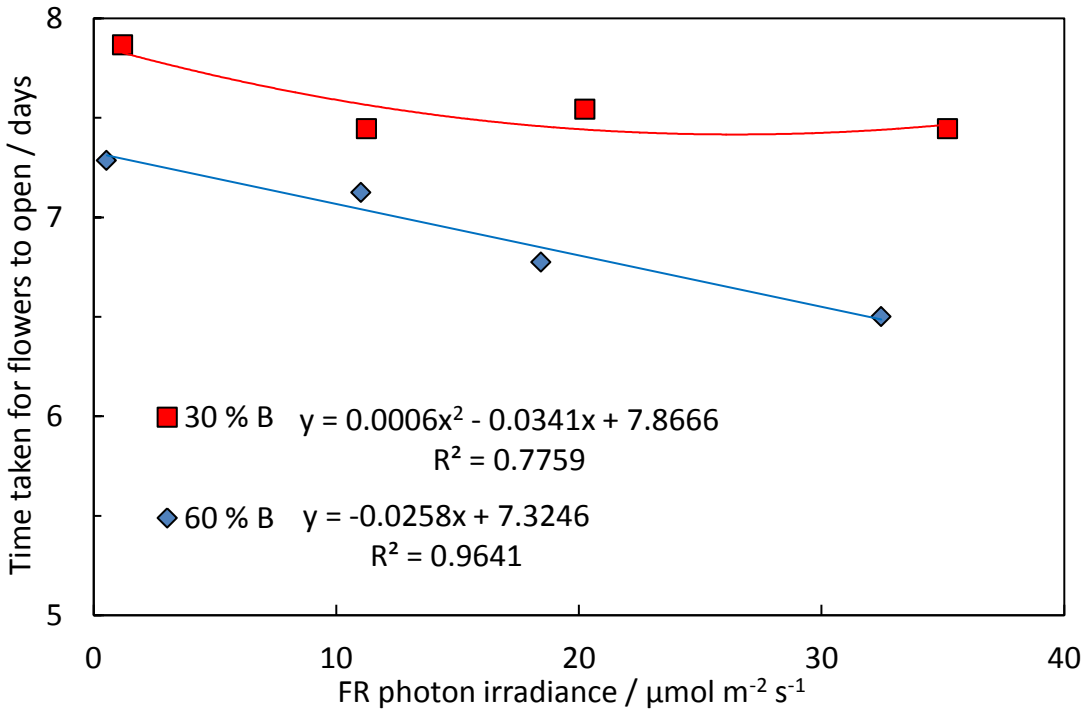

Figure 3.13. The influence of blue and far-red light on the time it takes petunia flowers to open.

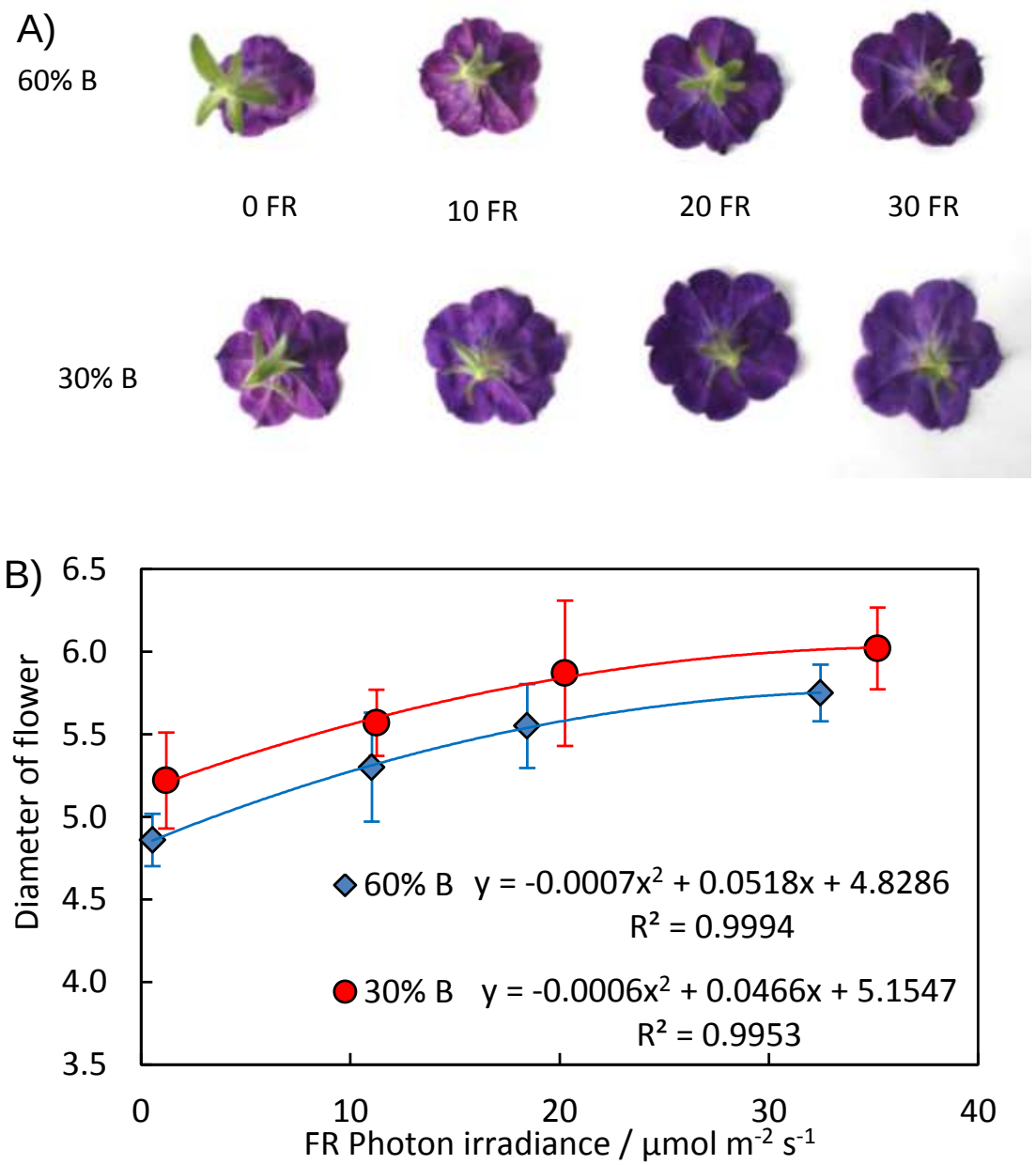

Figure 3.14. A) Photographs of Petunia flowers grown under the eight different red : blue : far-red light treatments. **B)** The influence of light quality on Petunia flower diameter

3.1.3. Key findings - Petunia

- Increasing the total PAR photon irradiance increased petunia growth rates, flowering speed and plant quality.

- Energy consumption increased non-linearly as light intensity increased. The optimum balance between running costs and plant quality is expected to be between 200 and 280 µmol m^{-2} s^{-1}, but may be higher if the benefits of increase plant quality can be recouped via higher sales values or volumes.

- The most compact petunia plants were produced under red: blue treatments containing ~60% blue light.

- The greatest biomass was achieved under treatments containing low blue percentages (9-11% blue).

- Far-red increased petunia flowering speed but reduced compactness and biomass.

- Combining red, blue and far-red treatments provides more control over petunia morphology and flowering time but the negative influence of far-red light on morphology was enhanced under the higher blue percentage treatments.

3.2. PANSY

The trials examining pansy light responses were performed in years one and two and are reported here in summary. For more details see the year one and year two reports.

3.2.1 Methods

Pansy (*Viola wittrockiana*) c.v. Dynamite Formula Mix for year one trials and Dynamite Strawberry for year two trials (CN Seeds) were sown in one inch cells and placed under the different light treatments in the LED4CROPS facility. Plants were transplanted to six packs containing Levington M2 substrate once they had achieved sufficient size.

Light treatments

Year 1 Trials. The effects of red:blue ratios were investigated using five light treatments with 0%, 11%, 15% 33% 58% and 100% blue light (Appendix: Light treatments, Table 1). The influence of far-red was examined using light treatments containing a standard red blue treatment (11% blue) provide by Philips production modules and four intensities of far-red light (0, 15,20 and 40 µmol m^{-2} s^{-1}) provided by Philips FR research modules (Appendix: Light treatments, Table 2).

Year 2 Trails. The influence of light intensity on growth and development was examined using four different light intensities (100, 180, 280 and 360 µmol m^{-2} s^{-1}) of red:blue light (11% blue) provided by Philip production models (Appendix: Light treatments, Table 3). The influence of red, blue and far-red treatments were examined using eight treatments. These treatments comprised two red:blue ratios (30% blue and 60% blue) with four far-red intensities (~0, ~10, ~20, ~30 µmol m^{-2} s^{-1}; Appendix: Light treatments, Table 4).

3.2.2. Results

Influence of light intensity on growth and development

The pansy plug plants from the four light intensity treatments were similar in appearance (Figure 3.15) but with some distinct differences. The plants under the 100 µmol m^{-2} s^{-1} treatment were showing slight signs of shade avoidance syndrome while the plants from the 360 µmol m^{-2} s^{-1} treatment looked perhaps too compact and bit stressed. Petiole length decreased with increasing light intensity. The 360 µmol m^{-2} s^{-1} was too much light for these seedlings and fewest usable plants were produced from this treatment. The pansies were all potted up to six-packs on 10th November 2015, 41 days after sowing.

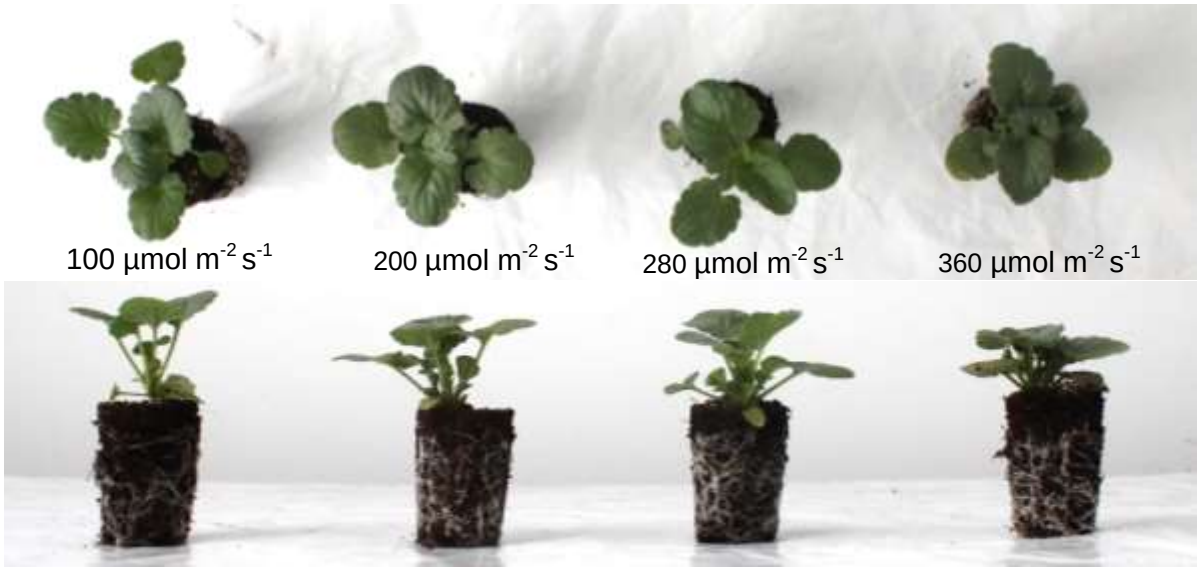

Figure 3.15. Pansy plug plants grown under four different photon irradiances. Photographs taken on the 10th November 2015 (41 days after sowing).

At the final harvest the plants from all treatments had grown well and had similar appearances (Figure 3.16). Plant mass correlated positively with light intensity (Figure 3.17A). Number of side branches produced per plant increased slightly with increasing light intensity (Figure 3.17B). Internode lengths were observed to decrease with increasing light intensity (Figure 3.17C) resulting in greater plant compactness. Leaf colour also varied with light intensity with leaves having a darker green colour (Figure 3.17D) and more robust feel at higher intensities.

Figure 3.16. Pansies from the four photon irradiance treatments taken shortly after the final harvest on the 14th December 2015, 74 days after sowing. **A)** Representative six-packs **B)** representative individual plants viewed from the side.

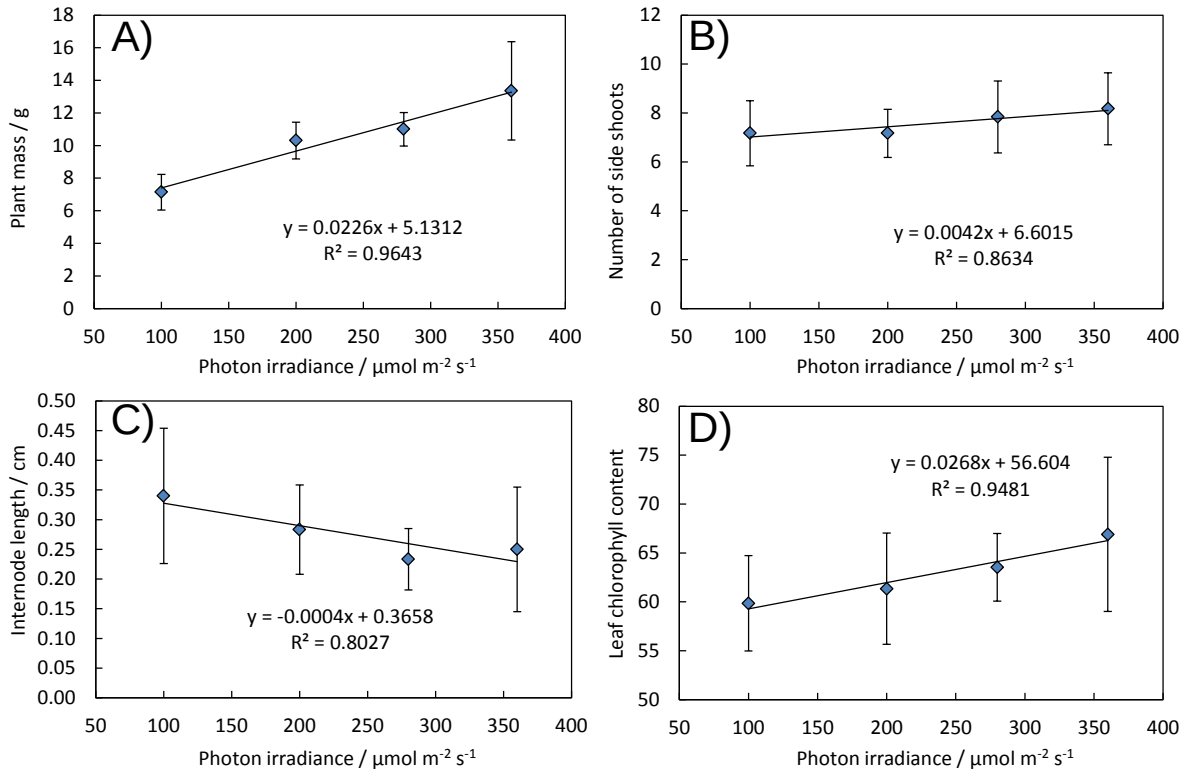

Figure 3.17. Influence of light intensity on the morphological parameters of pansy plants. **A)** Mean plant mass. **B)** Mean number of side shoots per plant. **C)** The length of the two internodes found below the node holding the first open flower. **D)** Estimate of leaf chlorophyll content made using a leaf chlorophyll content meter.

Flower development in the pansies was also influenced by light intensity. Open flowers were first observed in the 280 µmol m^{-2} s^{-1} treatment followed by the 200 µmol m^{-2} s^{-1} then the 360 µmol m^{-2} s^{-1} treatment. The 100 µmol m^{-2} s^{-1} treatment produced flowers last (Figure 3.18A). While the 360 µmol m^{-2} s^{-1} treatment was third to flower, at the end of the study this treatment had produced the most flowers and flower number correlated with light intensity. Increasing light intensity was also found to increase the diameter and mass of the pansy flowers. The amount of energy required to produce pansies was with one flower was calculated using the time required to produce flowering plants and the energy usage of the different light intensity installations. Energy consumption required to produce plants with one flower (Figure 3.18B) was observed to be similar between 100 and 200 µmol m^{-2} s^{-1} but to increase as light intensity increased further. In this case 200 µmol m^{-2} s^{-1} provides the optimal light intensity for pansy production and plant quality was good under this treatment.

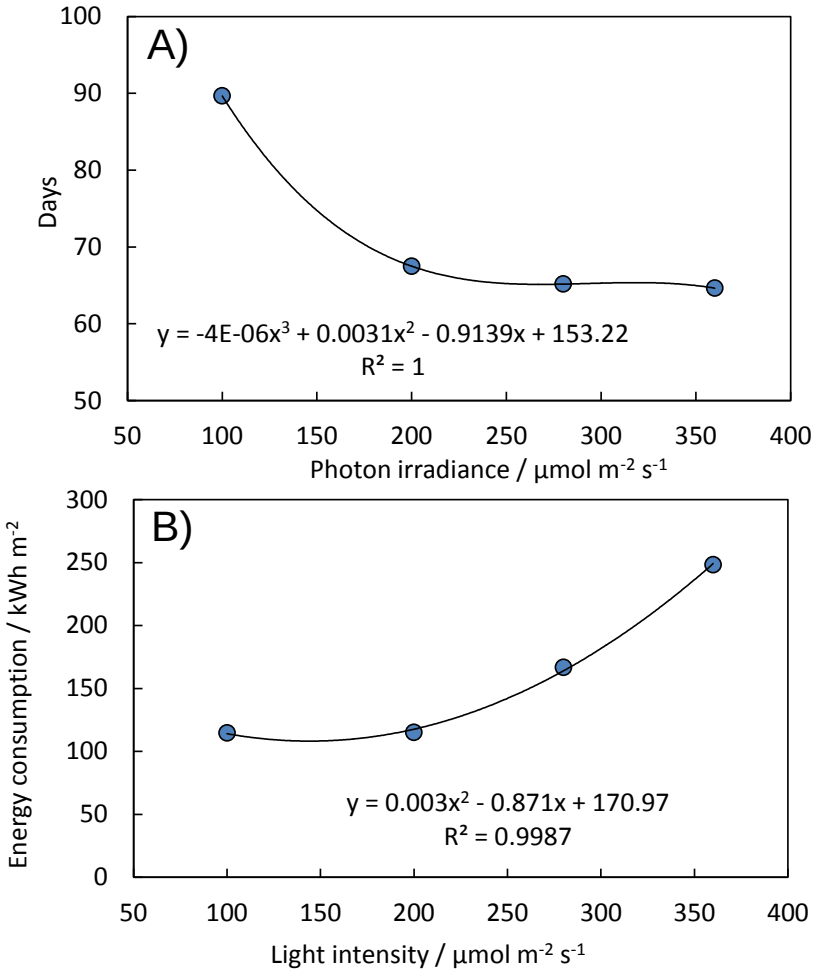

Figure 3.18. The influence of light intensity on **A)** duration of time required and **B)** electrical energy required to produce Pansy plants with 1 flower.

The influence of red: blue ratio on pansy

Plug plants were assessed after six weeks growth and size and quality was greatly influenced by light treatment (Figure 3.19). The lowest quality plants were produced under the 100% blue light treatments, and these plants were etiolated and produced the fewest leaves. The differences in quality between the other treatments were largely associated with total plant size, with the largest fastest growing plants observed under the 11% blue light treatment. The slowest growing and most compact plants were observed under the 58% blue light treatment. Root growth was poor under the 100% blue light treatments and the plugs disintegrated when handled. Root growth was sufficient in the other treatments to retail their structure when handled.

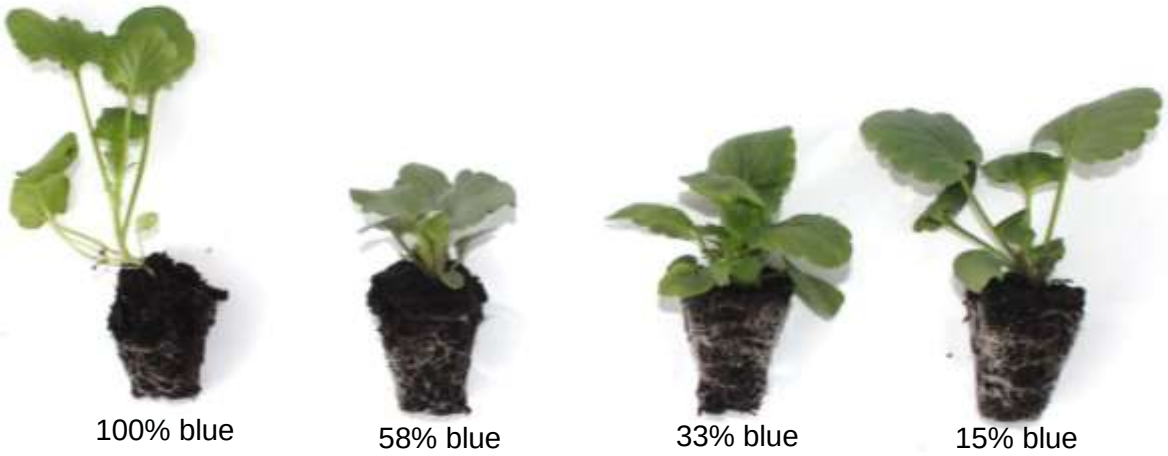

Figure 3.19. Representative pansy plug plants grown under four different red : blue light treatments after 42 days growth.

Figure 3.20. Images of pansy plants from the different red: blue light treatments 73 days after sowing.

After transplanting, the pansies grew rapidly and differences in plant quality and morphology persisted through the life of the plants (Figure 3.20). The plants grown under 100% blue light remained etiolated with internodes being almost 10 times greater than the internodes of plants from the other treatments (Figure 3.21). Stem diameter was observed to increase

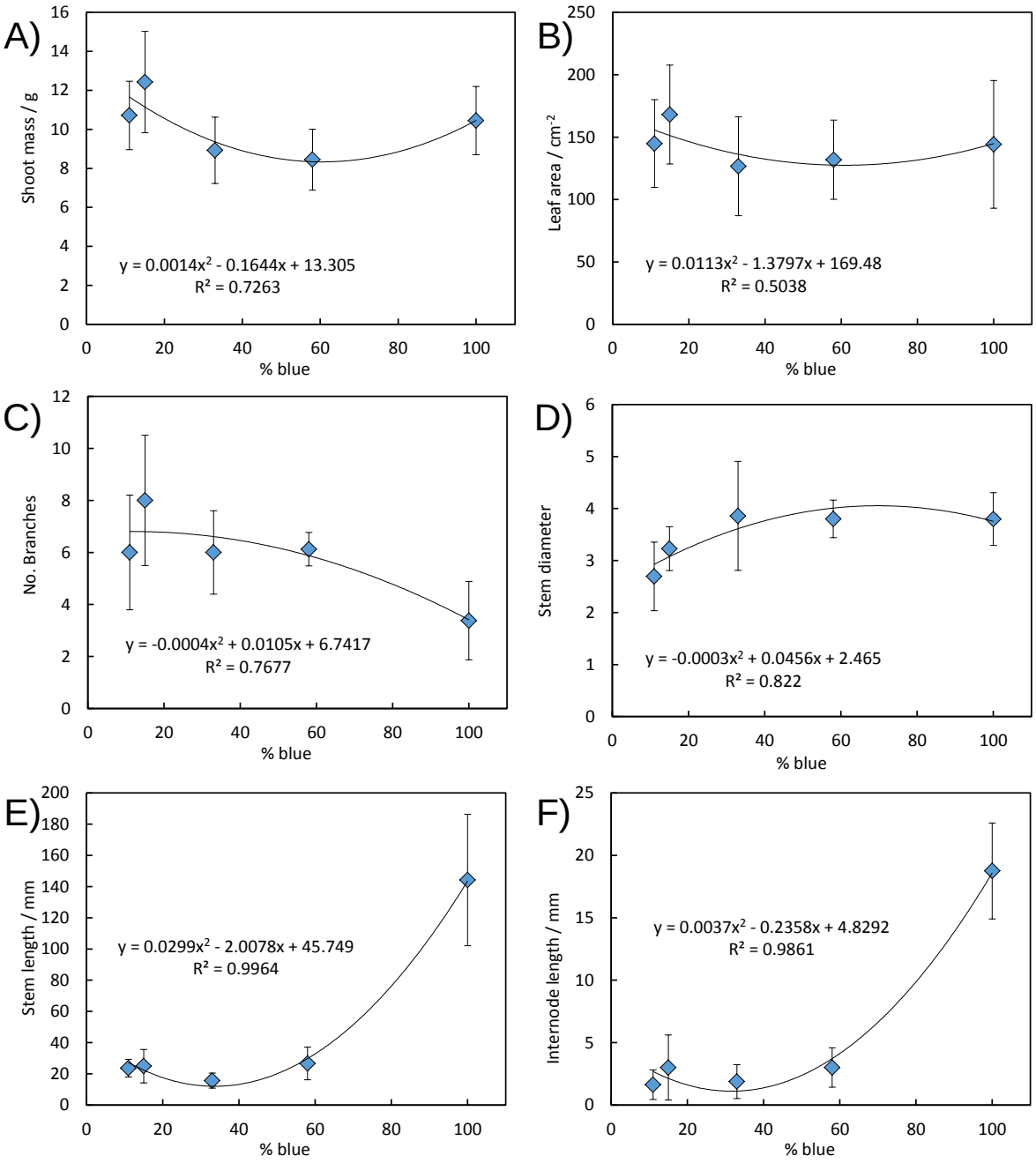

Figure 3.21. The influence of red: blue light treatments on the **A)** shoot mass, **B)** leaf area, **C)** number of branches, **D)** stem diameter, **E)** shoot length, and **F)** internode lengths of pansy plants at final harvest.

between 11 and 33% blue light but remained similar at greater blue light percentages. The number of side shoots was least in the 100% blue light treatments and greatest in the 15% blue light treatment. Light treatments also influenced flowering time and intensity. Flowering occurred earliest and most extensively in pansies grown under 100% blue light (Figures 3.22). Flower production was similar in the 11 and 15% light treatments and was slowest and similar for the 33 and 58% blue light treatments.

