Effects of Different Light Sources on the Growth of Non-heading Chinese Cabbage (*Brassica campestris* L.)

Huimin Li
College of Agronomy, Nanjing Agricultural University. Nanjing, Jiangsu, 210095, China
E-mail: 2009201005@njau.edu.cn

Canming Tang (Corresponding author)
College of Agronomy, Nanjing Agricultural University. Nanjing, Jiangsu, 210095, China
Tel: 86-258-486-0062 E-mail: cmtang@yahoo.cn

Zhigang Xu (Corresponding author)
College of Agronomy, Nanjing Agricultural University. Nanjing, Jiangsu, 210095, China
E-mail: xuzhigang@njau.edu.cn

Xiaoying Liu
College of Agronomy, Nanjing Agricultural University. Nanjing, Jiangsu, 210095, China
E-mail: liuxy@njau.edu.cn

Xuelin Han
Kingsun, optoelectronic co.,ltd. Dongguan, Guangdong, 523565, China
E-mail: ks-hxl@kingsun-china.com

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Abstract

To date, little is known about the effects of different light sources on the growth and quality of non-heading Chinese cabbage (*Brassica campestris* L.). The objective of present study was to evaluate the effects of light-emitting diodes (LEDs) light sources (blue, blue plus red, red), fluorescent lamps and sunlight on growth and vitamin C, soluble protein, sucrose, soluble sugar, starch and pigment concentrations in non-heading Chinese cabbage seedlings. The dry mass of shoots and the fresh and dry masses of roots were highest in seedlings grown under red LEDs with weak lights. The fresh mass of roots and starch concentration were highest under red LEDs despite of the altered photosynthetic photo flux density (PPFD) levels. The concentrations of chlorophylls and vitamin C were greatest under blue LEDs with altered PPFD levels. The numbers of flower buds and open flowers were highest under red LEDs and blue plus red LEDs and were higher under LEDs than fluorescent lamps. The duration of flowering was highest under red LEDs and blue plus red LEDs. The present results demonstrate that LED light sources are more effective than fluorescent lamps for vegetative and reproductive growth of non-heading Chinese cabbage. Moreover, blue LEDs benefit vegetative growth, while red LEDs and

blue plus red LEDs support reproductive growth in non-heading Chinese cabbage. In the artificial cultivation and subsequent transplanting of the life cycle of plants, the light source can be selected to meet the requirements of different growth stages of plants and be used to promote the subsequent process in the industrial production of non-heading Chinese cabbage.

Keywords: Light-emitting diodes (LEDs), Non-heading Chinese cabbage, Vitamin C, Starch, Pigment, Flower bud

1. Introduction

Light plays a key role in plant life, determining their photo-morphogenesis and photosynthesis rate (Avercheva *et al.*, 2009). The sun emits the most of its radiation in the visible range, it covers the range of wavelength from 400-700nm (Kolawole, *et al.*, 2010). The integration, quality, duration and intensity of red, far-red, blue, UV-A (320–500 nm) and UV-B (280–320 nm) light have a profound influence on plants by triggering physiological reactions to control their growth and development (Briggs *et al.*, 2001; Briggs and Olney, 2001; Clouse, 2001). LEDs are solid-state, long-lasting and durable sources of narrow-band light that can be used in a variety of horticultural and photo-biological applications (Stutte, 2009), including controlled research environments (Avercheva *et al.*, 2009), lighting for tissue culture (Li *et al.*, 2010) and supplemental and photoperiod lighting for greenhouses (Morrow, 2008). Because of their potential to be implemented in dynamic lighting strategies to control plant growth, development, physiological responses and production, it is important to learn more about the influence of light quality on these processes (Folta and Childers, 2008; Lefsrud *et al.*, 2008; Massa et al., 2008).