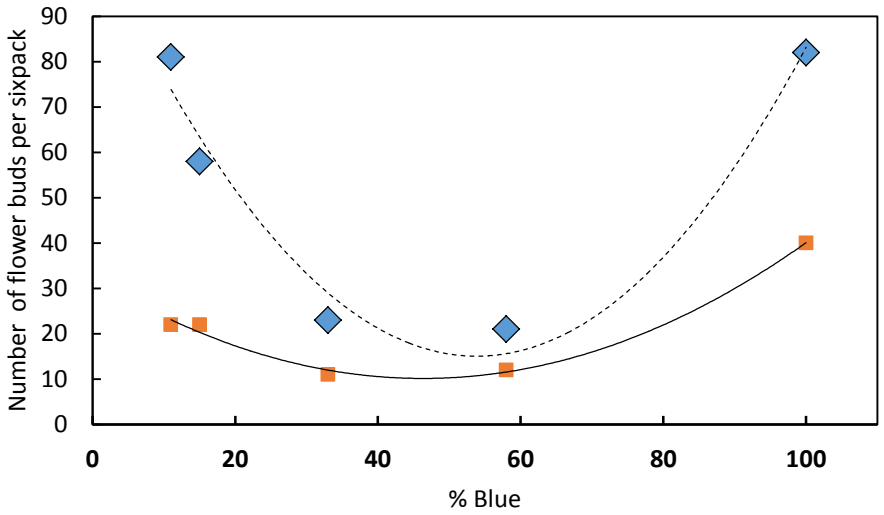

Figure 3.22. Effect of red blue light treatment on the total numbers of flowers produced by pansies grown under the different blue light percentage treatments on two dates: 13th March 14 (orange symbols) and 24th March 2014 (final harvest; blue symbols).

The influence of far-red photon irradiance on pansy

Pansy plug plants were found to grow taller and produce less compact plants as far-red photon irradiance increased. While the plants were taller and appeared larger when grown under the far-red light treatments, the number of leaves per plant was not influenced by far-red light. Leaf area and shoot mass were found to increase as far-red increased, though these responses were saturated at far-red intensities of about 30 µmol m^{-2} s^{-1}.

Following transplantation to six packs, treatment differences were observed to persist and increase as the plants grew (Figure 3.23). The plants remained very compact when grown without far-red light and they remained compact even after flowering had commenced. At the end of the study, all morphological parameters (Figure 3.24) except the number of branches were observed to increase with far-red light intensity up to about 30 µmol m^{-2} s^{-1} but showed no change with further increases in far-red.

Figure 3.23. Images of pansy plants showing the influence of far-red light on vegetative growth and flowering 52 days after sowing (5th March 15).

Pansy flowering was greatly advanced by the addition of far-red light (Figure 2.32 & Figure 3.25). In the presence of far-red light, flower buds were observed one week earlier than on plants grown without far-red light. Open flowers also appeared two weeks later on plants grown without far-red light. There was little increase in flowering as far-red increased from 18 to 48 µmol m^{-2} s^{-1} indicating that the flowering response was far-red saturated. It is expected that smaller amounts of far-red would promote flowering and that these treatments could have less impact on plant morphology.

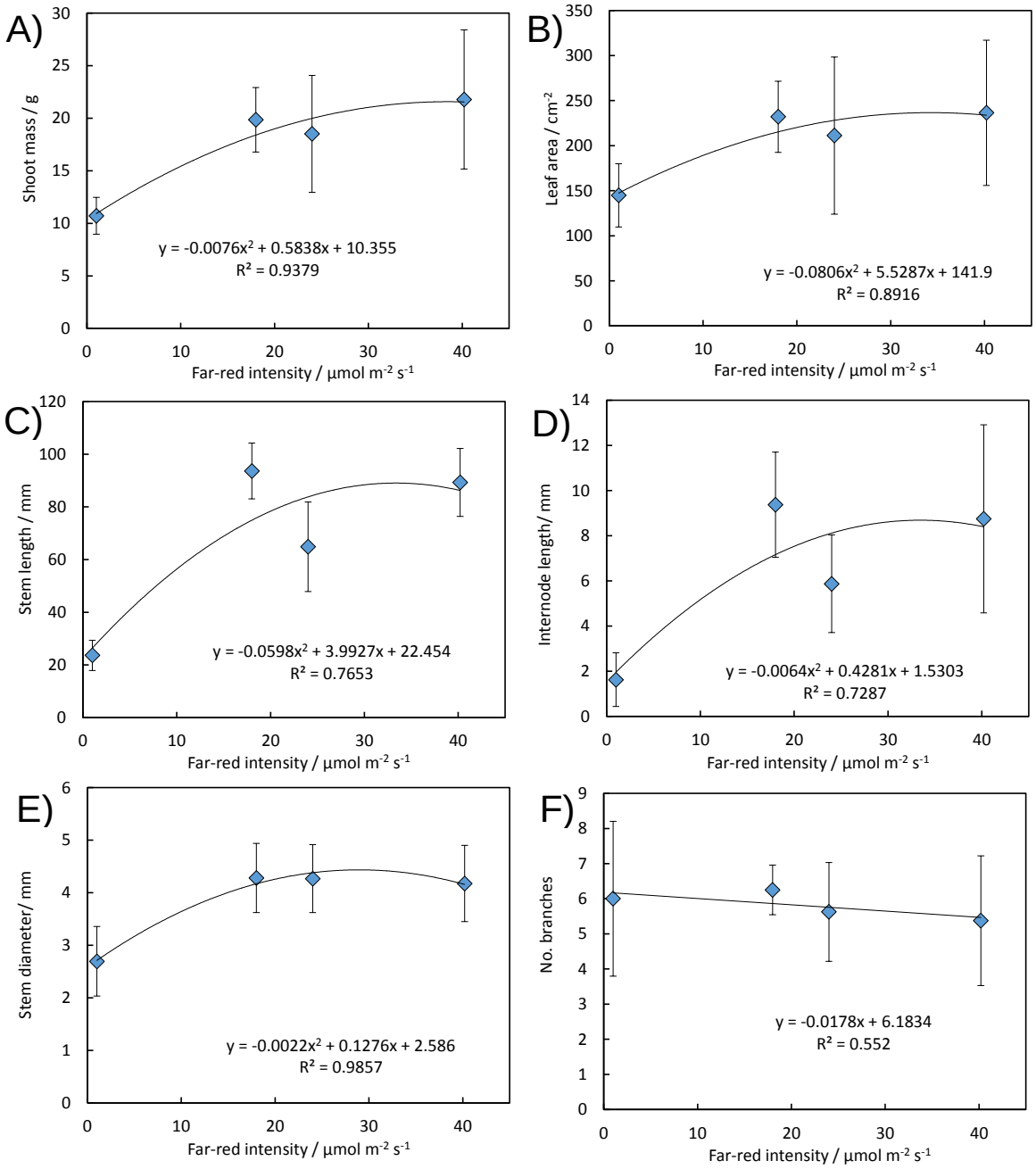

Figure 3.24. The influence of far-red light on the morphology of pansy plants at final harvest. **A)** Total shoot fresh mass, **B)** leaf area per plant, **C)** length of the primary stem, **D)** internode length, **E)** stem diameter, and **F)** number of branches.

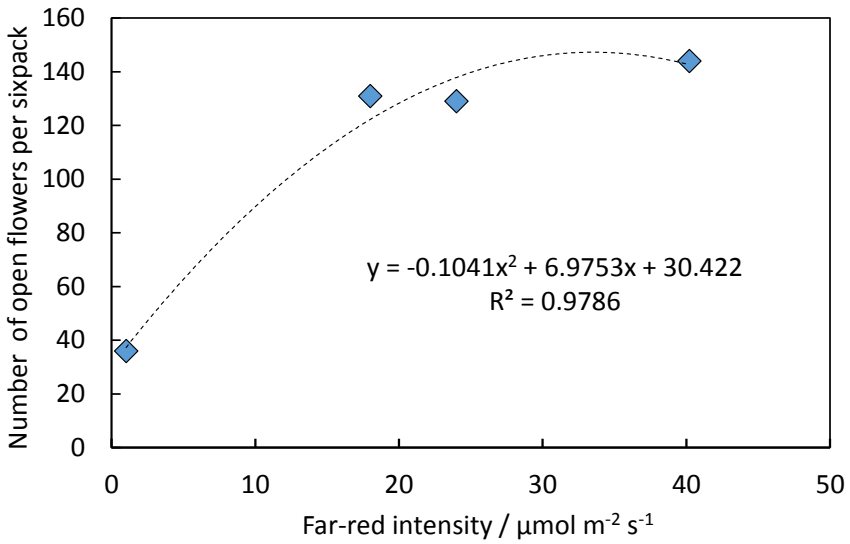

Figure 3.25. The relationship between far-red light intensity and number of flowers produced by pansies.

Combined red: blue: and far-red treatments

Pansy plug plants were grown under the eight light treatments with the aim of assessing whether the benefits of high blue (compact plants) and far-red (early flowering) can be combined in one treatment. The plants were similar in appearance between the treatments, though the plants grown in the absence of far-red light had shorter petioles and a more compact appearance. Pansy plug plants were ready for transplantation 40 days after sowing. Root development was good in all treatments and the plugs held together during handling. Following transplantation, the pansies grew rapidly and flower buds were visible in some of the treatments within one week. The differences in light treatment became more pronounced as the plants grew (Figure 3.26). The addition of far-red light to the spectrum was found to increase fresh mass (Figure 3.27A). In the 30% blue treatment the greatest mass was associated with the highest far-red intensity (35 µmol m^{-2} s^{-1}) but in the 60% blue treatments the fresh mass was observed to decrease between the 20 and 34 µmol m^{-2} s^{-1} far-red treatments. The number of side branches (Figure 3.27B) was found to decrease as far-red intensity increased, this response was greatest in the 60% blue light treatment. Internode lengths (Figure 3.27C) were observed to increase with the addition of far-red in the light spectrum, again this response was more pronounced in the 60% blue than the 30% blue treatment. Leaf length (Figure 3.27D) was observed to increase between 0 and 11 µmol m^{-2} s^{-1} for both the 30% and 60% blue light treatments. Further increases in far-red had no effect on leaf length. Leaf width (Figure 3.27E) was largely unaffected by the amount of far-red light in the spectrum. Chlorophyll content (Figure 3.27F) was observed to decrease as far-red intensity increased. Pansy flowering was influenced by both blue light percentage and far-red intensity. The number of flower buds produced per plant was greater

in the 30% blue than the 60% blue light treatments and this correlated with differences in plant mass (larger plants produced more buds). Numbers of flower buds were also observed to increase as far-red intensity increased. This was partially explained by differences in plant mass caused by far-red light but also partially by a far-red promotion of flower production. The highest far-red intensity treatments advanced flower bud production by approximately 5 days compared to the no far-red treatments. Far-red intensity also had a pronounced influence on flower opening. Flowering was advanced by 15 days in the highest far-red treatments compared with the no far-red treatments. Under the 60% blue light treatments less far-red light was required to achieve maximum flowering than in the 30% blue light treatments.

Figure 3.26. Pansy plants photographed on the 14th December 2016. 105 days after sowing.

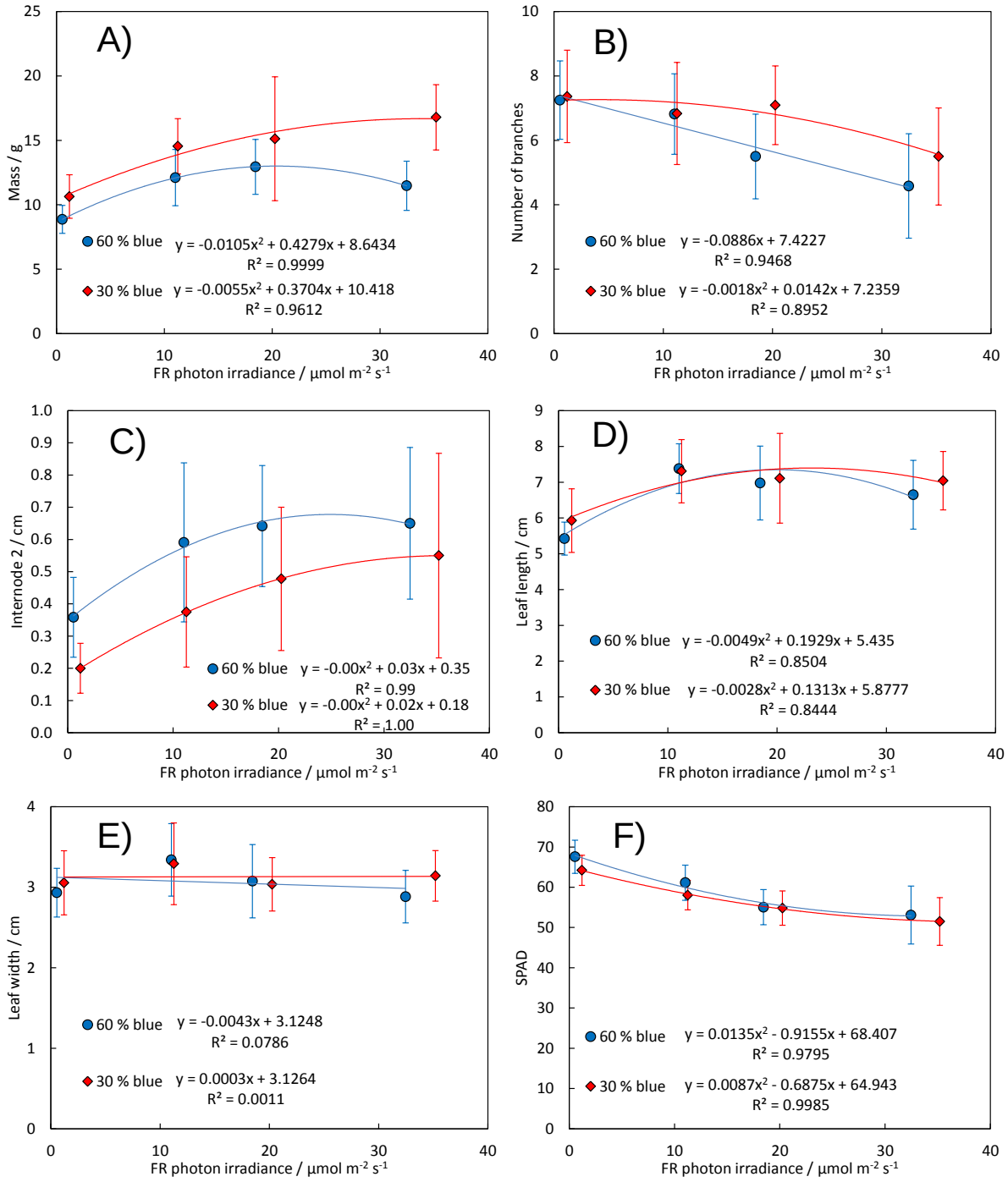

Figure 3.27. The influence of far-red light intensity on the growth and morphology of pansy plants grown under light spectra containing either 30% or 60% blue light. Plants were assessed 105 days after sowing.

3.2.3. Key Findings - Pansy

- Pansy plant biomass increased as light intensity increased but flowering speeds only increased up to 200 µmol m^{-2} s^{-1}.

- A light intensity of 200 µmol m^{-2} s^{-1} provides the optimal light intensity as it produced good quality pansies and consumed the least electrical energy.

- Light treatments with 60% blue light produced the most compact plants but biomass was greatest under low blue treatments (9-11% blue).

- Far-red light increased flowering speed but reduced plant quality by inducing stem elongation.

- High blue light treatments can not be used to prevent the etiolation caused by far-red light, though careful design of the light spectrum can produce high quality flowering plants with compact morphology.

3.3. PELARGONIUM

During the year one trials we examined the influence of blue light percentage and far-red photo irradiance on pelargonium growth and morphology. The results from the year one are provided here in summary (for more detail see the year 1 report) before a more detailed examination of the year 3 trial results.

3.3.1. Methods

Pelargonium seeds were sown on 10cm pots filled with Levington M2 substrate. Plants were placed under the different light treatments in the LED4CROPS facility. Plants were thinned to one plant per pot after germination.

Light treatments

Year 1 Trails. The effects of red:blue ratios were investigated using five light treatments with 0%, 11%, 15% 33% 58% and 100% blue light (Appendix: Light treatments, Table 1). The influence of far-red was examined using light treatments containing a standard red blue treatment (11% blue) provide by Philips production modules and four intensities of far-red light (0, 15,20 and 40 µmol m^{-2} s^{-1}) provided by Philips FR research modules (Appendix: Light treatments, Table 2).

Year 3 Trails. Fifteen treatments were examined. Twelve treatments comprising of four red:blue ratios (6% blue , 15% blue, 30% blue and 60% blue) each with three different far-red intensities (0, 20, 40 or 50 µmol m^{-2} s^{-1}). The PAR photon irradiance of these treatments was set as close to 200 µmol m^{-2} s^{-1} as possible (Appendix: Light treatments, Table 6). For these treatments light was provided by Philips GreenPower research modules. Three treatments with differing PAR intensities (100, 194 and 360 µmol m^{-2} s^{-1}) were also included (Appendix: Light treatments, Table 3). For these treatments light was provided by Philips GreenPower production modules (11% blue light).

3.3.2. Results

The influence of red blue treatments on pelargonium

The pelargonium plants grew well and produced healthy flowering plants after 10 weeks (Figure 3.28). Plant appearance was similar for the plants grown under light treatments with between 15 and 66% blue light, though the plants were smallest in the 66% treatment and largest in the 15% blue treatment. For the plants grown under the 100% blue light treatments, the petioles were extended and the leaves were cupped upwards when viewed from the side. Some differences in leaf pigmentation were also visible, with the deepest red leaves occurring under the 66% blue light treatment. Plant dry mass was found to decrease

as blue light percentage increased to 66% blue, but then remained similar at 100% blue light (Figure 3.29). Leaf area was observed to decrease with increasing blue light. Internode length was found to decrease as blue percentage increased towards 66% but then increased as blue percentage increased to 100%, with these internodes being similar in length to those observed in the 11% blue light treatment. When the leaf-to-stem dry mass ratio was determined, the greatest relative investment in leaf material was achieved in the 66% blue light treatment while the 11% and 100% blue treatments had a similarly low investment in leaf compared with stem.

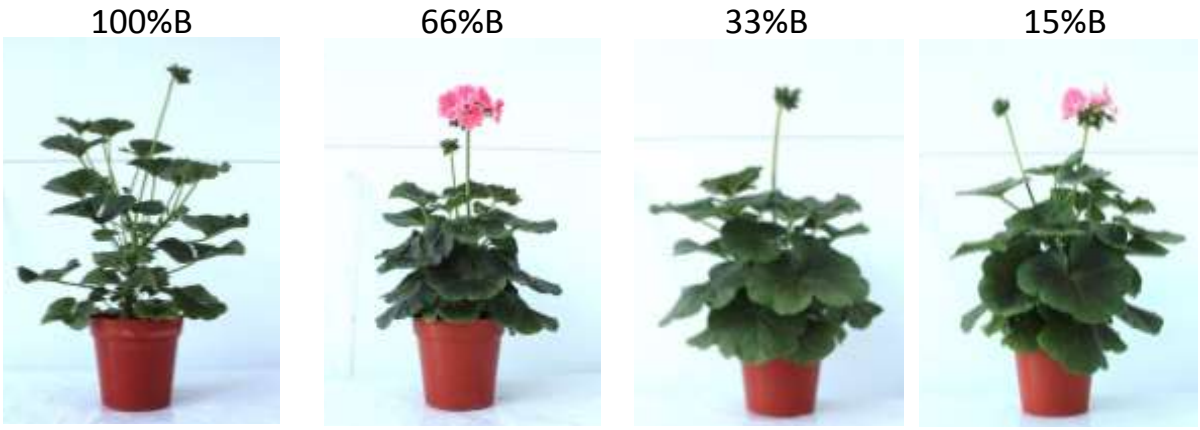

Figure 3.28. Images of pelargonium plants grown under the four red : blue light treatments. Images taken 11 weeks after sowing.

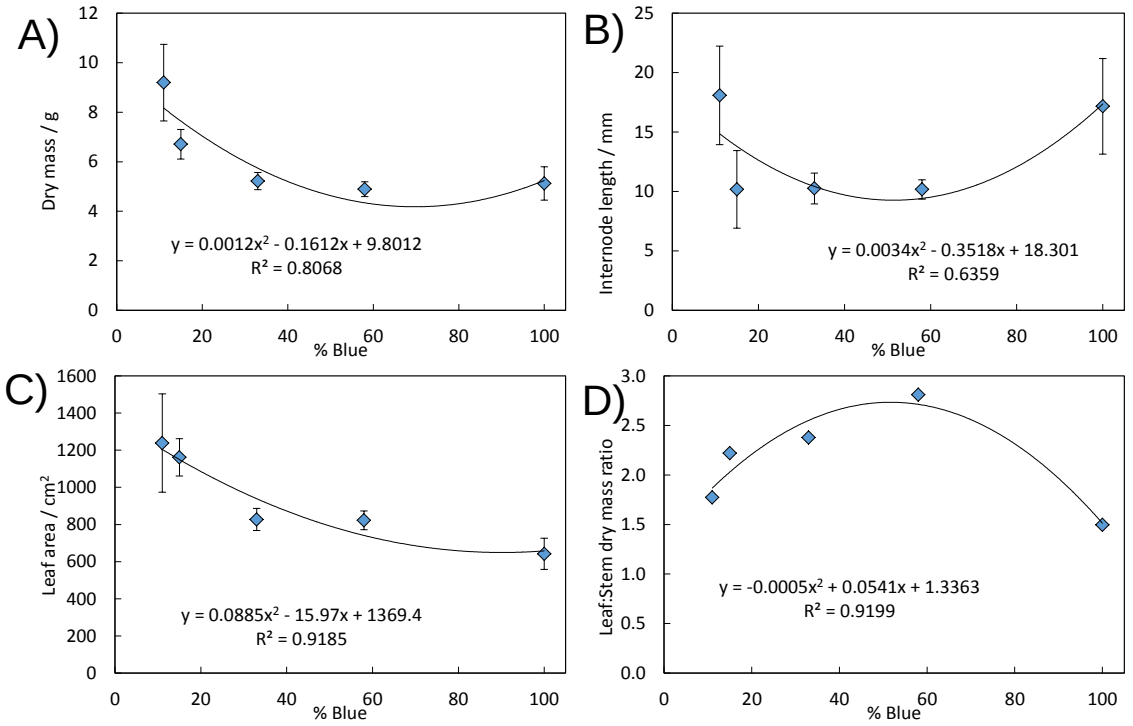

Figure 3.29. The influence of blue light percentage in red : blue light treatments on the **A)** dry shoot mass, **B)** the internode length, **C)** the leaf area, and **D)** the leaf to stem dry mass ratio of pelargonium plants.

Photosynthesis measurements were performed on the plants grown under the different red: blue ratios. Measurements were performed using the light source contained within the Licor 6400 head (red and blue LEDs), so any differences in photosynthetic responses are associated with differences in physiological state resulting from growth under the different light treatments rather than from direct influence of the different light treatments. The light response curves of the four different set of plants were very similar (Figure 3.30), with all treatments achieving a maximum photosynthetic rate at about 600 µmol m^{-2} s^{-1}. Maximum photosynthetic rates (P_{max}), light limited photosynthesis (alpha), and respiration rates (R) were found to be unaffected by the light quality under which the plants had been grown.

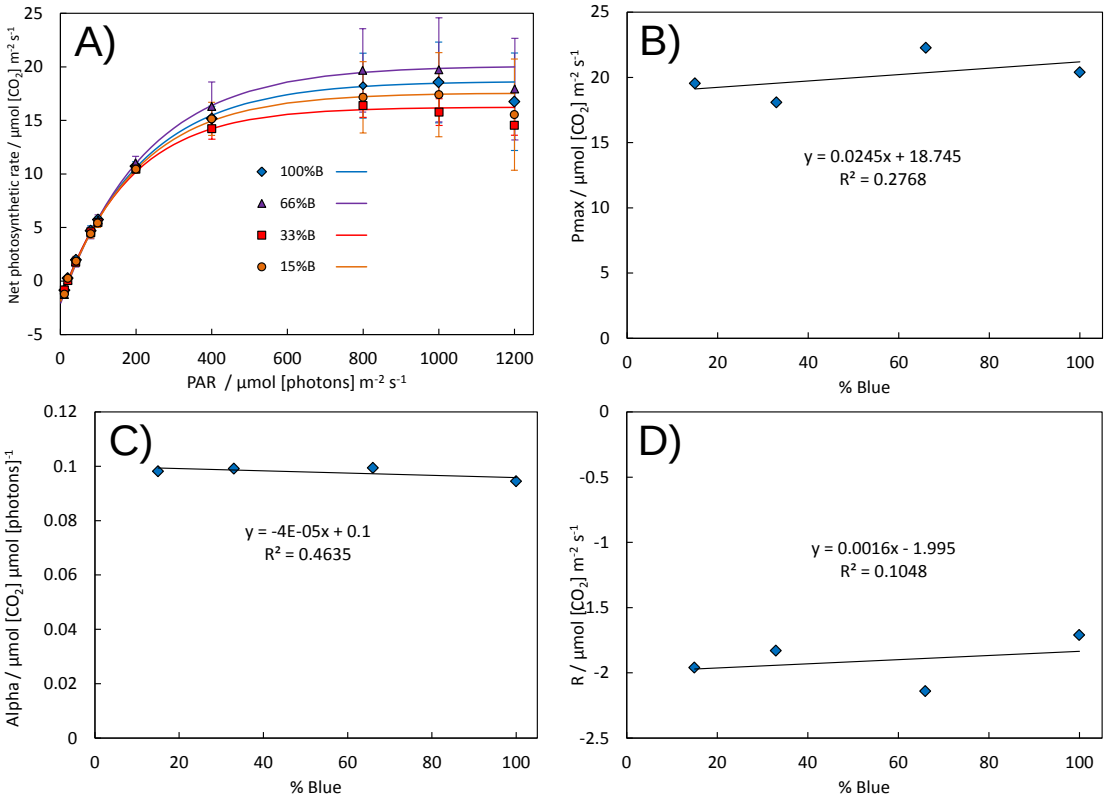

Figure 3.30. **A)** Net photosynthetic light response curves of pelargonium plants grown under four different light treatments. The influence of blue percentage (% blue) on **B)** maximum gross photosynthetic rate (P_{max}) and **C)** the slope of the net photosynthesis curve in light limiting conditions (Alpha). **D)** The measured respiration rate in darkness.

The influence of far-red on pelargonium

The pelargonium plants were slightly more compact in appearance when grown under the no-far-red treatment. This was most apparent when comparing the leaves near the top of the plant, where petiole extension was apparent in the high far-red treatments (Figure 3.31). Flowering occurred slightly earlier in the higher far-red treatments, and the flower stems were taller. The far-red treated plants were taller with longer internodes (Figure 3.32) and plant dry mass was also slightly greater.

Figure 3.31. Images of pelargonium plants grown under different far-red light treatments after 7 weeks growth.

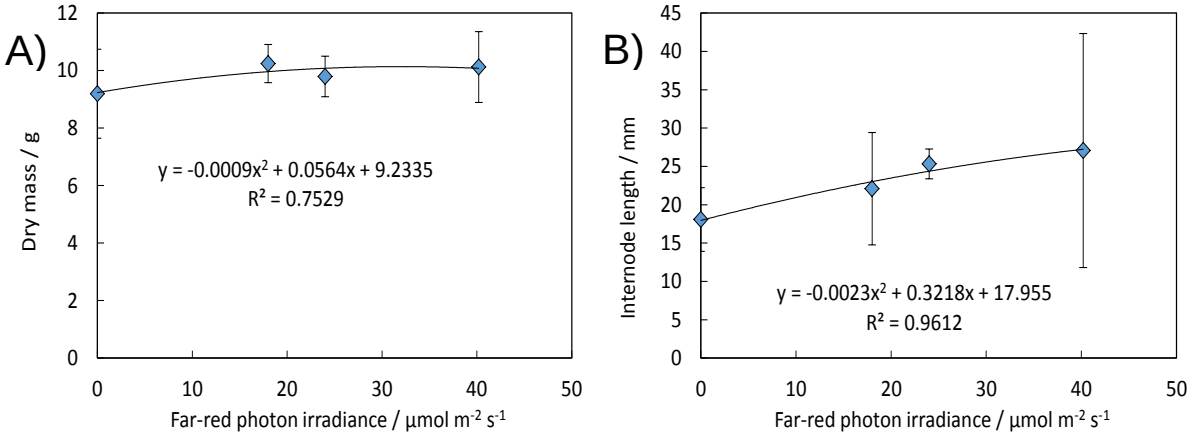

Figure 3.32. The influence of far-red light on **A)** the dry mass and **B)** the internode lengths of pelargoniums grown under different far-red light treatments for seven weeks.

The influence of photon irradiance on pelargonium

The pelargonium plants grown under 100 µmol m^{-2} s^{-1} remained green with no evidence of the purple disc of colouration expected for this variety (Figure 3.33). At 200 µmol m^{-2} s^{-1} the leaves possessed the purple disc and under the highest intensity the leaves were heavily pigmented. Petiole length decrease as the light intensity increased. The long petioles on the 100 µmol m^{-2} s^{-1} treatment caused these plants to appear taller while the short petioles of the 360 µmol m^{-2} s^{-1} treatment cased these plants to appear shorter and have unusual morphology with the leaves hanging downwards. As a consequence all the plants were similar in height. Fresh mass was observed to increase as the photon irradiance increased. Leaf number was found to increase slightly as intensity increased (Figure 3.34).

Figure 3.33. Pelargonium plants grown under three different light intensities.

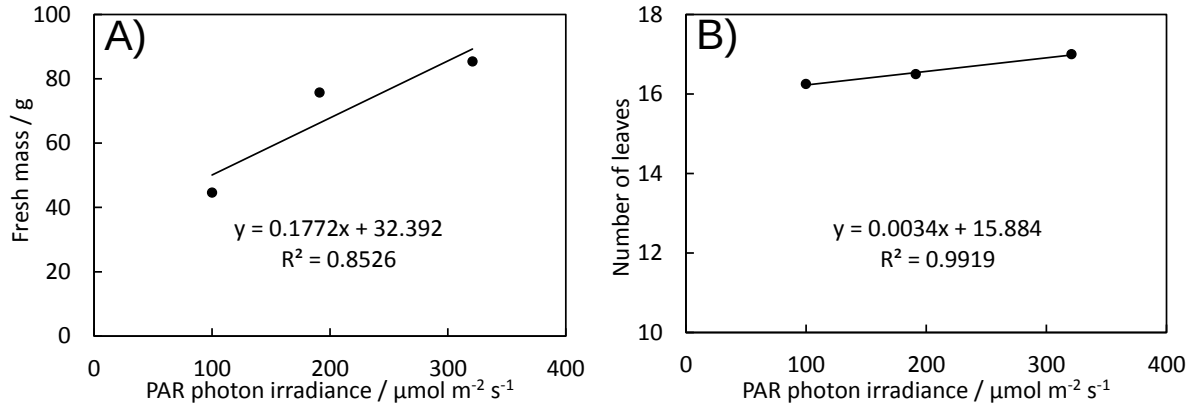

Figure 3.34. Relationship between PAR photon irradiance and **A)** fresh mass and **B)** number of leaves. Light spectrum contained 11% blue light and 89% red light.

The influence of combined red, blue and far-red on pelargonium

Pelargonium plants were grown from seed under 12 different light treatments each with a different combination of blue percentage (5, 15, 30 and 60% blue) and far-red photon irradiance (0, 30 and 43 µmol m^{-2} s^{-1}). The light treatments resulted in plants with considerable differences in morphology (Figure 3.35). Far-red light caused the most obvious changes in appearance with increasing far-red intensities resulting in taller plants with a more open canopy. Both plant height and petiole length were found to increase linearly with increasing far-red intensity (Figure 3.36). Far-red also caused leaves to have a reduced red colouration. Blue percentage also influenced plant appearance and pigmentation. Plants from the 5% blue treatment had the palest leaves and those from the 60% blue treatment were shortest and most strongly pigmented. Leaf size (length and width) was found to decrease as the blue light percentage increased (Figure 3.36). Changes in leaf size are important as they influence the appearance of the plant but also the growth rate. Leaf area was found to correlate with plant fresh mass (Figure 3.37).

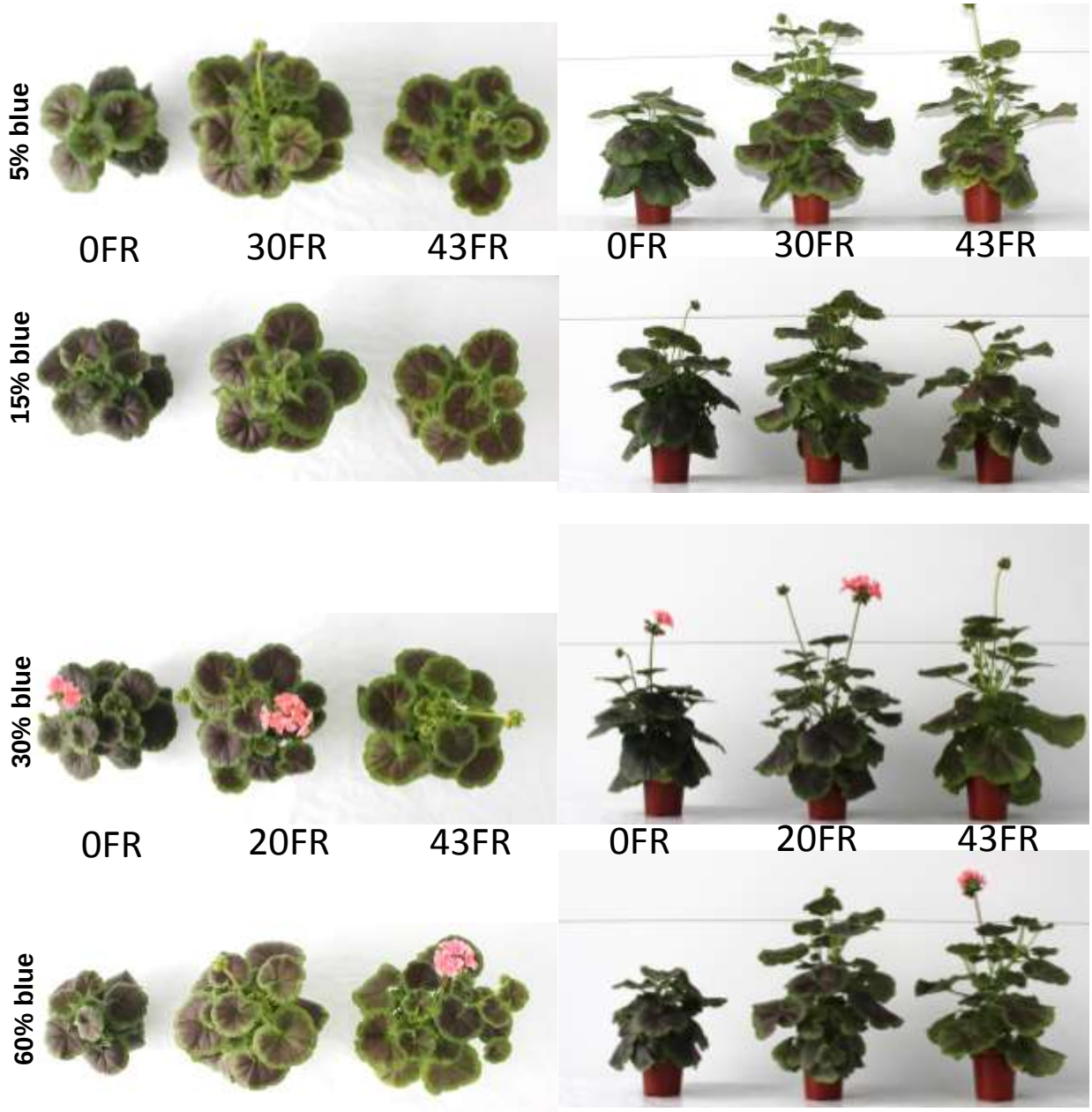

Figure 3.35. Photographs of the pelargonium plants from the twelve combined red, blue and far-red treatments, plants were imaged from above and from the side.

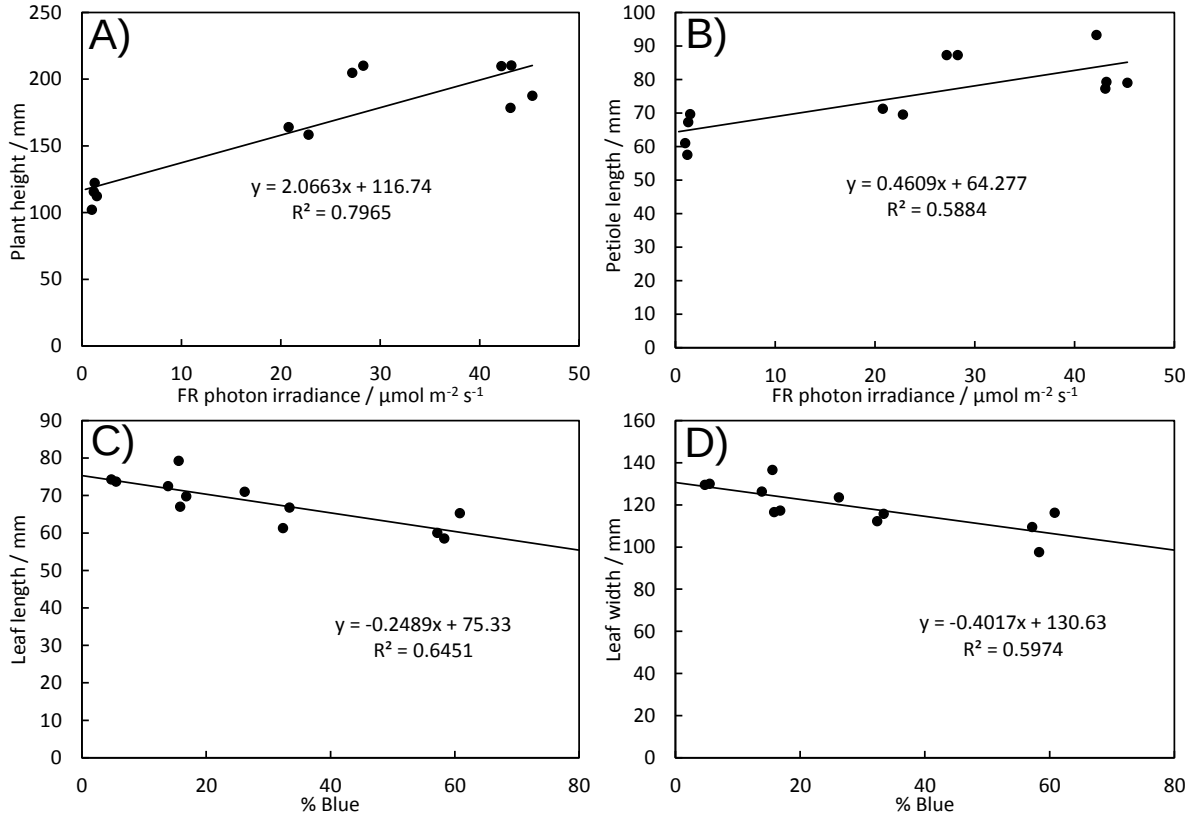

Figure 3.36. The influence of light quality on pelargonium morphology. Influence of far-red photon irradiance on **A)** plant height and **B)** petiole length. The influence of blue percentage on **C)** leaf length and **D)** leaf width.

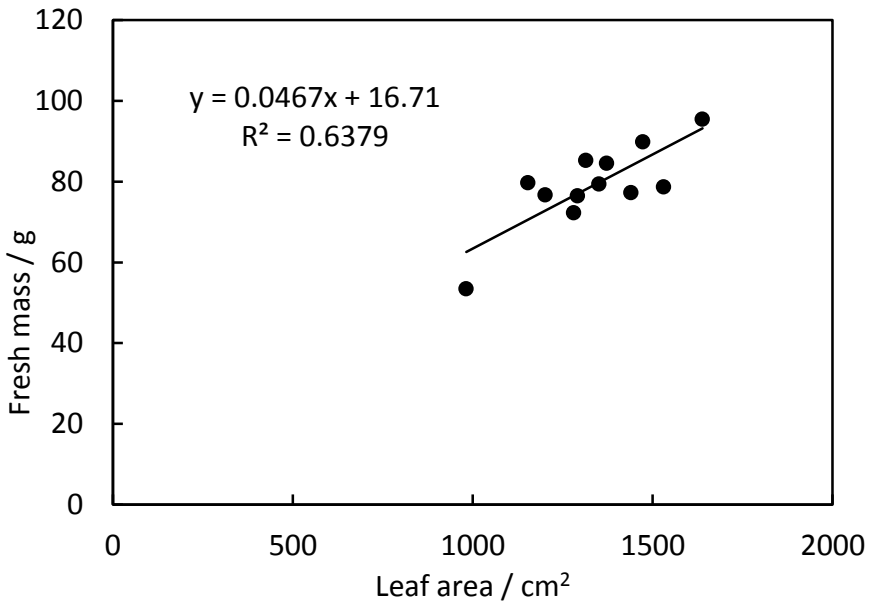

Figure 3.37. The relationship between total leaf area and fresh mass of pelargonium plants grown under twelve light treatments with different amounts of red blue and far-red light.

3.3.4. Key findings - Pelargonium

- For pelargonium leaf size and area was controlled by the red: blue ratio of light with higher blue light proportions resulting in reduced leaf size.

- Far-red light controls the length of the internode and petioles with more far-red light resulting in taller less compact morphology.

- Leaf area controls the biomass accumulation of pelargonium plants.

- Leaf pigmentation (red colouration of leaves) was enhanced under light treatments containing more blue light and reduced as the far-red light intensity was increased.

- Plants grown under the highest light treatments were very compact. The most compact plants were regarded as ‘too compact’ by growers. Light treatments could therefore be used in place of PGRs for pelargonium.

- Photosynthesis measurements found no evidence of acclimation to different light environments in these trials.

3.4. BEGONIA

The begonia trials were performed during year one. The results are provided here in summary. For more detail see the year one trial.

3.4.1. Methods

Seed of begonia (*Begonia semperflorens,* Super Olympia red F1 - CN Seeds) were sown, on Levington F2+sand substrate in one inch cells. Plants were transplanted when the plug plants were of sufficient size. Plants were transplanted into six-packs filled with Levington M2 substrate.

Light treatments

Year 1 Trials. The effects of red:blue ratios were investigated using five light treatments with 0%, 11%, 15% 33% 58% and 100% blue light (Appendix: Light treatments, Table 1). The influence of far-red was examined using light treatments containing a standard red : blue treatment (11% blue) provide by Philips production modules and four intensities of far-red light (0, 15, 20 and 40 µmol m^{-2} s^{-1}) provided by Philips FR research modules (Appendix: Light treatments, Table 2).

3.4.2. Results

The influence or red: blue ratio on begonia

Begonia seedlings grew slowly compared with the petunia and pansy seedlings sown at the same time, but plug plants were of sufficient size for transplanting after 11 weeks (Figure 3.38). The smallest plug plants were produced under the 58% blue light treatment and the largest under the 15% blue light treatment. Unlike the other bedding plants, the begonia plug plants grown under the 100% blue light treatments did not become significantly etiolated and overall morphology was similar to the other light treatments.

After potting-up, the plants continued to grow well. The 33% blue light treatment produced the smallest and most compact plants (Figure 3.39). The plants from the 100% blue and 15% blue treatments had a similar appearance but, on closer inspection, there were significant differences. Shoot mass and leaf area were found to decrease as the blue light percentage increased (Figure 3.40 A&B). Neither parameter showed a significant increase between 58 and 100% blue light. Leaf size was unaffected by light treatment but petiole length was found to increase as blue light percentage increased. Internode and petiole lengths were found to increase with an increase in blue light percentage, indicating

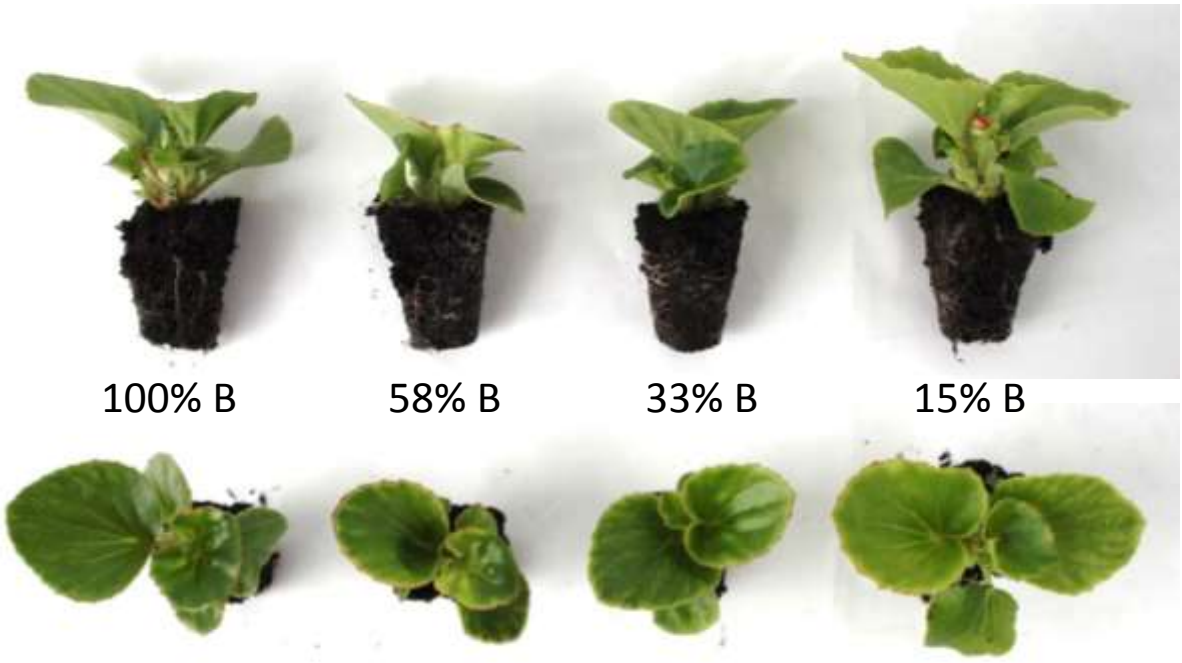

Figure 3.38. Images of the begonia plug plants from the different red: blue light treatments after 52 days growth.

Figure 3.39. Photographs of the begonia plants showing the influence of red: blue light treatments on flowering after 86 days growth.

an increase in etiolation. The fewest branches were observed in the 100% blue light treatment. The primary and secondary stem lengths were shortest in the 33% blue light treatment (Figure 3.40C). Primary stems were longest in the 100% blue light treatments, but secondary stems were a similar length in the 100% blue and 11% blue light treatments. While the secondary shoots in these two treatments were similar, the 100% blue treatment had fewer leaves per stem. The light treatments also affected flowering in the begonia plants. As with other species examined leaf area was found to correlate with plant biomass (Figure 3.40D). Flowering occurred earliest and most extensively in the plants grown under the 100% blue light treatment (Figures 3.41).