Various studies have shown that LEDs have been successfully used for cultivation in several horticultural plant species, including lettuce (Bula *et al.*, 1991; Hoenecke *et al.*, 1992; Yanagi *et al.*, 1996; Okamoto *et al.*, 1997; Yorio e*t al.*, 2001; Kim *et al.*, 2004; Kim *et al.*, 2006; Stutte *et al.*, 2009; Li and Kubota, 2009), cucumber (Menard *et al.*, 2006; Brazaityte *et al.*, 2009), pepper (Brown *et al*., 1995; Schuerger *et al.*, 1997), spinach (Yorio *et al.*, 2001), radish (Yorio *et al.*, 2001; Tamulaitis *et al.*, 2005), Chinese cabbage (Avercheva *et al.*, 2009) and tomato (Kaneko-Ohashi *et al.*, 2004; Menard *et al.*, 2006; Brazaityte *et al.*, 2010; Liu *et al.*, 2011). Although previous studies have identified various physiological and morphological effects of light quality in many plant species, few reports have addressed the effect of LED light sources, sunlight and fluorescent lamps on the growth of non-heading Chinese cabbage (*Brassica campestris* L.). Non-heading Chinese cabbage originated from China and has a long cultivation history. Its leaves contain many beneficial materials, and it is an important cultivated vegetable species in China (Hu and Hou, 2010). Variations in light conditions will affect the metabolic processes such as growth and yield (Jaimez and Rada, 2011). The objective of the present study was to examine the effects of blue LEDs, red LEDs, blue plus red LEDs (B:R=1:8), fluorescent lamps and sunlight on the growth and quality of non-heading Chinese cabbage seedlings at different stages of development and to select the best light sources for the cultivation of seedlings under a controlled environment.

2. Materials and Methods

2.1 Plant Materials

The experiments were performed in a greenhouse at Nanjing Agricultural University with non-heading Chinese cabbage (*Brassica campestris* L.) cultivar 605. Seeds with a similar size were selected for sowing. Seeds were sown in cells filled with vermiculite and peat (1:1 by volume) for cultivation, with one seed per cell. After seven days, seedlings with two expanded cotyledons were transferred to the different lights.

2.2 Light Treatments

Seedlings were grown under red light-emitting diodes (LEDs), blue LEDs, a mixture of blue plus red LEDs (B:R=1:8) and fluorescent lamps. The growth temperature was set at 24–26°C , and the relative humidity fluctuated between 40 and 50%. The photoperiod was 12 hours. Seedlings were randomly assigned to each light treatment, and LEDs arrays were randomly assigned positions in the greenhouse. Seedlings of the first group were kept at a photosynthetic photo flux density (PPFD) of 80 μ mol $m^{-2}s^{-1}$ (weak light) for 60 days (60 days). Seedlings of the second group were first grown at weak light for 30 days, then transferred to sunlight (normal level of 350 μ mol $m^{-2}s^{-1}$) at the 31st day and cultured for 30 days (60 days). Seedlings of the third group were first grown at weak light for 30 days, then transferred to a normal level of sunlight on the 31st day and cultured for 30 days, and then transferred to weak light on the 61st day until flowering (90, 120 days). Numbering the flower buds and open flowers was from 90^{th} to 120^{th} days. Each group had 30 seedlings. Each experiment was replicated three times. The spectral energy distribution of the blue plus red LEDs, blue LEDs, red LEDs, sunlight and fluorescent lamps was measured using an OPT-2000 spectral photometer (Optpeco, Beijing, China). FL:

Fluorescent lamps. B+R: 11.1% blue plus 88.9% red LEDs. B: Blue LEDs. R: Red LEDs. a: Growth under LEDs and FL at a PPFD level of 80 μmol $m^{-2}s^{-1}$ (weak light) for 60 days. b: Iinitial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days. c: Initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days and then weak light at 61 days until flowering.

(1) The blue plus red LEDs array (B+R) was supplied with 11.1% blue light with peak emission at 460 nm and 88.9% red light with peak emission at 660 nm (20 nm band-width at half-peak height).

(2) The blue LEDs array (B) was supplied with 100% blue light with peak emission at 460 nm (20 nm band-width at half-peak height).

(3) The red LEDs array (R) was supplied with 100% red light with peak emission at 660 nm (20 nm band-width at half-peak height).

(4) The fluorescent lamp array (FL) was supplied a broad spectrum of light with peak emission at 400–700 nm.

(5) The sunlight light array (SUN) was supplied a mean PPFD of 350 μ mol $m^{-2}s^{-1}$ with peak emission at 380–2600 nm.

2.3 Growth Measurements

Seedlings were destructively sampled after 60 (the first and second group) and 90 (the third group) days of growth. To determine dry mass, the seedlings were dried at 85°C until a constant mass was reached. The mass of each seedling was measured using an electronic balance.