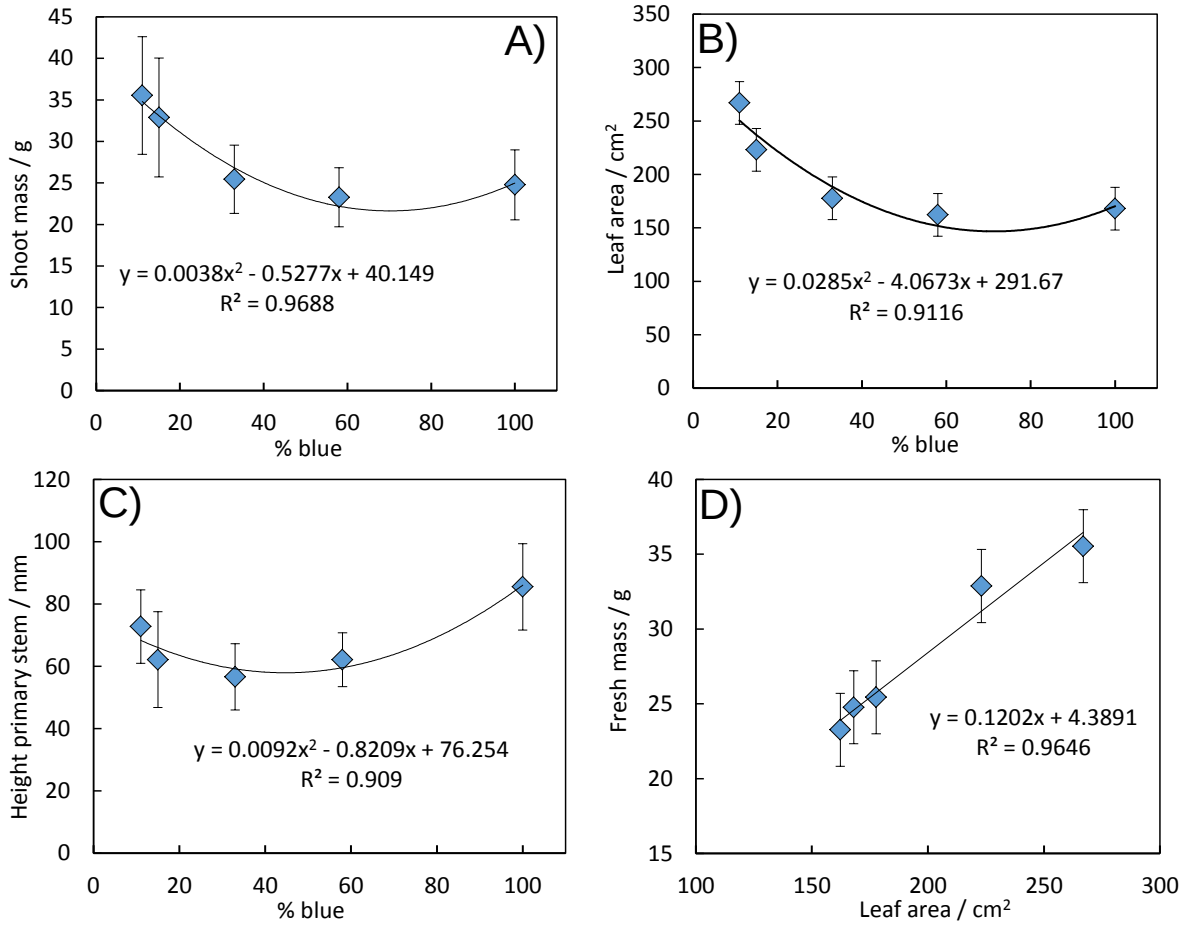

Figure 3.40. The influence of blue light percentage on **A)** shoot mass, **B)** total leaf area, **C)** length of the primary shoot of begonia plants grown under the different red:blue light treatments. **D)** The correlation between leaf area and fresh mass.

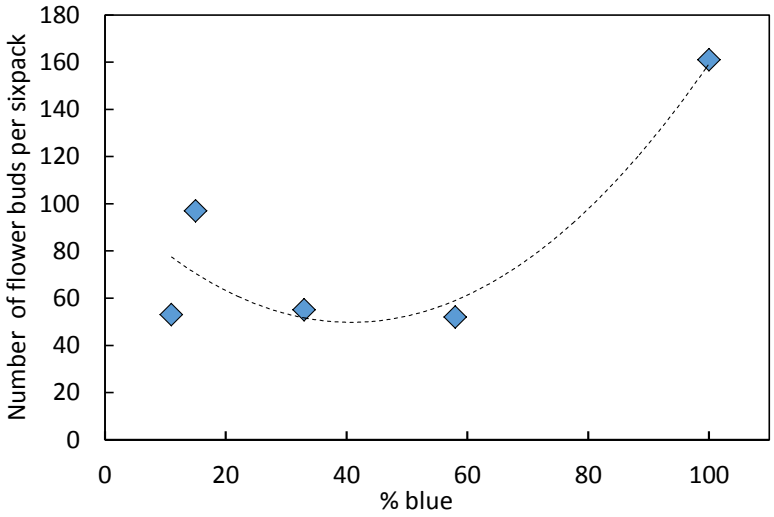

Figure 3.41. The relationship between blue light percentage and number of flower buds on begonia plants grown under the different light treatments.

Far-red effects on begonia

The begonia plug plants were observed to grow slightly larger in the presence of far-red light (Figure 3.42), though these differences were small compared to those observed in petunia and pansy. Following potting-on, the plants grew more rapidly and treatment effects if anything reduced slightly (Figure 3.43). At the final harvest, the shoot mass was observed to decrease as far-red intensity increased (Figure 3.44A). Leaf area was observed to decrease as far-red intensity increased (Figure 3.44B) this was a consequence of a reduction of both number of leaves and size of leaves. In contrast to other species examined the inclusion of far-red light with a photon irradiance of <30 µmol m^{-2} s^{-1}resulted in a reduction in petiole and internode length (Figure 3.44 C&D). Under far-red intensities >30 µmol m^{-2} s^{-1}, petiole and internode lengths were observed to increase.

Flowering was observed to commence at a similar stage in all the light treatments. However, two weeks after the first flowers were observed, flower number increased more rapidly in the light treatments containing far-red light. At the end of the trial, the no far-red treatments were approximately one week behind other far-red treatments. The number of flowers (Figure 3.45) was not observed to increase with far-red intensities between 18 and 40 µmol m^{-2} s^{-1}, indicating that the flowering response was saturated at a lower light intensity.

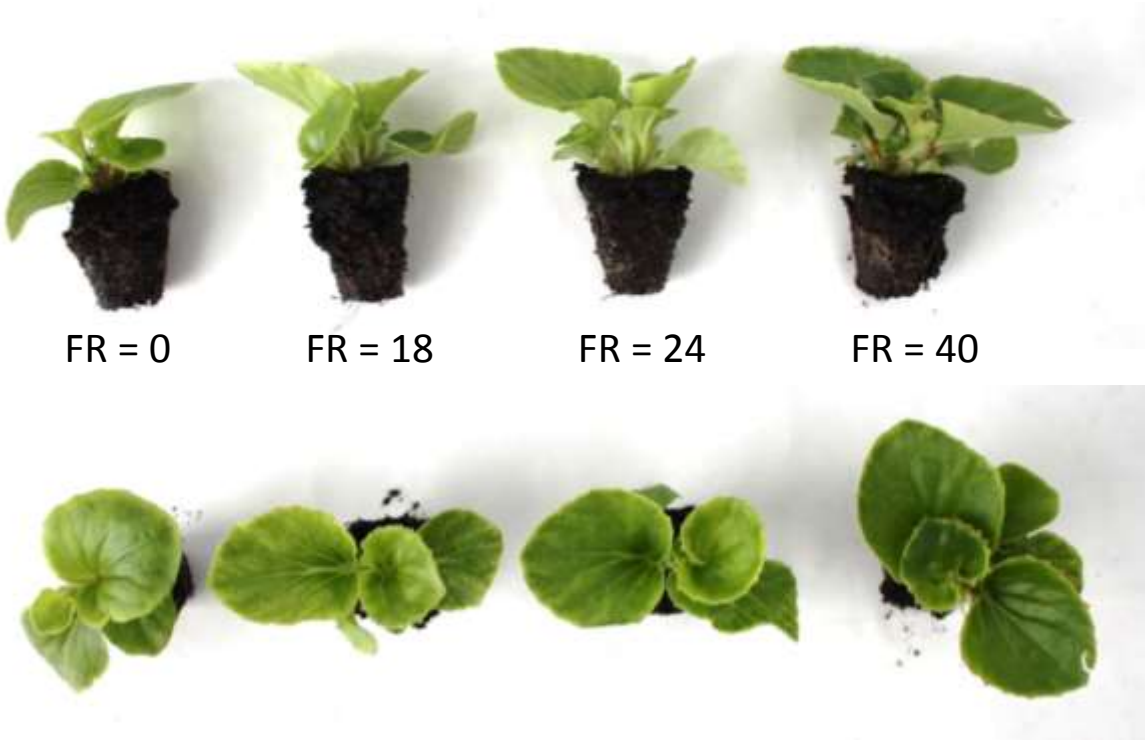

Figure 3.42. Images of begonia plug plants grown under different far-red light treatments after 52 days of growth.

Figure 3.43. Images of begonia plants grown under different far-red light treatments for 86 days.

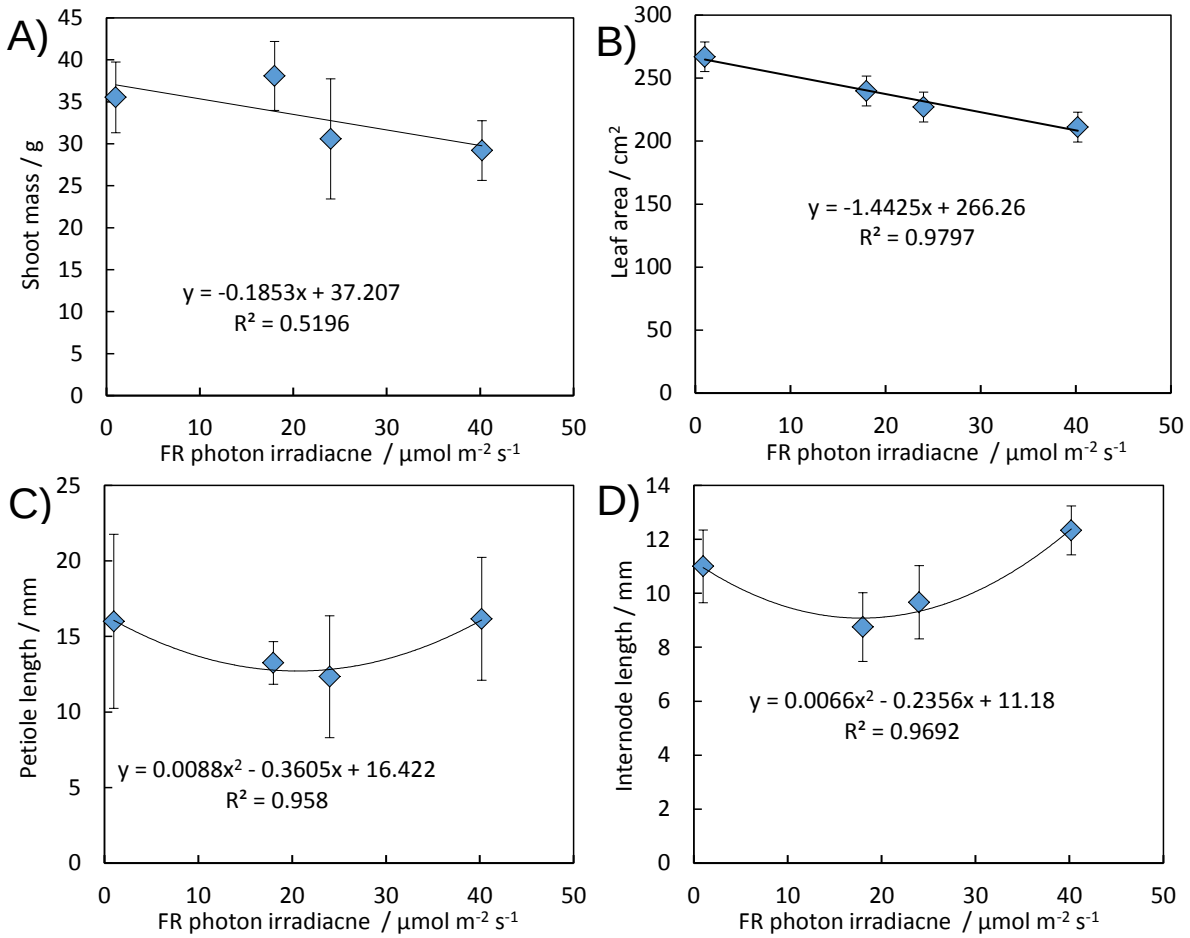

Figure 3.44. The influence of far-red light on **A)** shoot fresh mass, **B)** total plant leaf area, **C)** petiole length and **D)** internode length of begonia plants.

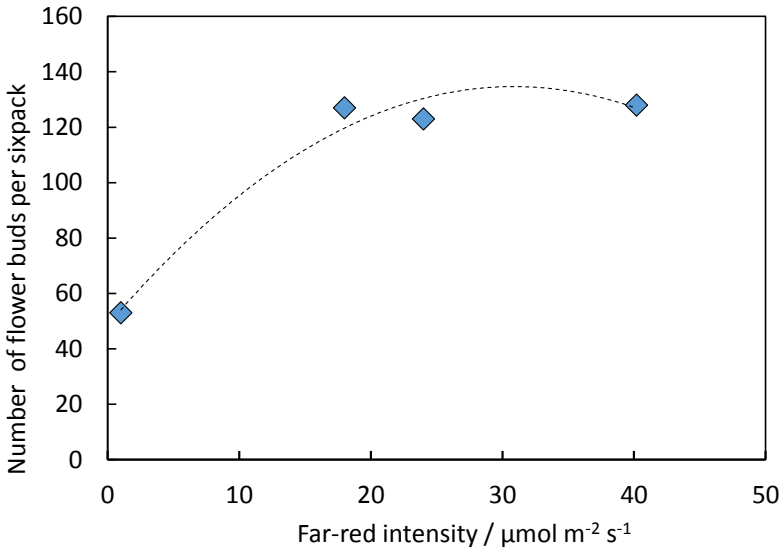

Figure 3.45. The influence of far-red light on total number of visible begonia flower buds at the end of the trial.

2.4.3. Key Findings - Begonia

- 33% blue produced the most compact begonia plants.

- Far-red promoted flowering but had less effect on morphology than has been observed in other species.

- Spectral manipulation did influence begonia morphology but saleable plants were generated from all the light treatments examined. This may suggest that for production of this type of begonia LED units should be selected for energy efficiency (high efficacy values see CP139) rather than spectrum.

3.5. CHRYSANTHEMUM

3.5.1. Methods

The trial was performed in three stages 1) the effect of light quality on rooting, 2) the effect of light quality on vegetative growth (long days) and 3) the effect of light quality on flowering (short day treatments). Cuttings of chrysanthemum 'Chrystal Blanche' (supplied and treated with rooting power by double H) were planted in Levington M2 compost in 96 cell plug trays on the 8th June 2016 and placed under the different light treatments with a day length of 16 hours. Ten plants from each light treatment were harvested and used to assess rooting on the 15th June 2016 (7 days after planting). The remaining plants were transplanted in to 11cm pots (Levington M2 substrate) on the 27th June 2016. Plant height and morphology were assessed on the 11-12th July 2016 and again on the 18-19th July 2016. On the 18th July 2016 the day length was reduced to 8 hours to induce flowering.

A second rooting trial was performed to further examine the influence of far-red on rooting. For this experiment cuttings of chrysanthemum 'Chrystal Blanche' (supplied and treated with rooting power by double H) were grown in the LED4CROPS facility under a 11% blue light treatment. Cuttings were collected from these plants and were 'stuck' in 1 inch cells filled with M2 compost. These cuttings were not treated with rooting powder.

Light treatments

Rooting cuttings. During the first rooting trial cuttings were placed under 6 light treatments. Four examined the influence of red: blue ratio (0%, 15 , 60 and 100% blue) and two examining the influence of far-red light (8 and 16 µmol m^{-2} s^{-1} of far-red light under a background red : blue light containing 15% blue). The PAR photon irradiance in all these treatments was set to 75 µmol m^{-2} s^{-1} (Appendix: Light treatments, Table 8). For the second rooting trial the influence of far-red light was investigated over a wider range of far-red photon irradiances 0, 25, 50 and 75 µmol m^{-2} s^{-1} of far-red light in addition to a red:blue background light containing 15% blue (Appendix: Light treatments, Table 9).

Vegetative growth. Twenty treatments were examined. Four examined the influence of low intensity (100 µmol m^{-2} s^{-1}) light with different red: blue ratios (0%, 15 , 60 and 100% blue – Appendix: Light treatment, Table 7). Twelve treatments comprising of four red: blue ratios (6% blue , 15% blue, 30% blue and 60% blue) each with three different far-red intensities (0, 20, 40 or 50 µmol m^{-2} s^{-1}). The PAR photon irradiance of these treatments was set as close to 200 µmol m^{-2} s^{-1} as possible (Appendix: Light treatments, Table 6). For these treatments light was provided by Philips GreenPower research modules. Three treatments with differing PAR intensities (100, 200, 250 and 360 µmol m^{-2} s^{-1}) were also included

(Appendix: Light treatments, Table 3). For these treatments light was provided by Philips GreenPower production modules (11% blue light).

Flowering stage. All the light treatments were kept the same during the flowering stage, but the day lengths were reduced from 16 hours to 8 hours.

3.5.2. Results

The influence of light quality on rooting of chrysanthemum cuttings.

The chrysanthemum cuttings were rooted under four different red: blue light mixtures ranging from 0% blue (100% red light) through to 100% blue light (Figure 3.46). Three treatments containing 16% blue light and three different far-red intensities were also examined (8 and 16 µmol m^{-2} s^{-1}). In all treatments strike rates were near to 100%. Blue light percentage, however, was observed to have an influence of the number of roots formed and the length of the longest root produced (Figure 3.46 A&C). Root numbers and lengths were lowest under the 100% blue light treatment and increased as the blue percentage decreased. The number of roots was observed to decreases slightly between 16% blue and 0% blue (this may indicated a limitation of root development caused by stomatal limitation of photosynthesis) but root length was greatest under 100% red light.

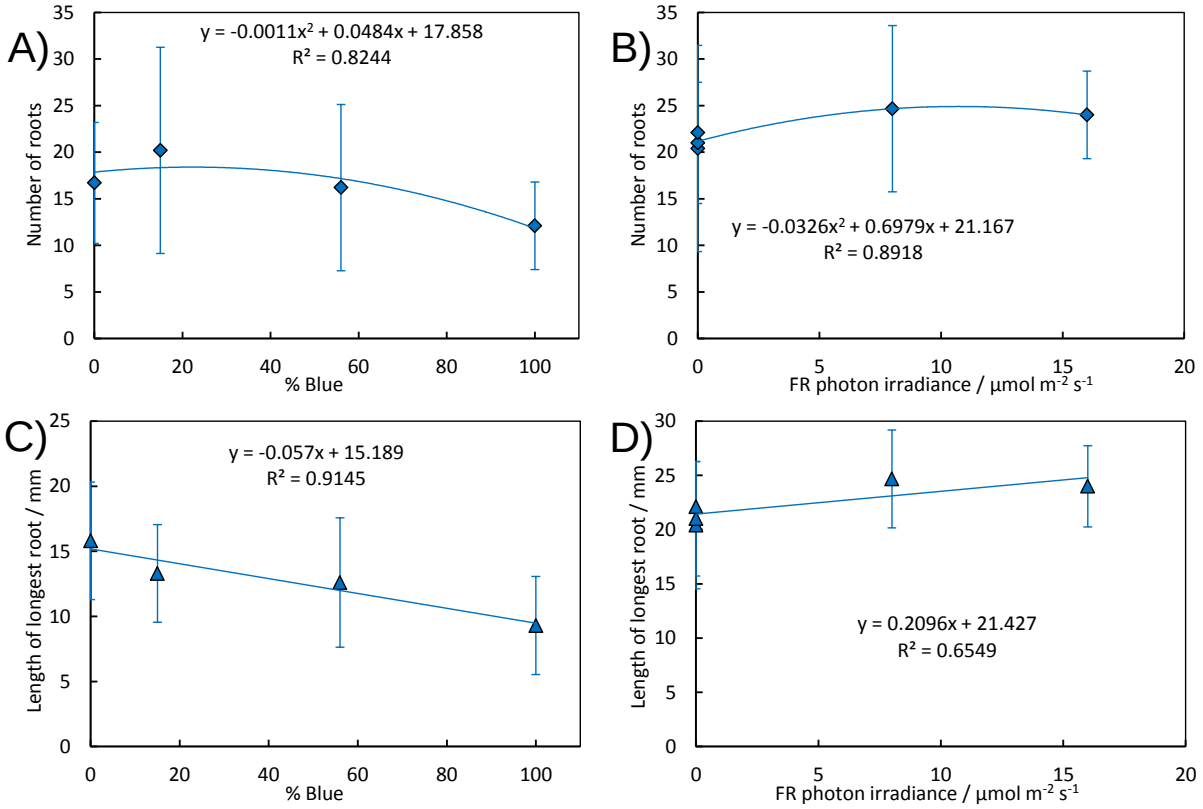

Figure 3.46. The influence of percentage of blue light **(A&C)** and far-red photon irradiance **(B&D)** on rooting of chrysanthemum cuttings that had been treated with rooting powder. **A&B)** Number of roots produced per cutting and **C&D**) the length of the longest root.

Far-red light was also found to have a positive influence on rooting in these cuttings with cuttings producing greater numbers of longer roots (Figure 3.46 B&D).

In the rooting experiments reported elsewhere in this report (see section 5) far-red was found to have a negative impacts on both cutting survival and root development. To further explore the benefits of far-red on chrysanthemum we rooted cuttings that were not dipped in rooting powder because this would reduce rooting allowing us to elucidate the benefits of far-red. We also examined a greater range of far-red intensities with treatments containing up to 70µmol m^{-2} s^{-1} of far-red light (Figure 3.47). Without rooting powder rooting speeds were reduced and at the time of assessment only 50% of the cuttings with no far-red light had rooted while for treatments with far-red light over 90% of cuttings had rooted. Numbers and length of roots were also greatly increased by the presence of far-red light. At the highest far-red intensity root length and numbers were observed to decrease suggesting that the application of too much far-red would diminish the benefits of far-red light and waste electricity.

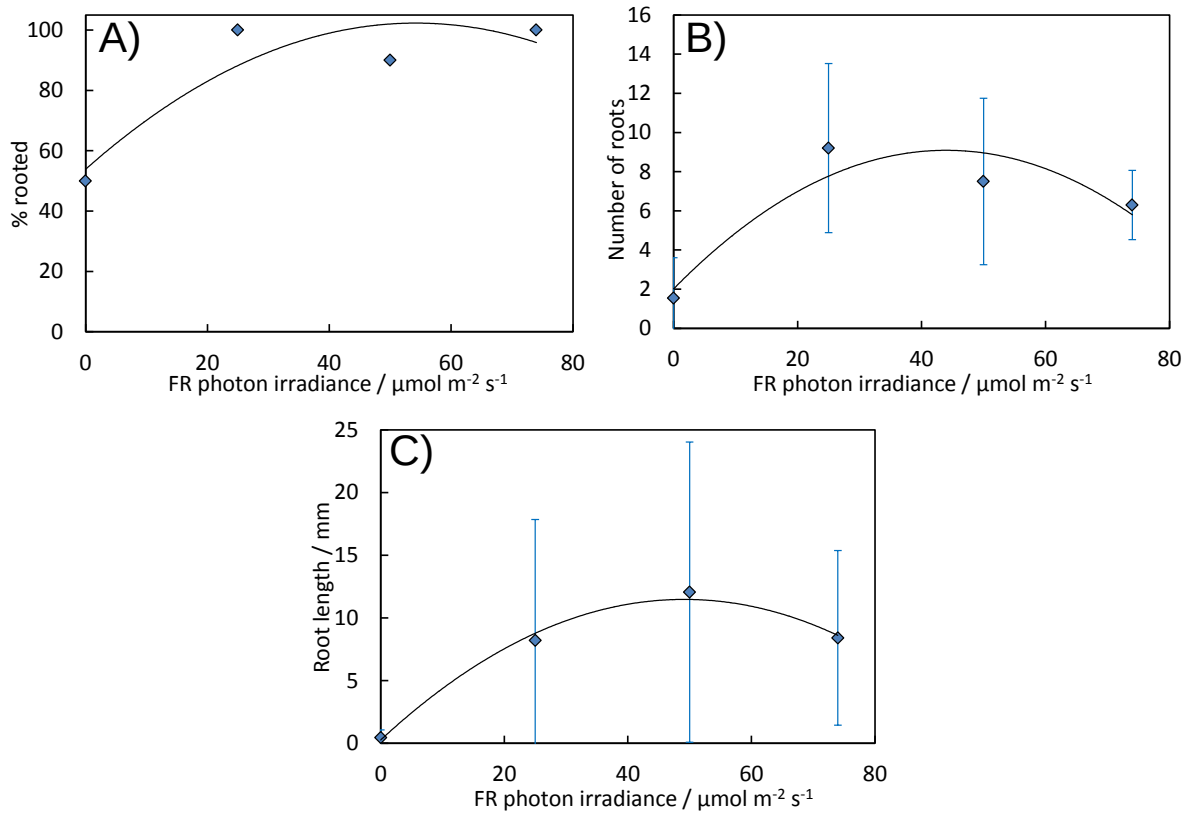

Figure 3.47. The influence of far-red (FR) photon irradiance on the rooting of chrysanthemum cuttings that were not treated with rooting powder. Cutting material was collected from plants grown in the LED4CROPS facility. **A)** Percentage of cuttings that rooted **B)** number of roots produced per cutting **C)** length of the longest root per cutting.

The surviving cuttings from the first rooting trial were transplanted to 11 cm pots and distributed between the sixteen light treatments that were to be examined in the subsequent crop growth trials (plants from each propagation light treatment were placed under several different plant growth light environments). Immediately following transplantation the morphology of the cuttings was measured to both assess the influence of cutting light treatments on morphology and so these effects could be accounted for in subsequent measurements. As well as affecting the rooting of chrysanthemums the light treatments affected the shoot morphology (Figure 3.48). The tallest plants with the longest internodes and most leaves were observed under the 0% blue (100% red) light treatment. The most compact plants (shortest internodes) were observed under the 60% blue light treatment. Plant height was similar under the 60% and 100% blue light treatments though the 100% blue light plants produced fewer leaves and had longer internodes. The far-red light treatments had little influence of morphology of the cuttings in this experiment.

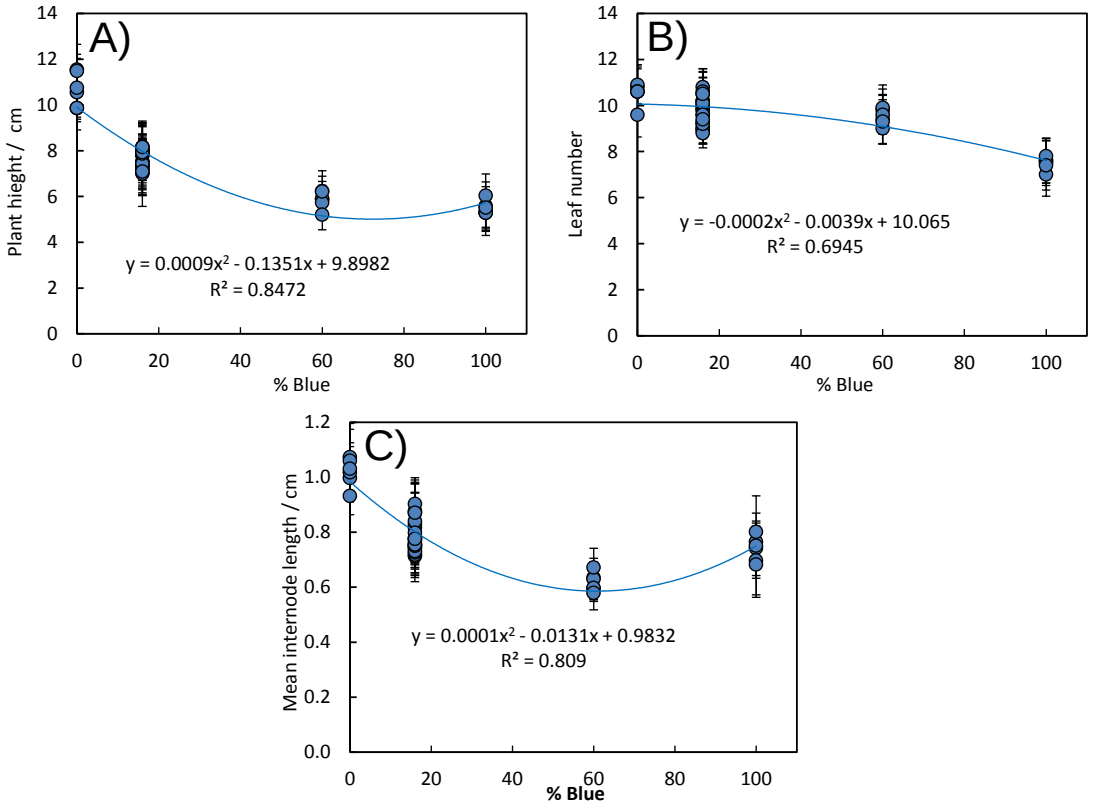

Figure 3.48. The influence of blue percentage on the morphology of chrysanthemum plants at the end of the propagation period, **A)** plant height, **B)** leaf number and **C)** mean internode length.

The influence of light quality on chrysanthemum morphology under long day conditions.

Low light conditions (100 µmol m^{-2} s^{-1}). Following propagation some plants were potted up and placed under low light conditions to grow (100 µmol m^{-2} s^{-1}). Blue percentage was observed to have a considerable influence on plant morphology and quality (Figure 3.49). Under 100% red light plants grew tall and leaves were observed to hang downwards. Internode lengths and leaf numbers followed similar trends to those observed in the propagation phase of production. Leaf area was greatest under 16% blue light and lowest under 100% blue light (Figure 3.50A). Leaf to stem dry mass ratio, a measure of biomass partitioning, increased from two under the 0% blue light to five under 60% blue light but decreased slightly under the 100% blue light treatment (Figure 3.50B). Higher blue light treatments are often associated with greater branching, however, in these experiments the number of side shoots observed decreased linearly with increasing blue light (Figure 3.50C). Leaf area was found to be a major factor driving shoot dry mass accumulation (Figure 3.50D). Net primary productivity (dry mass divided by leaf area) was observed to decrease linearly as blue light percentage increased (Figure 3.50E), as did the light use efficiency (LUE = net assimilation divided by light intensity; Figure 3.50F). The decrease in LUE with increasing blue light percentage suggests that the colour of the light is influencing the light limited photosynthetic rate of these plants.

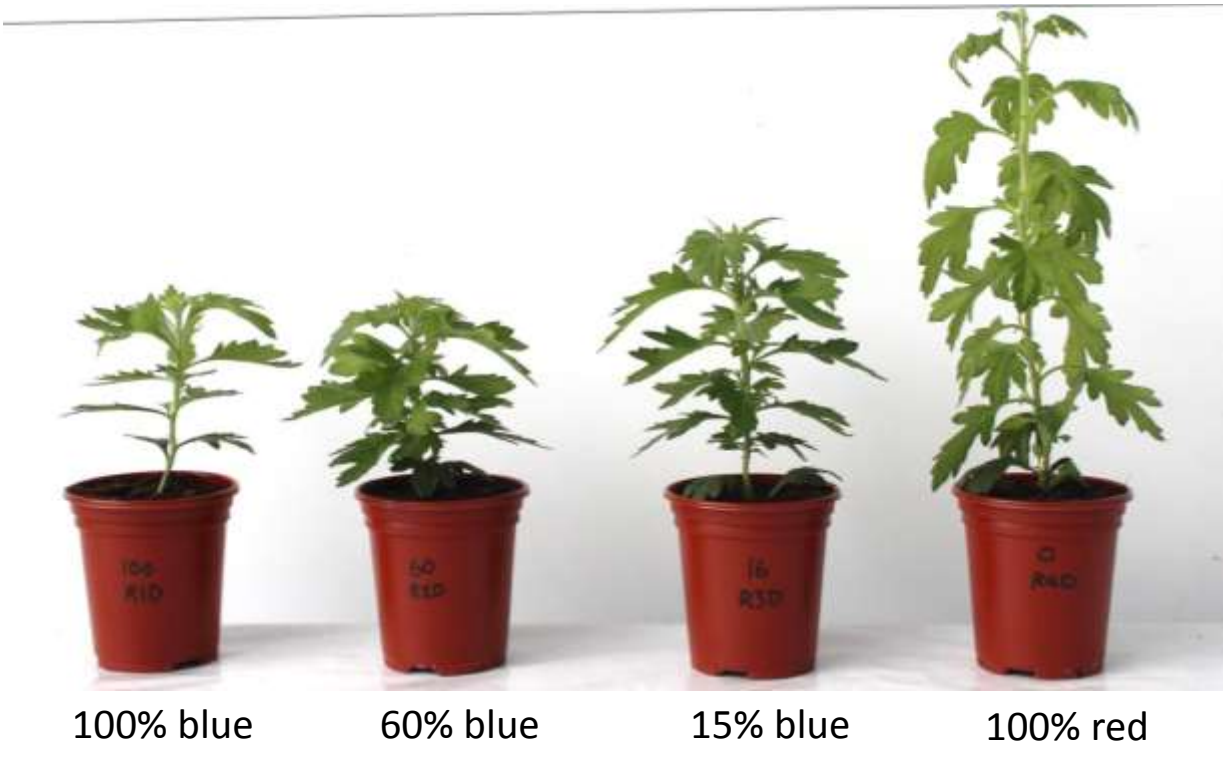

Figure 3.49. The influence of blue percentage on the morphology of chrysanthemum plants grown under a photon irradiance of 100µmol m^{-2} s^{-1}.

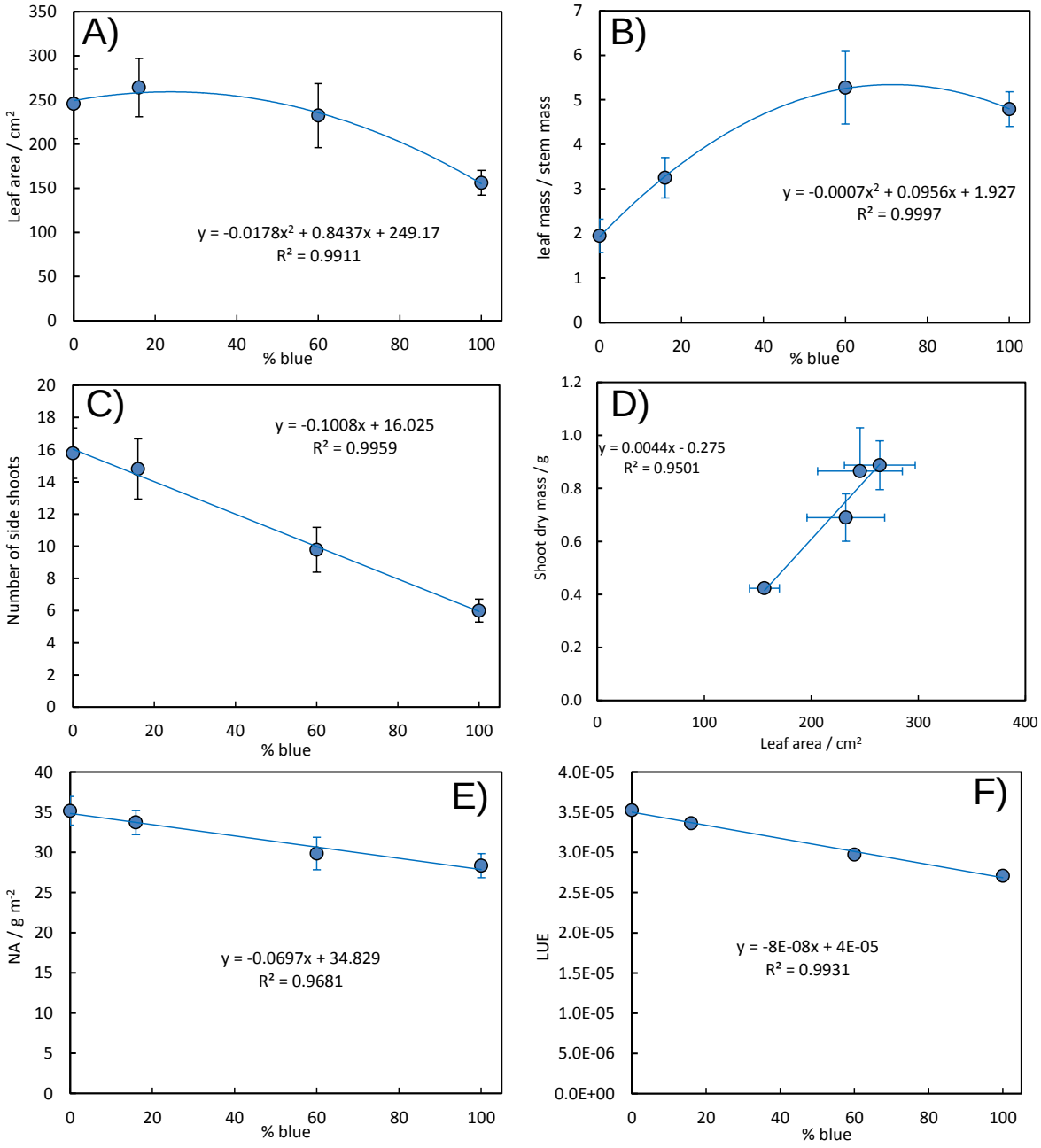

Figure 3.50. The influence of blue light percentage on morphological and growth parameters of the chrysanthemum plants grown under a PAR photon irradiance of 100 µmol m^{-2} s^{-1}. **A)** leaf area, **B)** biomass partitioning between the leaves and stems **C)** number of side shoots per plant, **D)** the relationship between leaf area and shoot dry mass, **E)** the changes in net assimilation (NA) and **F)** changes in light use efficiency (LUE).

Moderate light conditions (200 µmol m^{-2} s^{-1}). For the main growth experiment plants were moved to one of 12 light treatments with a PAR light intensity of ~200 µmol m^{-2} s^{-1}. Light treatments ranged in blue light percentage (6%, 16%, 30% and 60% blue light) and far-red photon irradiance (0, 20, 30, 40 and 50 µmol m^{-2} s^{-1}). The differences in plant height caused by the propagation light treatments persisted throughout the trial (Figure 3.51) even though the new growth was similar in morphology between plants.

Figure 3.51. Photograph of chrysanthemum plants grown under a light treatment containing 6% blue light. Plants differ in height due to the different percentages of blue light the plants were exposed to during propagation (white text).

As with the low intensity light treatments the most compact plants were observed under the 60% blue light treatment. The tallest plants were observed in the 6% blue light treatment. Leaf area was greatest for the 16% blue light treatment indicating that 6% blue light is too low to maximise leaf expansion and therefore growth rates of chrysanthemum (Figure 3.52A). Biomass partitioning between leaves and stems was observed to increase in a similar manner to the plants grown under lower light intensities though investment in stem remained higher in these plants than those from the low light treatments (leaf stem ration only increased to ~3; Figure 3.52B). Number of side shoots (Figure 3.52C) and the relationship between dry mass and leaf area (Figure 3.52D) also had similar trends to the plants grown under lower light intensities. However, when we examine the net assimilation (Figure 3.52E) and LUE (Figure 3.52F) data there were no observable effects of light quality. This suggests that at the higher light intensity, growth rates and LUE is limited by some factor other than the quantum yield of light limited photosynthesis and that leaf area and light intensity alone drive growth rate.

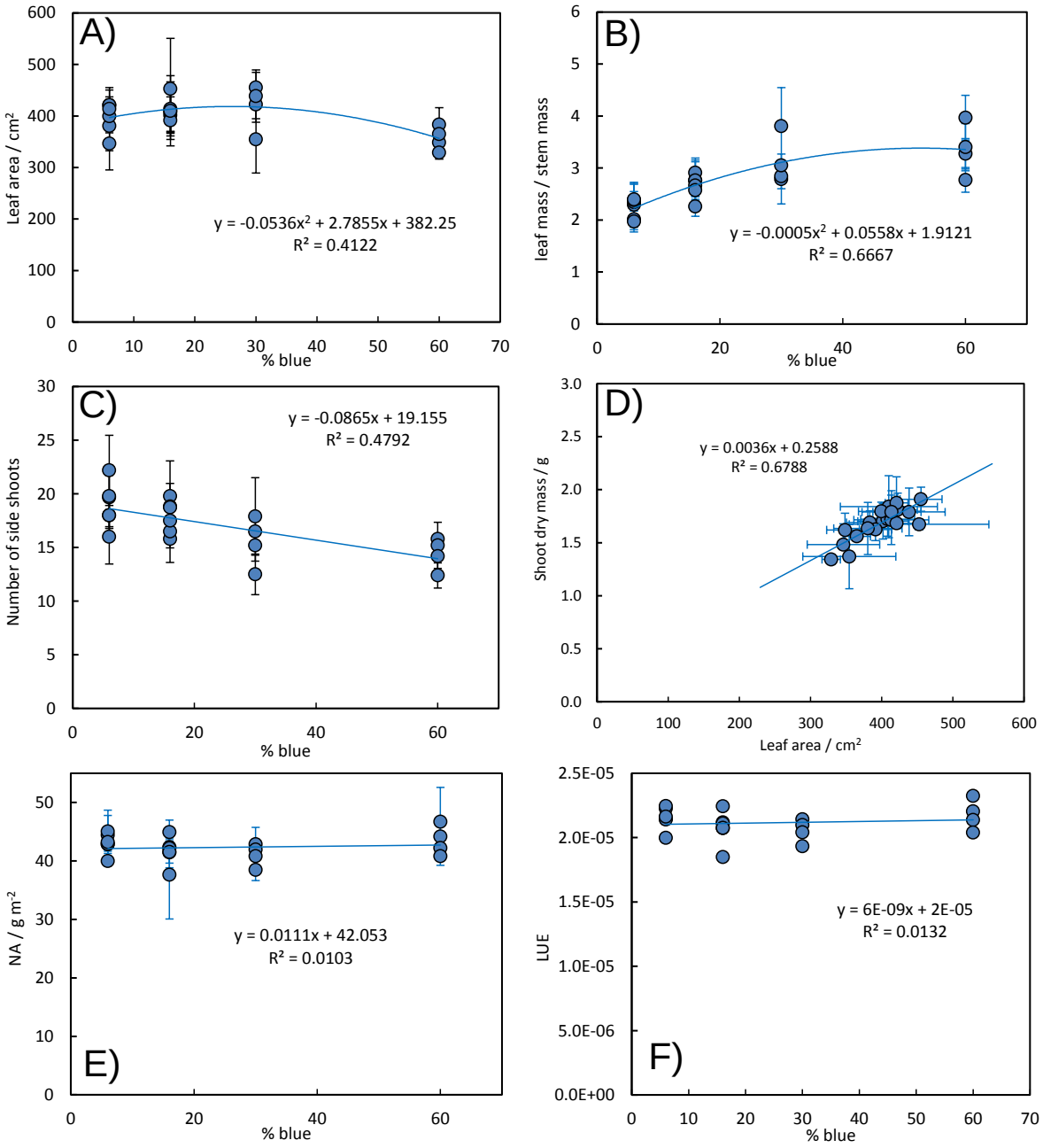

Figure 3.52. The influence of blue light percentage on morphological and growth parameters of the chrysanthemum plants grown under a PAR photon irradiance of 200 µmol m^{-2} s^{-1}. **A)** leaf area, **B)** biomass partitioning between the leaves and stems **C)** number of side shoots per plant, **D)** the relationship between leaf area and shoot dry mass, **E)** the changes in net assimilation (NA) and **F)** changes in light use efficiency (LUE). The multiple data points associated with each light treatment represent the data measured from plants grown under different propagation light treatments.

Plants grown under different far-red intensities

The plants grown under the different far-red light intensities looked similar in appearnce (Figure 3.53). Plant height and internode length both increased slightly as the far-red

intentisy increased, thought leaf number decreased. Total leaf area remained similar as far-red increased (Figure 3.53A). The leaf to stem dry mass ratio (Figure 3.53B) decreased as far-red intensity increased (proportionaly more mass invested in stems), this is consistent with an increased internode length. The number of side shoots (Figure 3.53C) was observed to initailly drop as far-red intensity increased upto 40 µmol m^{-2} s^{-1} but to increase again at 50 µmol m^{-2} s^{-1}. As was the case for other results presented leaf area was a robust predictor of plant dry mass (Figure 3.53D). In contrast to the data from the other light treatments both net assimilation and LUE (Figure 3.52E & 3.52F) were observed to increase as the far-red intensity increased. This could indicate that either far-red is improving the effciency of photochemistry or that the longer internodes allow better light distribution and capture by the canopy.

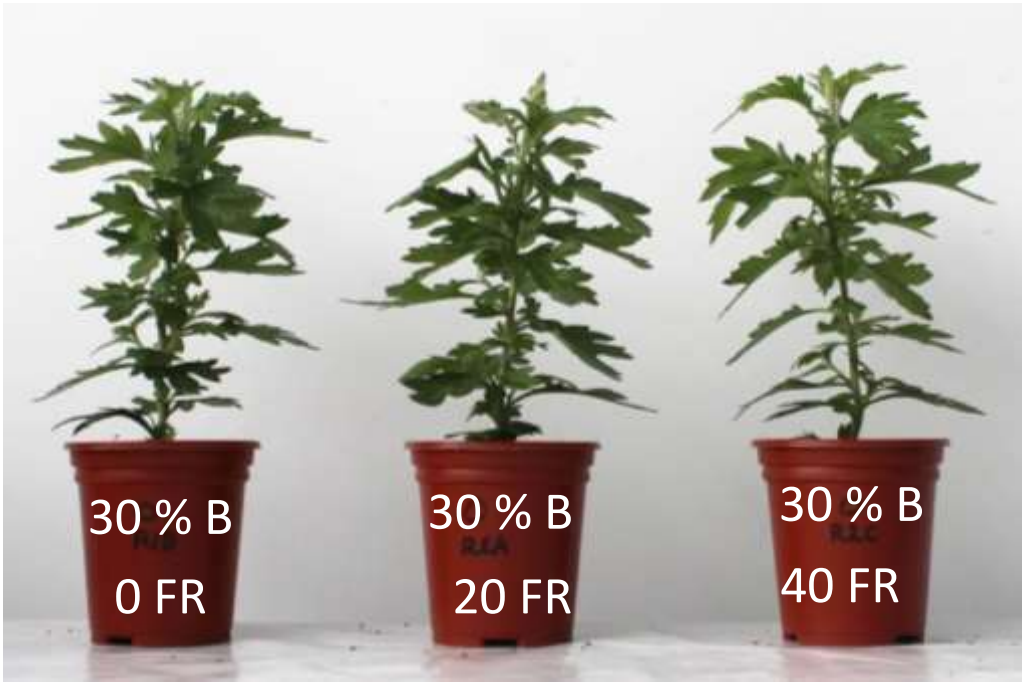

Figure 3.53. Photograph of chrysanthemum plants grown under ligth treatmetns containing 30% blue ligth and increasing amounts of far-red light. **Note:** the far-red light results in a less dense leaf canopy. These plants experienced the same light treatment during propagation.

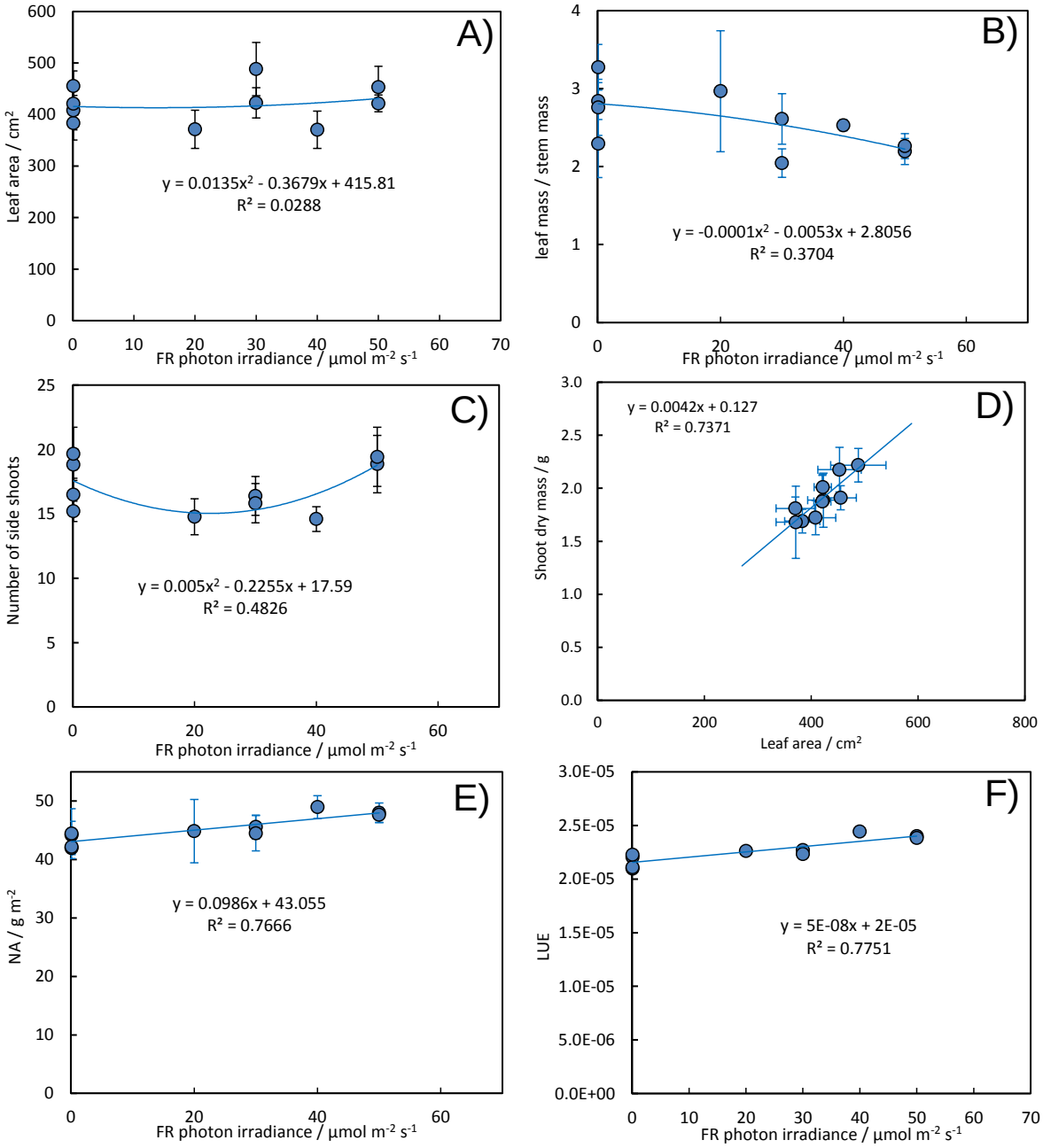

Figure 3.54. The influence of far-red photon irradiance on morphological and growth parameters of chrysanthemum plants grown under a PAR photon irradiance of 200 µmol m^{-2} s^{-1}. **A)** leaf area, **B)** biomass partitioning between the leaves and stems **C)** number of side shoots per plant, **D)** the relationship between leaf area and shoot dry mass, **E)** the changes in net primary production (NET ASSIMILATION) and **F)** changes in light use efficiency (LUE). The multiple data points associated with each light treatment represent the data measured from plants grown under different red:blue ratios. Only data from plants propagated under 16% blue are shown.

Plants grown under different PAR intensities

The plants grown under different PAR photon irradiances were similar in height despite a three-fold change in the light intensity. Plants from the lowest light intensity treatment produced fewer leaves and side shoots than those from the other treatments and longer internodes. These plants also had the lowest leaf area (Figure 3.55A). Leaf to stem dry mass ratio was observed to decrease as the intensity increased (Figure 3.55A). This is consistent with the feel of the plants as the strength/robustness of the stems increased with intensity. Even though proportionally more mass was invested in the stems the total investment in leaves also increased and leaf thickness increased linearly with PAR intensity. Numbers of side shoots also increased with intensity (Figure 3.55C). Shoot mass was correlated with the product of PAR photon irradiance and leaf area as both factors contribute to plant light interception (Figure 3.55D). This also resulted in a linear increase in net assimilation as the light intensity was increased (Figure 3.55E). Light use efficiency decreased non-linearly as the light intensity increased (Figure 3.55F).

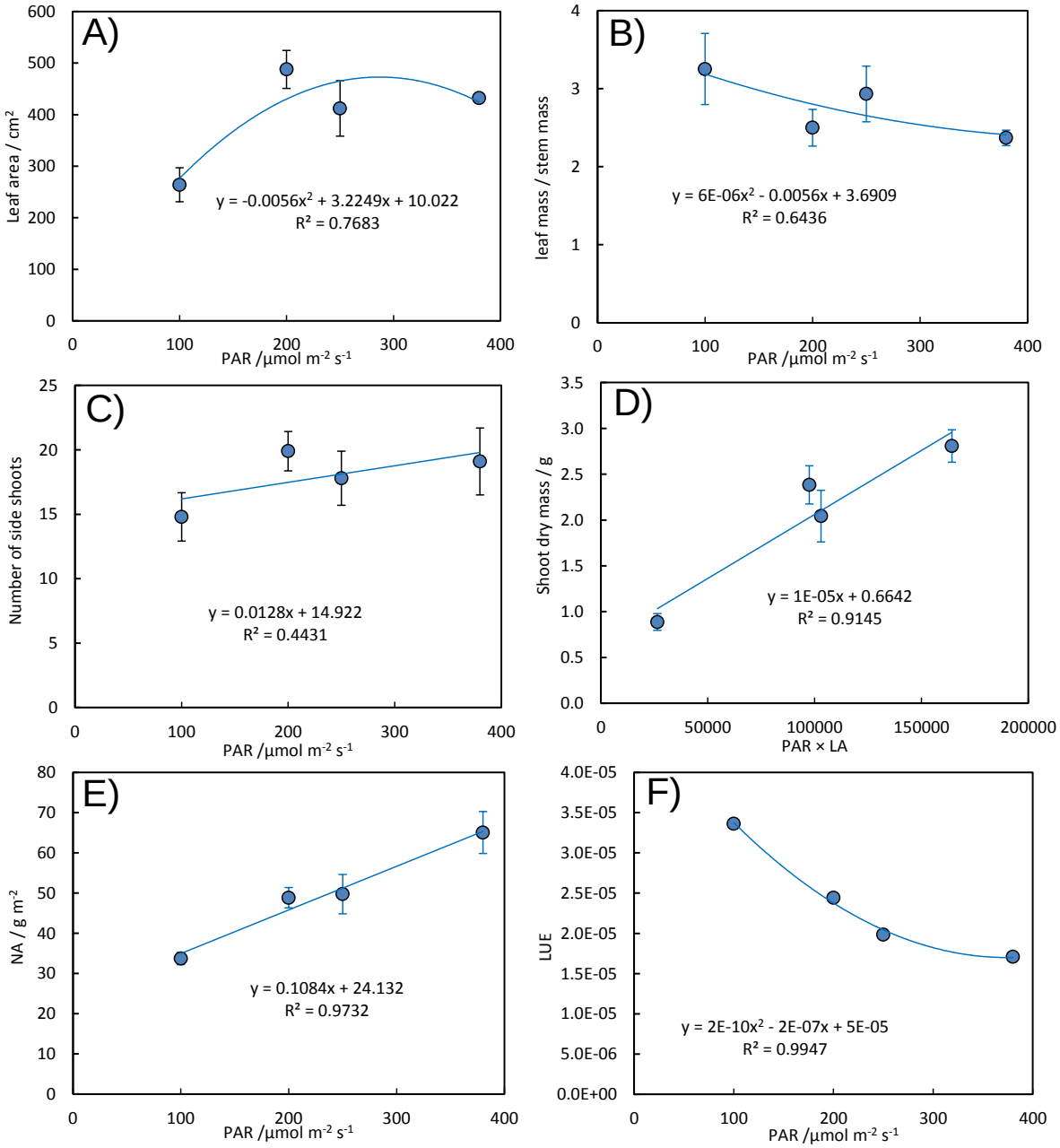

Figure 3.55. The influence of photosynthetically active radiation (PAR) photon irradiance on morphological and physiological/ growth parameters of chrysanthemum plants. **A)** leaf area, **B)** biomass partitioning between the leaves and stems **C)** number of side shoots per plant, **D)** the relationship between leaf area and shoot dry mass, **E)** the changes in net primary production (NET ASSIMILATION) and **F)** changes in light use efficiency (LUE).

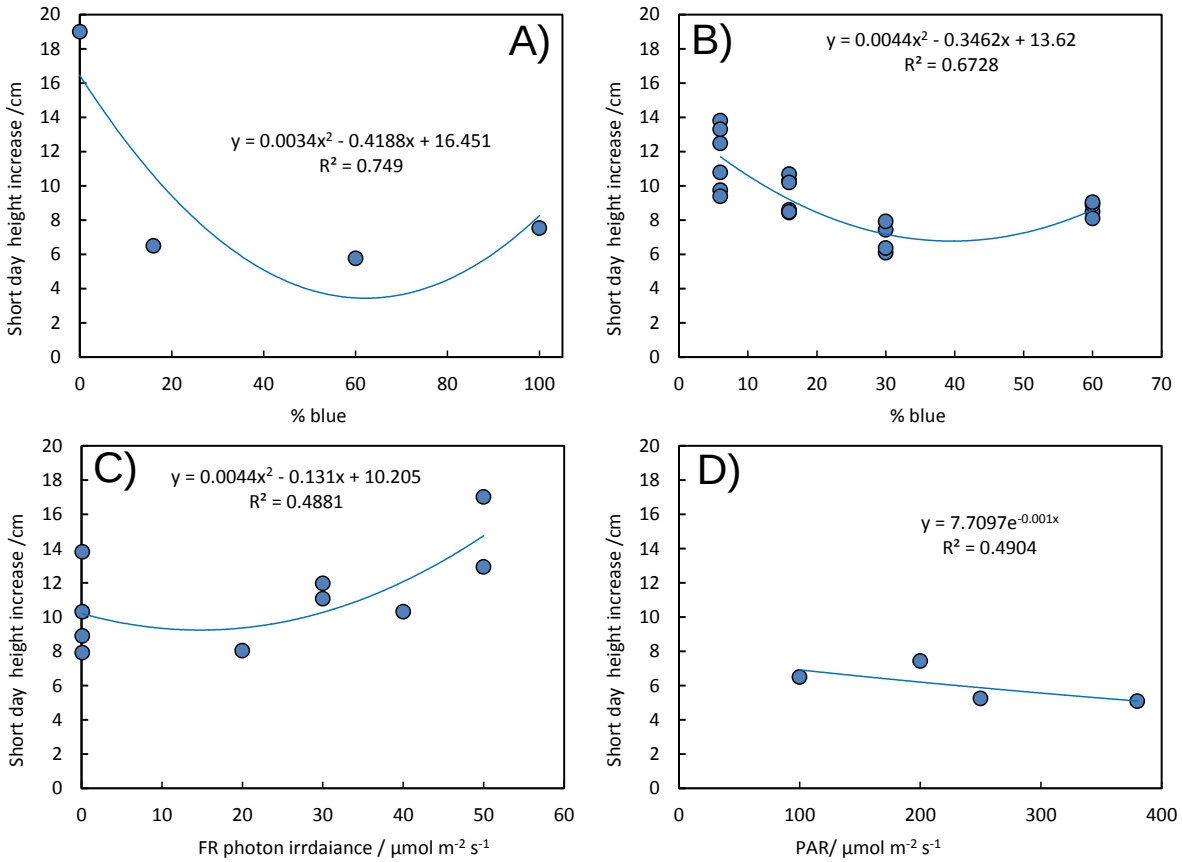

Figure 3.56. The change in plant height under the different light treatments after plants were transferred to short day conditions to induce flowering. **A)** The influence of blue light percentage for plants grown at a photon irradiance of 100 µmol m^{-2} s^{-1}, **B)** influence of blue light percentage for plants grown at a photon irradiance of 200 µmol m^{-2} s^{-1}, **C)** the influence of far-red light and **D)** the influence of photon irradiance of photosynthetically active radiation (PAR).

The influence of light quality on chrysanthemum morphology and flowering under short day conditions.

After the day length was reduced the plants continued to grow and the morphology of the new growth was found to have similar responses to differences in light quality as was observed under the long day conditions (Figure 3.57). Under low light conditions 100% red light treatments resulted in extremely etiolated morphology (Figure 3.57A). Under the 200 µmol m^{-2} s^{-1} treatments the least new growth occurred in the 30% blue treatments (Figure 3.57B). Far-red treatments with intensities of less than 20 µmol m^{-2} s^{-1} have little impact on morphology but higher intensities resulted in stretching (Figure 3.57C). Increasing the PAR intensity resulted in new growth that was more compact (lower increases in plant height: Figure 3.57D).

Under the long day treatment none of the plants flowered even under the high far-red light treatments. After the plants were switched to short day conditions it took approximated two weeks for the first flower buds to become visible. After seven weeks of short days the plants under the 100 µmol m^{-2} s^{-1} treatments had produced less than 14 flower buds and none were near to opening. The most buds were produced under the 16% blue treatment and the least under the 60% blue treatments. This indicates that flower production was light limited under these conditions. Under the 200 µmol m^{-2} s^{-1} treatments the fewest flowers were produced under the 30% blue light treatments. Far-red light was observed to result in a slight increase in flower numbers. Increasing PAR was, as expected, observed to result in a greater number of flowers. While light quality was found to influence flower production in chrysanthemums the numbers of flower buds was also observed to correlate with the dry weight of the plants (Figure 3.58).

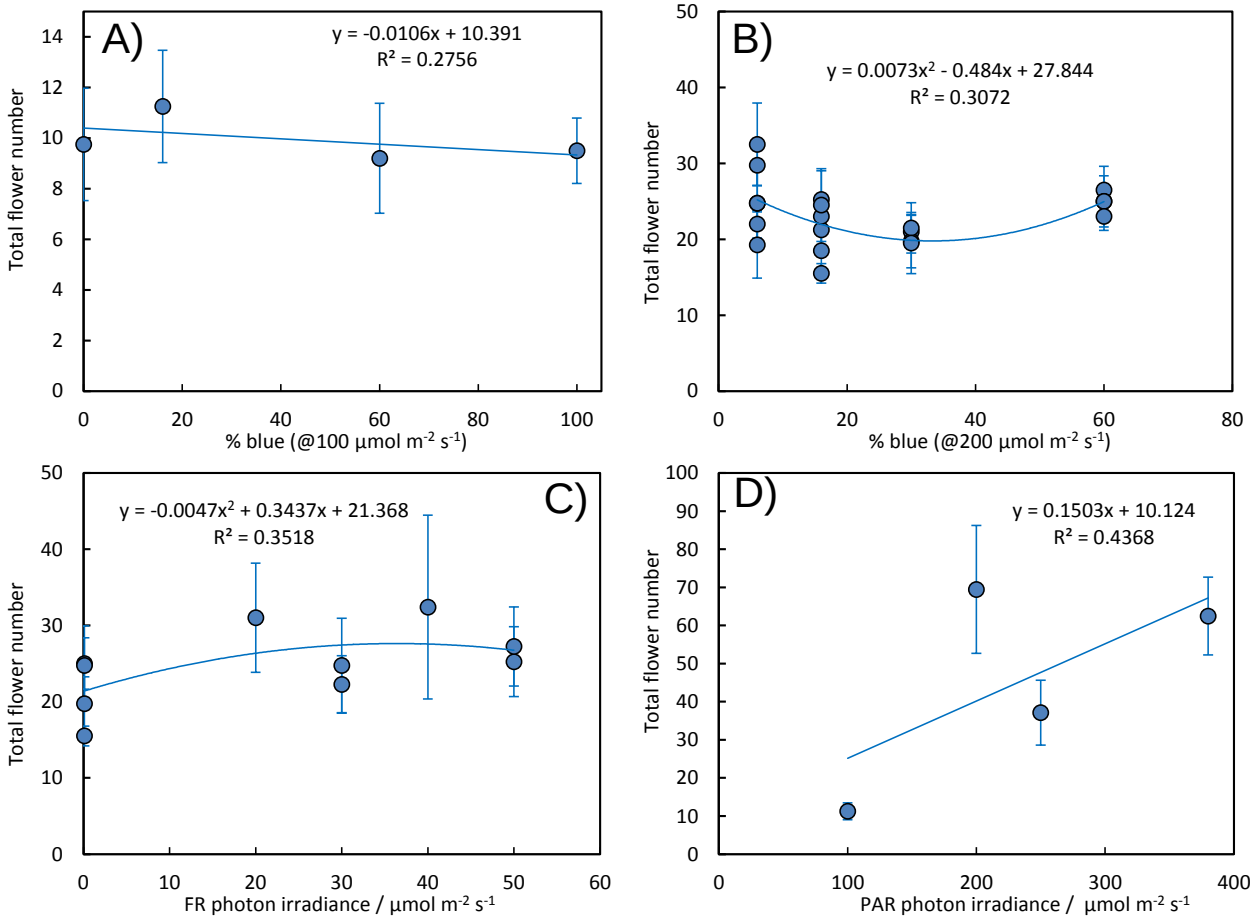

Figure 3.57. The influence of light quality in the total number of flower buds produced by the chrysanthemum plants in this study. The influence of blue percentage when the photon irradiance was **A)** 100 µmol m^{-2} s^{-1} and **B)** 200 µmol m^{-2} s^{-1}. The effect of far-red **C)** and photosynthetically active radiation (PAR) **D)** photon irradiance.

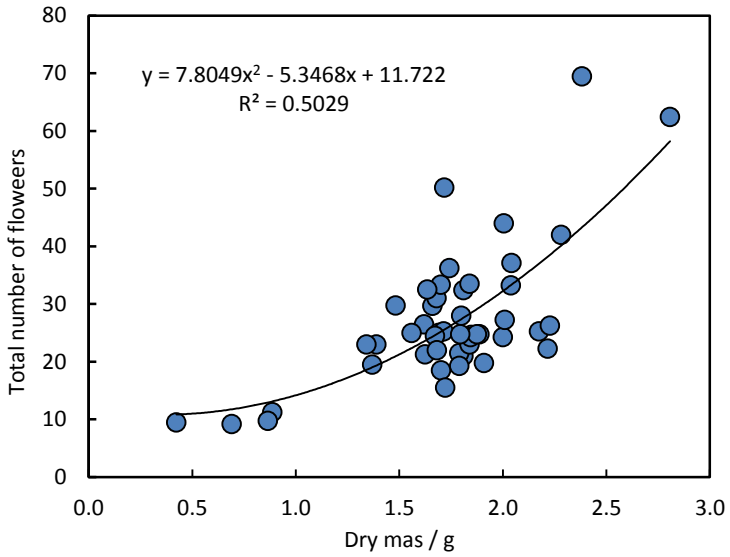

Figure 3.58. The correlation between dry weight and the number of flower buds per plant.

3.5.3. Key Findings - Chrysanthemum

- Low blue light environments benefit rooting of chrysanthemum cuttings.

- The inclusion of far-red light in the spectrum benefits rooting in chrysanthemum. Greater numbers of longer roots were produced as far-red intensity was increased. These benefits were most pronounced when no rooting powder was used.

- Leaf size, number and total leaf area were dependant on the light quality.

- Biomass accumulation was proportional to leaf area under all light treatments.

- LUE efficiency decreases as the light intensity increases. At low intensities (100 µmol m^{-2} s^{-1}) LUE correlated negatively with blue percentage but this relationship was absent at higher light intensities (200 µmol m^{-2} s^{-1}). Far-red light was found to result in an increase in LUE.

- Under short day conditions far-red light resulted in a greater stretching response than was observed during long day conditions.

- Numbers of flowers per plant increased as the biomass of the plants increased.

3.6. DISCUSSION AND ANALYSIS FOR PO CROPS

Light quality, morphology and flowering

The LED light treatments examined in these trials were able to produce good quality flowering plants for all the ornamental species examined. Morphologically, all the species responded similarity to light quality, with the most compact plants occurring under treatments with 60% blue light. While these plants were the most compact they were also often the slowest growing and this lower growth rate is thought to partially contribute to the compact appearance. The fastest growing plants (those achieving the highest biomass) were observed in the treatments containing close to 11% blue light. These findings are similar to those observed in edible crops as discussed in Section 2 and are in line with other studies examining morphological responses of ornamental crops to LED light spectra (Ouzounis et al. 2014, Islam et al 2012). The effects of far-red light were more diverse in the ornamental plants examined than in the PO crops discussed in section 2. Petunia, pansies, and pelargoniums responded to inclusion of far-red in the spectrum by etiolating: these responses were largely similar to those of the PO plants. Begonia, however, was observed to grow more slowly and even produce more compact plants at moderate far-red intensities. It is possible that, as a shade plant, begonias are adapted to remain compact in shaded environments. Under long day conditions, chrysanthemum plants were observed to etiolate little in the presence of far-red light, and blue percentage provided the greatest influence on internode lengths. Under the short day conditions, however, far-red light resulted in considerable etiolation of chrysanthemum plants and they rapidly became un-marketable. The data from chrysanthemum and pelargonium showed that leaf area was the major factor in regulating growth rates as was observed for the PE crops (Section 2).

The majority of these experiments were performed under 16 hour days and all species but the chrysanthemums were long day flowering plants. For the long day flowering species, far-red was found to induce more rapid flowering while red light was found to inhibit flowering. These results can be explained from our understanding of phytochromes (which sense the red: far-red ratio of light). Phytochromes are important in regulating flowering time and act to induce flowering if they sense the onset of shaded conditions (equivalent to treatments with more far-red light). This ensures plants flower before they are crowded out by other larger plants, maximising their chances of reproductive success. The far-red promotion of flowering in long day plants has previously been demonstrated by Runkle and Heins (2001). Although increasing the far-red intensity hastened flowering, overall, far-red light tended to reduce the quality of the plants by inducing stretching. It is possible that providing short term far-red treatments will be sufficient to induce flowering without having

an adverse effect on morphology. Further research will be required to assess the best short term treatments for inducing flowering. For the short day chrysanthemums, flowering was completely inhibited under the long day conditions under all light treatments. Following the transition to short days, all treatments showed signs of bud initiation after about two weeks. Light treatments had significant impacts on numbers of flowers and speed of flower opening. Overall, the plants that achieved greatest biomass produced the most flowers.

In this study, we have correlated flowering and other responses with the absolute photon irradiance of far-red light, as most of the results indicate a linear response to far-red intensity. Other studies have correlated flowering and morphological responses with a calculated value for phytochrome photostationary state (PSS, Sager and McFarlane, 1997, PSS values provided in the light data appendix). Under the 100% red light treatments used in this trial the PSS value was 0.87 and the value decreased as more far-red light was included in the spectrum. For the highest far-red light treatments the PSS value was 0.5. A low value is, therefore, associated with shaded conditions, which result in etiolation and advanced flowering. The PSS value can also be used to explain why the plants from the 100% blue light treatments flowered more rapidly and had etiolated morphology. Under the 100% blue treatments used in our trials the calculated PSS value was 0.56. While PSS values can be used to describe plant responses to light, the calculation is based purely on spectrum and is independent of light intensity. PSS calculations are, therefore, only of use when comparing treatments with similar PAR values and they are of limited use for assessing the effects of different light intensities.

Increasing the PAR intensity was found to result in plants with increasing compactness, thicker leaves, stiffer stems, and greater biomass. In the case of petunia, the best quality plants were observed under the highest light intensity and under short day conditions the highest light intensities produced chrysanthemums with compact structure and large numbers of flowers. However, for pansies and pelargoniums the treatments with the greatest PAR intensities resulted in plants that were ‘too compact’. For pansies, where increased light intensities did not result in more rapid flowering, the optimum light intensity was near to 200 µmol m^{-2} s^{-1}. For the other species the optimum intensity was less obvious and further analysis of the benefits versus the costs would be required.

Chrysanthemum propagation

Unlike the other PE crops, which were grown from seed, chrysanthemums were propagated from cuttings. Light treatments with high proportions of red light were found to result in rapid rooting, as was the observed for all the crops examined in Section 5 of this report. In contrast to the findings of Christiaens *et al* 2015, the best rooting occurred under 15% blue

light, suggesting that some stomatal opening boosts photosynthetic carbon gain which benefits rooting. Overall, our cuttings rooted more rapidly and produced more roots than those described in Christiaens et al (2015), through this was probably because our cuttings had been treated with rooting powder. Chrysanthemum cuttings were observed to root more rapidly under treatments containing far-red light. The benefits of far-red on chrysanthemum rooting have been observed previously (Kurilčik et al 2011). In this trial, the benefits of far-red were greatest when rooting powder was not used, suggesting that light treatments could be used to replace the use of rooting powder in chrysanthemum. It is interesting to note that in the rooting trials reported in Section 5 of this report, far-red was observed to have negative impacts on cutting rooting and survival. These contrasting responses suggest differences in either the hormonal requirements for induction of rooting or differences in the synthesis and transport of hormones between species. More research will be required to assess the hormonal status of the different species under different light treatments.

Pigments

Appearance is particularly important for ornamental species. Leaf colour forms a significant attribute for these crops, especially where leaves have red pigmentation. As with the edible crops, leaf chlorophyll content (which correlates with leaf greenness) was observed to increase as the blue percentage increased to 60% (Figure 2.59). Visual observations indicated that under 100% blue light, leaf colouration (greenness) decreased. Far-red light was also found to reduce leaf chlorophyll content in all species except chrysanthemum. In chrysanthemum leaf colouration was only affected by red: blue ratio. No effects of light spectrum were observed on flower colour in these trials; however, flower size was affected by light treatment and this potentially has a greater impact on appearance than strength of flower pigmentation.

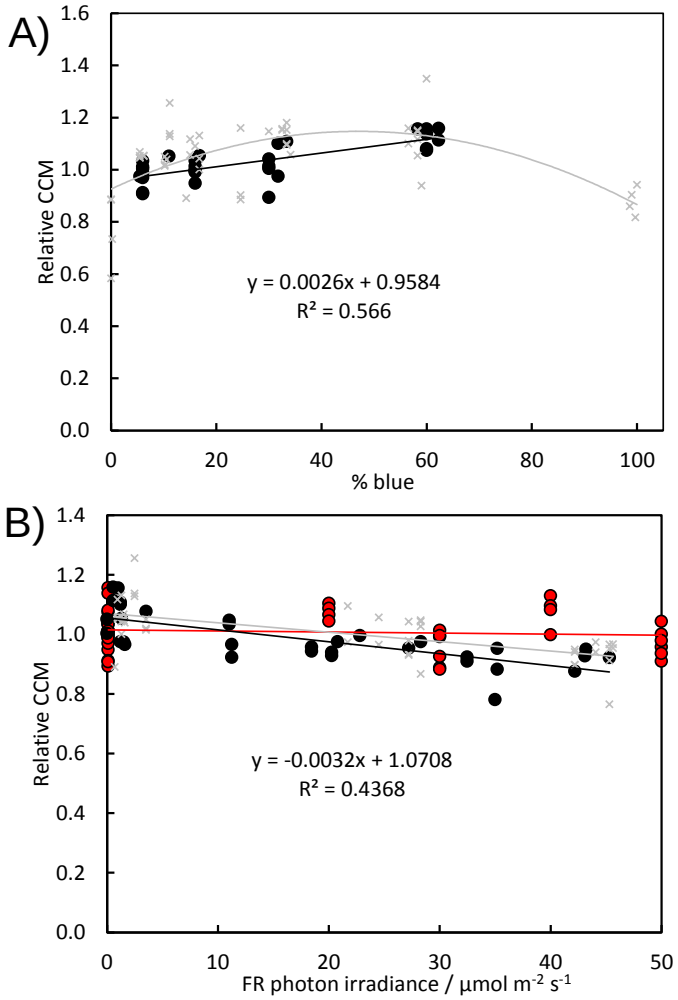

Figure 3.59. Effects of **A)** blue percentage and **B)** far-red photon irradiance on the chlorophyll content of pansy, petunia, chrysanthemum, and pelargonium. Red points and line in figure B show the data from chrysanthemums. Grey lines and crosses in A&B) show the chlorophyll measurements made on PO species for comparison (see Figure 2.49)

Section 4. Spectral effects on plant growth: Glasshouse trials

4.0. INTRODUCTION

The results presented in Section 2: Protected Edibles and Section 3: Protected Ornamentals demonstrate that light quality has strong, consistent and reproducible influences on crop morphology and development. The results highlight the potential benefits that LEDs can provide to the horticulture industry. However, all the results presented were performed in a closed (no sunlight) multi-tiered growth chamber where the effects of sunlight are excluded so a detailed understanding of crop responses to LED light with specific qualities could be determined. However, the majority of growers that are considering installing LEDs would be expected to install lights in glasshouse situations. In glasshouses sunlight, which contains all regions of the spectrum and has high light intensities could reduce or remove the benefits of spectral manipulation achieved with LED lights. The benefits that LEDs provide are expected to be most apparent during the winter months when day lengths are short and solar radiation is at its lowest intensity. As this is the period of the year when growers are most likely to experience the greatest challenges associated with poor crop morphology/quality LEDs have the potential to improve crop quality enabling season extension/year round production. In these experiments we examine the influence of LED spectrum when provided as supplemental lighting through the winter months.

4.1. Methods

Plant material

Rooted cuttings of Huechera ‘Lime Marmalade’ and Lavender ‘Devon Compact’ supplied by Kernock Park Plants were planted in six packs in Levington M2 substrate on 14th November 2016. These plants were re-potted on the 26th Jan 2017 in to 2l pots again using Levington M2 substrate.

Seed of lettuce varieties Frank and Matriosk (supplied by Moles Seeds) were sown in peat blocks and covered with vermiculite on the 31st October 2016. Plants were assessed and harvested on the 16 December 2016.

Petunia (*Petunia hybrida,* Mirage Blue F1, CN Seeds) and pansy (*Viola wittrockiana* c.v. Dynamite Formula Mix) seed were sown in one inch cells and placed under the different light treatments. Plants were transplanted into six-packs filled with Levington M2 substrate when the plug plants were of sufficient size.

Light treatments.

Sunlight- Natural solar radiation was measured by the site computer at STC every 5 minutes. Radiation measurements were made using a global radiation sensor in units of Wm^{-2}. These units were converted in the units of $\mu mol_{[PAR]}\ m^{-2}\ s^{-1}$ using the methods provided in the AHDB Technical Guide- Lighting: The Principles. In summary, the measured light data was multiplied by a value of 0.42 to change the measurement of global radiation to a measurement of PAR radiation. This PAR radiation measurement was then converted to a value of PAR photon irradiance by multiplying the value by 4.62. These values were used to calculate the daily light integral by summing the values and multiplying the summed value by number of seconds between measurements (5 minutes × 60 = 300 seconds) before dividing by 1,000,000 to get a DLI measurement in $mol_{[PAR]}\ m^{-2}\ d^{-1}$. These values represent the light intensity outside the glasshouse. To accurately determine the light reaching the plants in each light treatment would require continuous measurements at each location within the glasshouse, such measurements were not available. For the purposes of reporting the light levels in the glasshouse we have assumed 70% of the light enters the growing area.

Measurements of natural light levels within each compartment were made to assess the magnitude of any differences between the compartments. Light levels were measured using a hand held PAR meter (Skye Instruments) at the centre of each compartment at midday with the artificial lights were turned off.

Supplemental radiation - Five supplemental light treatments were created in the glasshouse. An unlit control was included that only received solar radiation. A high pressure sodium treatment with a light intensity of 63 µmol $m^{-2}\ s^{-1}$ provided by 600W HPS lamps. The three LED treatments were provided by LED lamps that were not necessarily designed for installation in glasshouses. These lamps were mounted approximately 1.5 meters above the plants. A white light treatment with an intensity of 104 µmol $m^{-2}\ s^{-1}$ was provided by Valoya AP 673L lamps. An 11% blue 89% red treatment with an intensity of 70 µmol $m^{-2}\ s^{-1}$ was provide by Philips production modules. An 30% blue 70% red treatment with an intensity of 67 µmol $m^{-2}\ s^{-1}$ was provide by Philips hi blue production modules. To separate the five light treatments and ensure no light contamination between the treatments white plastic screens were suspended between the light zones (Figure 4.1). While the screens were necessary to separate the treatments they did potentially cause differences in natural light levels at the plants by causing shading. To minimise these effects the outside walls of the glasshouse were whitewashed. Between the 1st November 16 and 18th January

2017 the supplemental lighting was provided for 12 hours, after which the supplemental lighting was provided for 14 hours.

Figure 4.1. Picture of the glasshouse trials with screens in place between the supplemental light treatments.

4.2. RESULTS.

4.2.1. Glasshouse Climate

Solar radiation

The daily light integral changed 8 fold during this trial with an average DLI in December of 2 mol m^{-2} d^{-1} but 16 mol m^{-2} d^{-1} in April. The light data were within the ranges expected for this location and time of year. For the majority of the experiment the weather conditions were cloudy which would create a diffuse light environment. Under diffuse conditions the light in the glasshouse will be more uniform and the difference between the treatments caused by location will be minimised. On days when the conditions were predominantly sunny (measured values were close to the theoretical light) the differences between treatments would have been at their greatest.

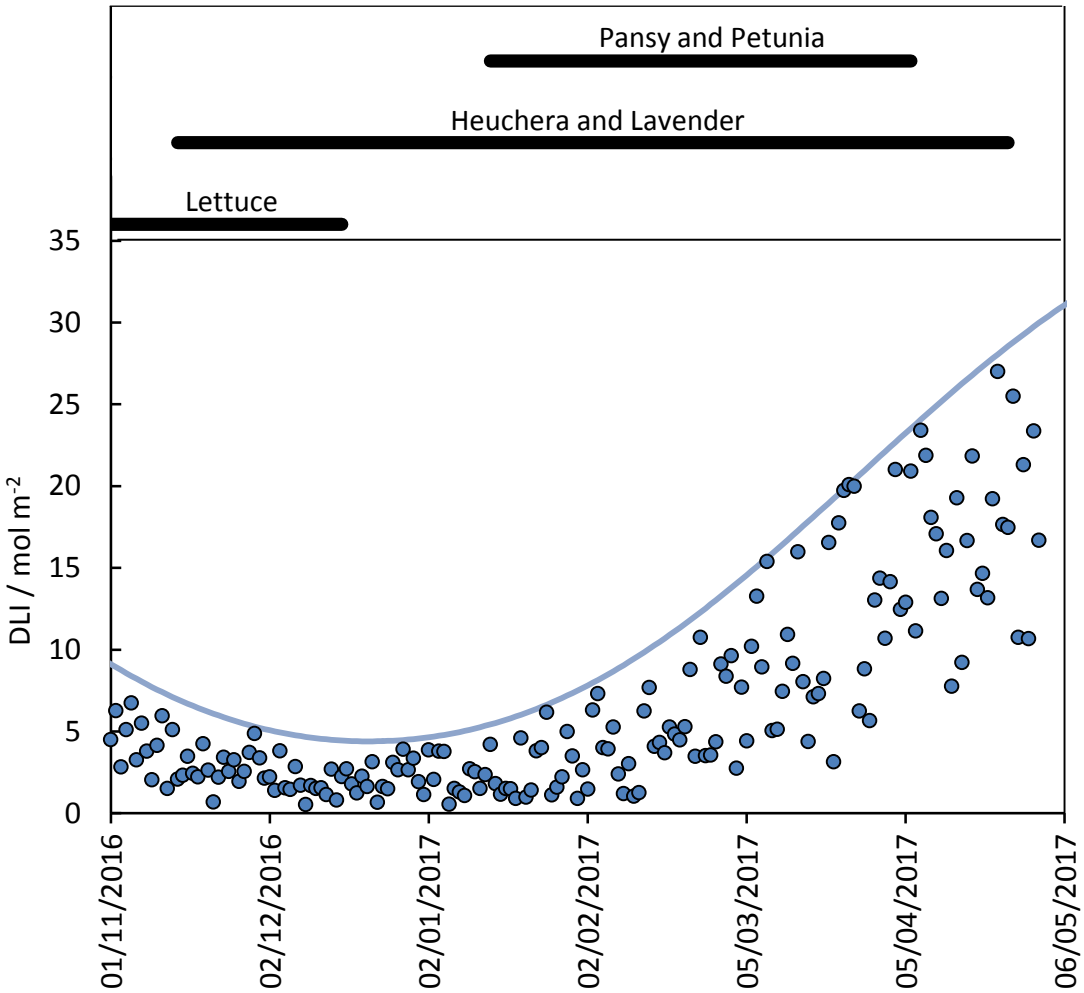

Figure 4.2. Graph of solar daily light integrals at STC during the glasshouse trials. Blue line indicates the max possible light intensity that can be achieved on a sunny day. Black bars indicate the period when the different crops were in the glasshouse.

Leaf temperature and irrigation

In addition to the different light spectra the HPS lamps generate significant radiative heat. This radiative heat was absent from the LED treatments. Under cloudy environmental conditions the leaf temperatures were up to 3°C warmer under the HPS treatments than those from the LED treatments. Under direct sunlight solar heating resulted in similar leaf temperatures between the treatments. However, with the prevailing conditions being cloudy the HPS treatment would have been warmer than the other treatments for the majority of the trial, especially when the lights were on before dawn. This is consistent with the observed differences in water consumption between the treatments. Plants grown under the HPS treatments required more regular irrigation and experienced more pronounced wetting/drying cycles.

4.2.2. HEUCHERA GLASSHOUSE TRIALS

In the six packs the heuchera plants grew well and produced good quality plants. The plants in six packs were of sufficient size to required transfer to 2l pots by 26th January 2017 (ten weeks after planting – Figure 4.3). At this point the plants from the no light treatments were significantly smaller than those from the other light treatments. The three LED treatments were also slightly larger than the HPS treatment. This was thought to be due to the HPS plants drying out more rapidly than the LED treatments. Once in the 2 l ports the plants continued to grow well and plant remained disease free. When viewed by professional growers the colour of the heucheras grown under the 30% blue treatments were regarded to be 'too-green' for the 'Lime Marmalade variety'. This is consistent with the findings in the LED4CROPS facility were higher blue light environments enhances leaf pigmentation. At the end of the trial (25th April 2017 Figure 4.3) the no light treatment plants were still smaller than those from the lit treatments, and plants from the lit treatments were of considerable size. While all the plants were of high quality there were differences between the plants, though identifying the absolute qualities that differed was difficult. Of the lit treatments the 30% blue treatment remained the most compact in appearance and those from the HPS treatment were the palest in colour.

4.2.3. LAVENDER GLASSHOUSE TRIALS

After 10 weeks growth in six packs the lavender plants were potted up to 2 l pots and photographed (Figure 4.4). The plants from the 30% blue treatment were the shortest and most compact plants following transplanting. The plants from the other three light treatments were similar in stature and morphology. The unlit treatments were similar in size to the lit treatments though they were less dense plants and the new growth was slightly etiolated and relatively weak. Following the increase in day length of the supplemental lighting to 14 hours the lavender plants from the lit treatments began to bolt and by the end of the trial the HPS treatment had finished flowering while the unlit treatments was just beginning to flower. The advanced flowering of the HPS treatment compared to the other lit treatments was thought to be caused by the higher plant temperature resulting from the radiant heat of the HPS lamps. The three LED treatments were different in morphology. The 30% blue treatment resulted in the plants with the fewest stems and were slowest to flower. The Valoya treatment and the 11 % blue treatment resulted in denser canopies than the 30% blue treatment. The Valoya treatment flowered sooner that he 11% blue treatment and had slightly longer stems (possibly due to earlier bolting). Of the four lit treatments the Valoya and 11% blue treatment produced the best quality plants, possibly due to the slightly higher light intensity.

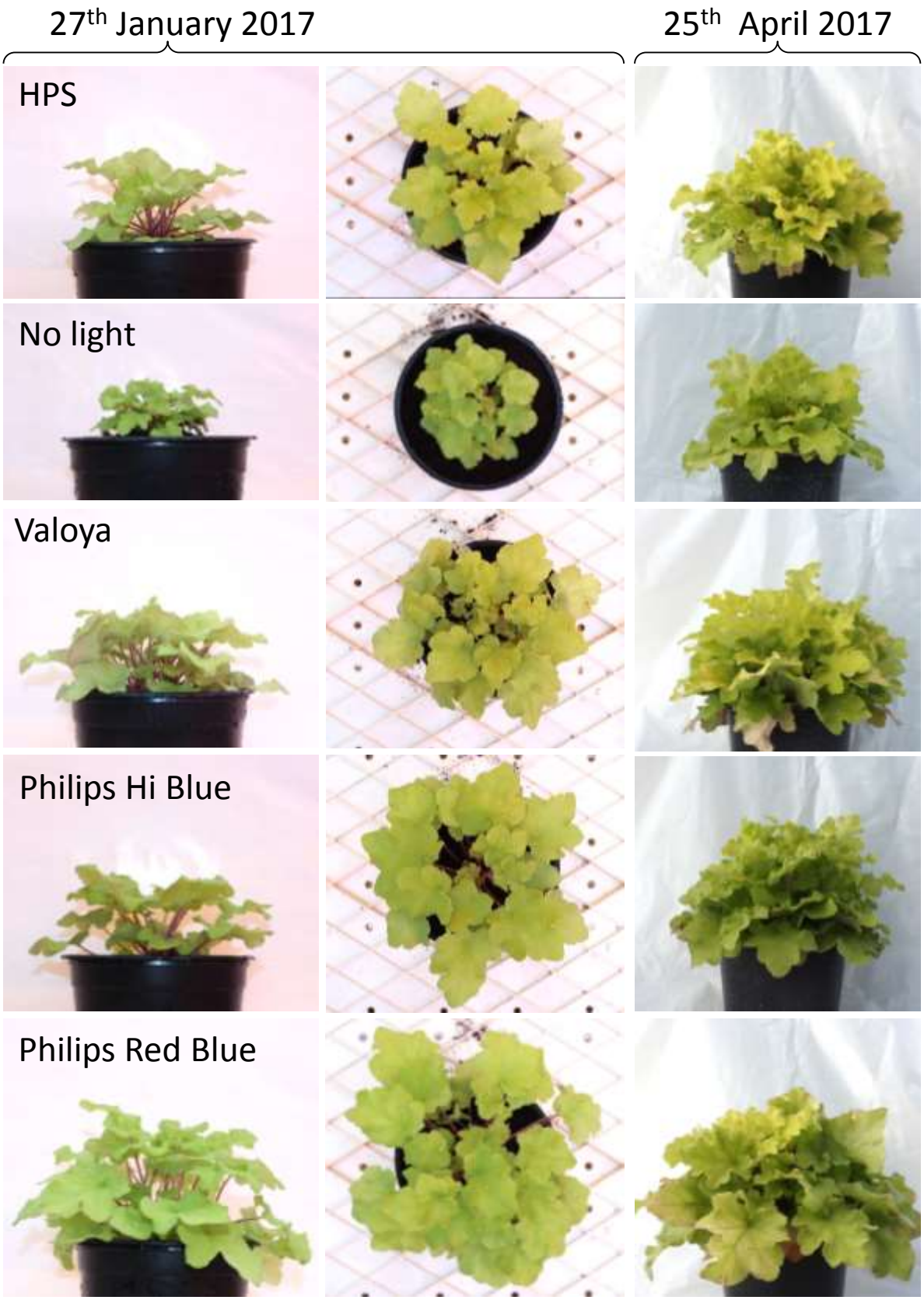

Figure 4.3. Heuchera 'Lime Marmelade' plants grown under the different supplemental light treatments in the glasshouse.

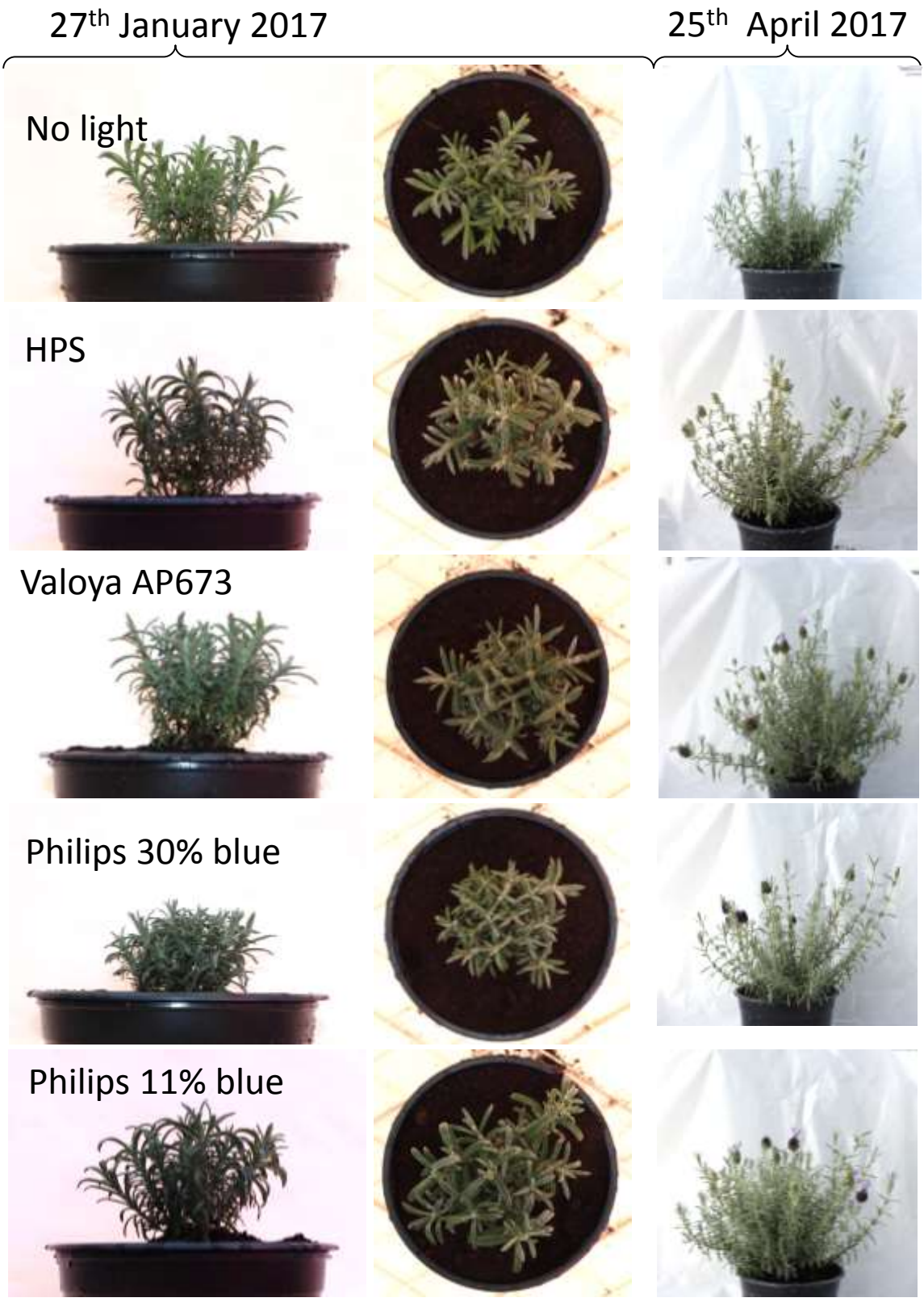

Figure 4. Lavender ‘Devon compact’ plants grown under the different supplemental light treatments in the glasshouse.

4.2.4. PETUNIA GLASSHOUSE TRIALS

The petunia plug plants (Figure 4.5) were observed to be smallest, have the fewest roots, and have the lowest overall quality in the no-light treatment that received only solar radiation. For these plants root development was insufficient to hold the plugs together which disintegrated when handled. All supplemental lighting treatments resulted in an increased growth and root development and plugs remained intact during handling. The plants from the HPS treatment were most advanced developmentally and flower buds were visible. The plants from the 30% blue treatment were the most compact. Following

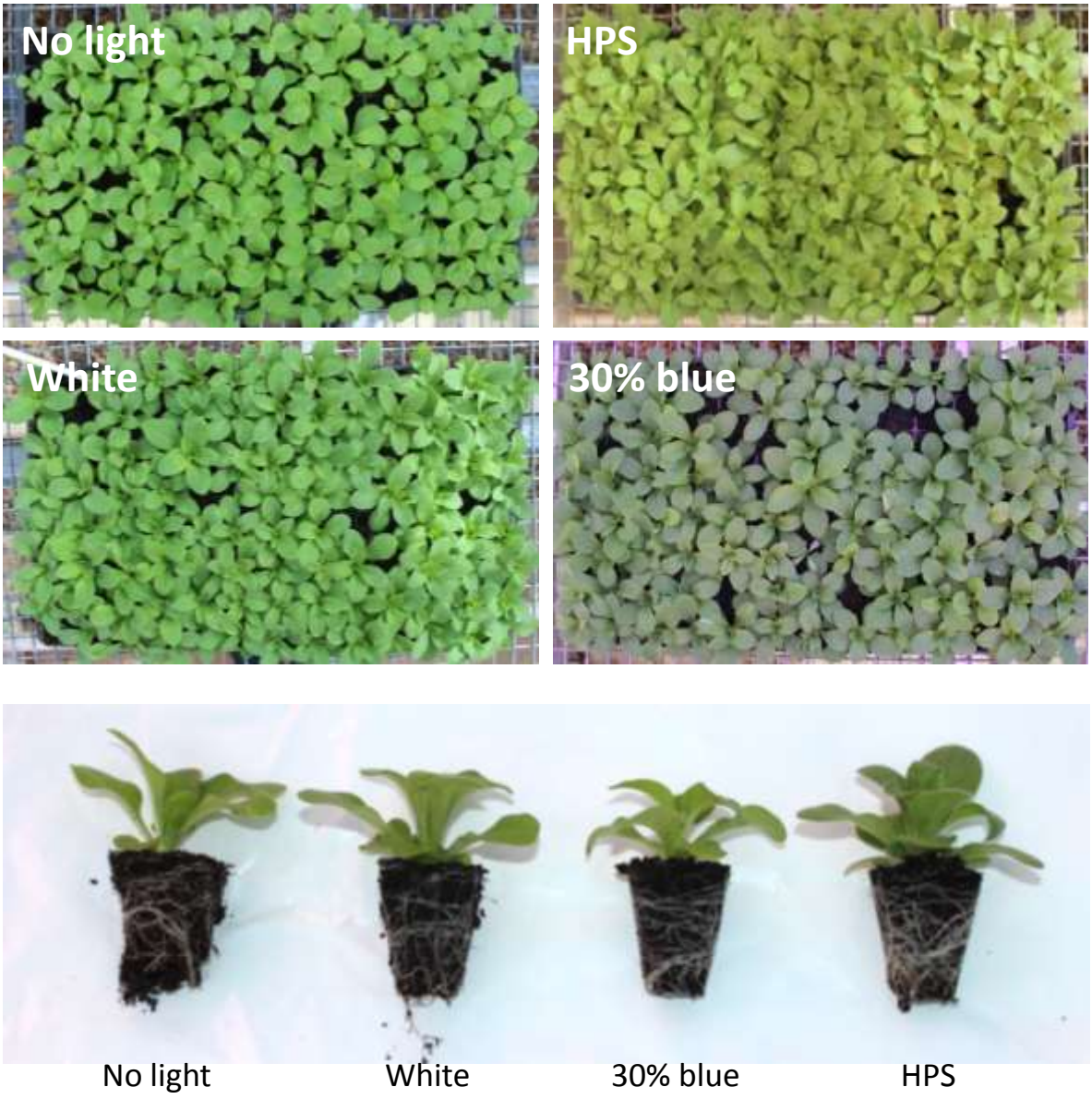

Figure 4.5. Petunia plug plants grown in a glasshouse with four different supplemental light treatments. **A)** Images of the plug trays viewed from above. **B)** Individual plugs showing the root growth. Photographs taken on the 15th March 2017.

transplantation to six packs the petunias grew rapidly. The no light treatments were slower growing throughout the trial and were last to flower. However, by the end of the trial 5th April 2017 the no light treatment plants were growing rapidly as the natural light levels increased, had begun flowering (Figure 4.6) and their fresh mass was almost as large as

Figure 4.6. Six packs of petunia plants grown in a glasshouse at STC under four supplemental light treatments. Photographs were taken on the 5th April 2017.

that of the HPS plants. The no light treatment plants were less compact than the lit treatments and had the largest leaves (Figure 4.7) and fewest open flowers. For the three lit treatments the numbers of flower buds were similar, though the HPS treatment had more open flowers, presumably due to the higher plant temperature. Fresh mass was greatest for the Valoya light treatment and similar for the HPS and 30% blue treatment.

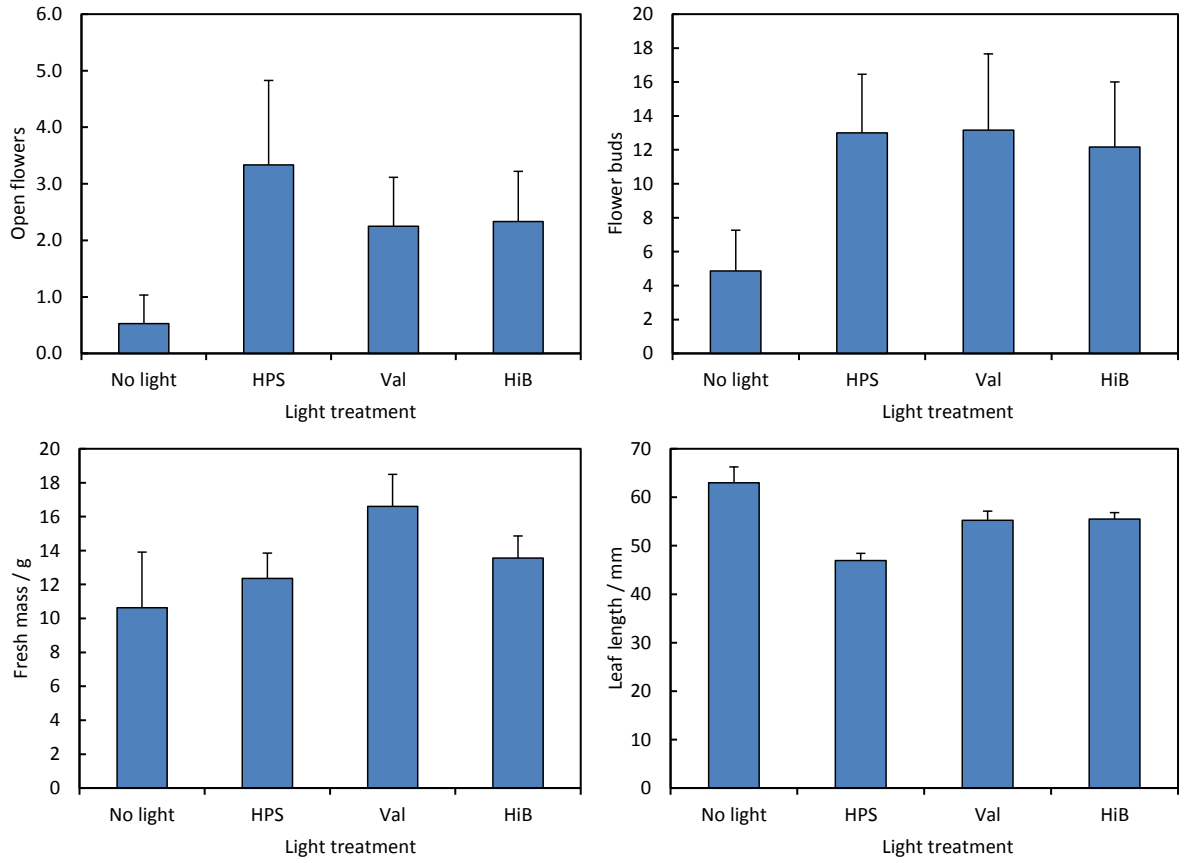

Figure 4.7. Petunia flowering and morphology measurements made on the 6th April 2017 in the glasshouse at STC.

4.2.4. PANSY GLASSHOUSE TRIAL

Superficially all the pansy plug plants looked similar (Figure 4.8). On closer inspection there were significant differences in plant quality. The pansy plants propagated under the no light treatments (only solar radiation) produced the largest leaves and the longest petioles but the fewest leaves. Biomass was also lowest in these plants and root development was minimal resulting in plugs that disintegrated when handling. The best roots were produced in the treatment containing 30% blue light. These plants remained compact and presumably invested a greater proportion of their biomass to create the dense root balls.

The sodium treatments also produced good quality plants but in this case the roots were slightly browned, this was thought to be the result of the plugs drying out between watering. Overall the plugs from the LED treatments retained a more consistent moisture content and resulted in the plants experiencing less stress. By the end of the trial plants from all treatments were in flower though the plants from the lit treatments were past their best (Figure 4.9).

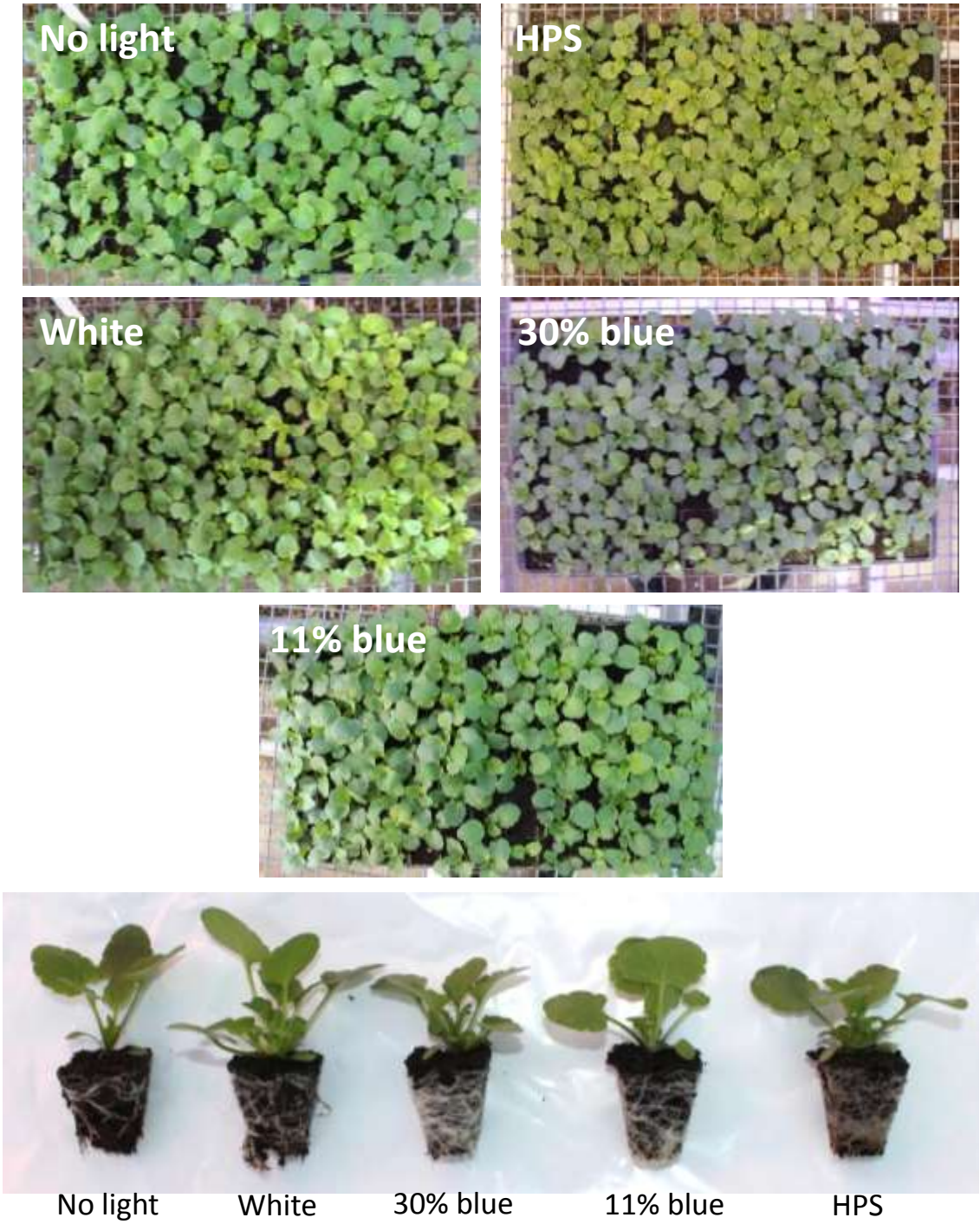

Figure 4.8. The influence of supplemental light treatment on the quality of pansy plug plants.

Figure 4.9. Pansies grow under the different supplemental lighting strategies in a glasshouse at STC. Photographs were taken at the end of the trial on 25th April 2017.

Fresh mass of the pansies was greatest under the Valoya treatment and lowest under the 30% blue Philips treatments. These differences in plant mass correlated with the differences in leaf area, indicating that light quality is influencing growth rates via manipulation of plant morphology. This is consistent with the findings made in the LED4CROPS facility.

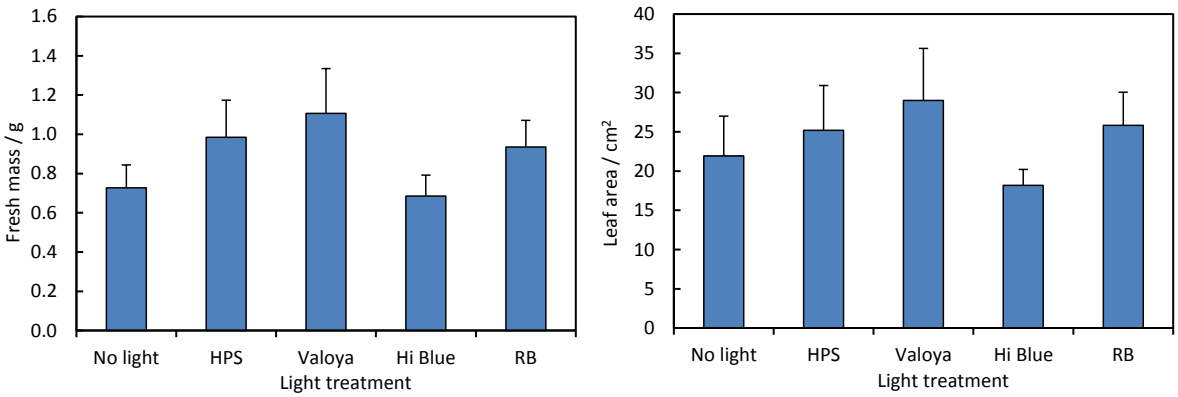

Figure 4.10. Influence of supplemental light treatment on pansy **A)** fresh mass and **B)** leaf area.

4.5. LETTUCE GLASSHOUSE TRIAL

We grew two varieties of lettuce in the glasshouse a green variety (Frank) and a red variety (Matrioska). The red colouration of the Matrioska differed with the colour and intensity of the light incident on the plant (Figure 4.11). In the no supplemental light treatment the survival and growth of the lettuce was patchy and the plants produced mostly green leaves. Plant survival was greater and growth was more uniform in the supplemental light treatments. Pigmentation of both varieties was influenced by the colour of the supplemental light received (figure 4.12). As the blue percentage was increased so did the chlorophyll content of leaves. The red pigmentation of the Matrioska variety was also found correlate positively with the blue percentage. As was the case for the lettuce plants grown in the LED4CROPS facility leaf length was also observed to decrease as the blue percentage of the supplemental light increased (Figure 4.13).

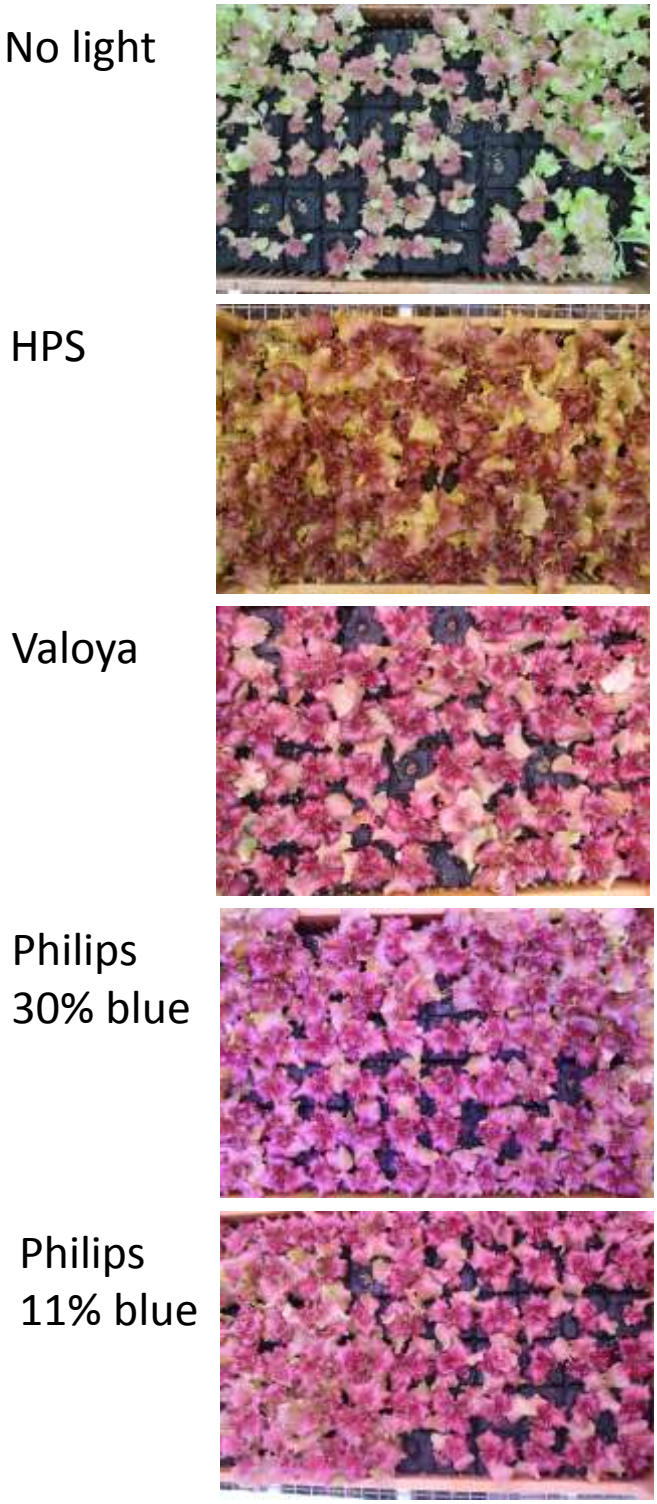

Figure 4.11. Red lettuce variety Matrioska grown under the different supplemental light treatments in a glasshouse at STC.

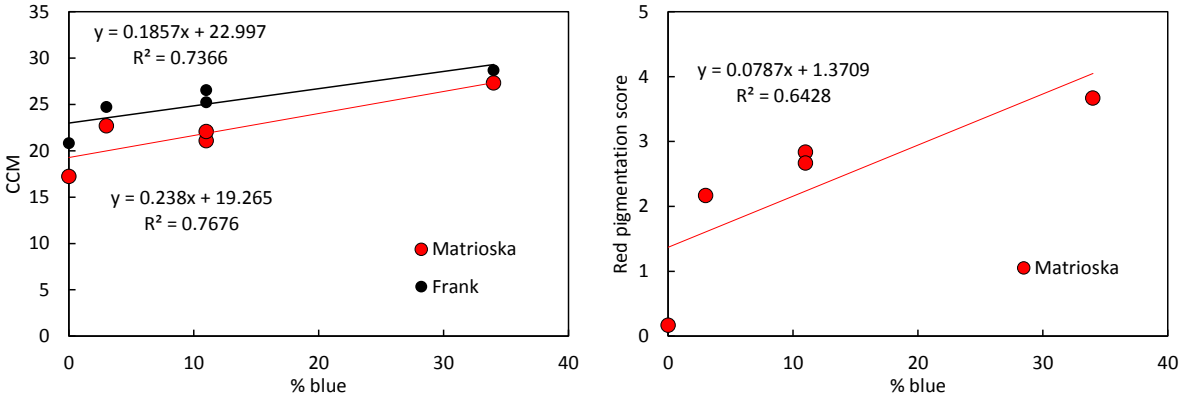

Figure 4.12. The influence of the blue light percentage of the supplemental light source on **A)** the chlorophyll content of leaves measured using an AtLeaf chlorophyll content meter (CCM) and **B)** the red pigmentation of a red lettuce variety.

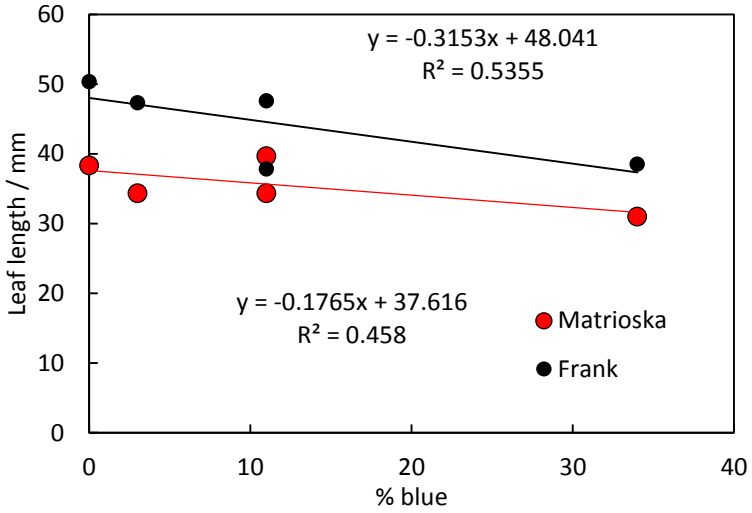

Figure 4.13. The effect of supplemental light quality on the length of the 2nd true leaf of two lettuce varieties, Frank and Matriska.

4.6. DISCUSSION

Solar radiation provides the largest source of light available for crop growth in a glasshouse. In the summer, when light levels are high and day lengths are long, growth rates are often light-saturated and certain crops may require shading to prevent scorch and protect plant quality. In the winter, however, when light levels are low and day lengths are short, plant growth is light-limited and morphology exhibits etiolation. Maintaining plant quality under these conditions can be challenging and many ornamental crops receive applications of plant growth regulators (PGRs) to maintain compactness. The work reported in sections 2 and 3 of this report demonstrated that light quality can be used to manipulate the morphology and growth rates of a wide range of ornamental and edible crops, providing the potential to improve crop quality and replace PGRs. However, those experiments were performed in the absence of sunlight and the question remained as to whether spectral

manipulation was effective in the presence of sunlight. The trials reported in this section have demonstrated that spectral manipulation can be used to influence plant morphology in the glasshouse during the winter months. Supplemental lighting increased the growth rates of all the crops examined, compared to the unlit treatments, and light quality influenced morphology and pigmentation in a similar fashion to plants grown in the absence of sunlight. Higher proportions of blue light resulted in more compact plants. These results are consistent with other LED supplemental light trials performed in glasshouses. Poinsettias grown with supplemental lighting containing 20% blue were 20-34% shorter than those grown under HPS (5% blue) lamps (Islam *et al.* 2012). Roses were observed to be shortest when grown under 40% supplemental blue light (Ouzounis *et al.* 2014). Increasing the proportion of blue light reduced stem lengths in multiple species (Moon *et al.* 2006, Nanya *et al.* 2012).

In these trials petunias, pansies, and lavender were found to flower sooner under the supplemental treatments compared to the unlit treatments. This advanced flowering was mostly likely caused by a combination of increased growth rate and the extended day length in these treatments. Of the lit treatments, the plants from the HPS treatments were observed to flower slightly earlier, which was probably a result of the higher plant temperatures. Phytochromes are important for regulating flowering and are sensitive to temperature as well as to red:far-red ratios of light (Franklin 2009). Thus, the elevated temperature may have contributed to advanced flowering.

While these results demonstrate the potential for the use of spectral manipulation during the short days of winter, similar effects of spectral manipulation are not necessarily expected to be achievable in the summer months when solar radiation and day lengths are higher. The effects of solar radiation were increasing towards the end of this trials. This small-scale trial employed shade screens between the treatment areas to prevent light spill. During the winter period, when the sunlight was predominantly diffuse (due to low solar angles and clouds), similar amounts of sunlight reached each crop production area. However, as the solar angle increased and more sunny days occurred, after the start of March, different amounts of sunlight were received in the different treatment areas. This compromised the results of trials examining the effects of light on basil, pepper, and tomato crops as it was not possible to separate the influences of light intensity from the spectral effects of the supplemental lighting. This highlights the need to perform larger scale trials designed to assess the influence of supplemental light treatments through the seasons. With such trials it would be possible to quantify the effects of LED spectra in comparison to changing solar radiation and provide guidelines as to when lighting systems are expected to be most beneficial for morphology and growth rates.