For *2.4*, *2.5*, *2.6* and *2.7* measurements described below, seedlings were all destructively sampled after 60 (the first and second group) and 90 (the third group) days of growth. After sampling, leaves were weighed as required.

2.4 Pigment Measurements

Leaves were weighed to 0.1 g (fresh weight, W), and 10 ml (V) of 80% acetone was added to 0.1 g of leaf samples placed into a mortar with quartz sand. The chlorophyll was extracted until the leaf turned white. The optical density (OD) was measured with a UV-1200 spectrophotometer (Jin Peng, Shanghai, China) at 470 nm for carotenoid (OD_{470}), at 663 nm for chlorophyll a (OD_{663}), and at 645 nm for chlorophyll b (OD_{645}). The concentrations of chlorophyll a, chlorophyll b and chlorophyll (a+b) were determined using the following equations (Lichtenthaler and Wellburn, 1983):

Chlorophyll a (mg / g) = (12.72 OD_{663}－2.59 OD_{645}) V / 1000 W

Chlorophyll b (mg / g) = (22.88 OD_{645}－4.67 OD_{663}) V / 1000 W

Chlorophyll (a＋b) (mg / g) = (8.05 OD_{663} + 20.29 OD_{645}) V / 1000 W

Carotenoid (mg / g) = (1000 OD_{470}－3.27 C_a－104 C_b) V / (229×1000 W)

Where V is the total volume of acetone extract (ml), W is the fresh weight (g) of the sample, C_a is the concentration of chlorophyll a, and C_b is the concentration of chlorophyll b (Li *et al.*, 2010).

2.5 Soluble Protein Measurements

Leaves (1.0 g of fresh weight, W) were ground in a mortar with liquid nitrogen, to which 5 ml (V_1) of 0.067 mol/l potassium phosphate buffer (PBS) was added, and were then filtered through filter paper. The extract was centrifuged at 12,000 g for 10 min, and the supernatant was removed. The extract (1 ml, V_2) and Coomassie brilliant blue G-250 (5 ml) was thoroughly mixed. The optical density was measured using a UV-1200 spectrophotometer at 595 nm. To determine a standard curve, 0, 0.2, 0.4, 0.6, 0.8, and 1 ml of 100 μg/l bovine serum albumin was added to 6 volumetric flasks, and distilled water was added to reach a volume of 1 ml. The optical density was measured by a UV-1200 spectrophotometer at 595 nm (ρ). The concentration of soluble protein was determined using the following equation: soluble protein (mg / g) = ρ V_1 / W V_2 (Li *et al.*, 2010).

2.6 Vitamin C Measurements

Leaves of (1.0 g, fresh weight, W) were ground in a mortar with liquid nitrogen. Next, 5 ml (V_1) of 5% trichloroacetic acid (TCA) was added and the mixture was filtered through filter paper. The extract was centrifuged at 10,000 g for 10 min, and the supernatant was removed. The extract (1.0 ml, V_2) and 1.0 ml of ethanol were thoroughly mixed. Next, 0.5 ml of 0.4% phosphoric acid-ethanol, 1 ml of 0.5% 1, 10-phenanthroline-ethanol and 0.5 ml of 0.03 g/l ferric chloride were added for a total volume of 5 ml. The optical density was measured using a UV-1200 spectrophotometer (Jin Peng, Shanghai, China) at 534 nm. To obtain a standard curve, 0, 0.2, 0.4, 0.6, 0.8, or 1 ml of 100 mg/l bovine serum albumin was added to 6 volumetric flasks,

and distilled water was added to reach a volume of 1 ml. The optical density was measured by a UV-1200 spectrophotometer at 534 nm (ρ). The concentration of vitamin C was determined using the following equation: vitamin C concentration (mg / g) = $\rho V_1 / W V_2$ (Li *et al.*, 2010).

2.7 Sugar and Starch Measurements

Leaves (0.5 g, dry weight) were ground in a mortar with liquid nitrogen. Then 1 ml of 80% ethanol was added, and the mixture was filtered through filter paper. The filtrates were recovered, and the residues were washed again with 70% ethanol and filtered. Both filtrates were mixed, and 3 ml of distilled water was added. The extract was centrifuged at 12,000 g for 15 min, and 1 ml of supernatant was collected. Soluble sugar concentration was determined by the sulfuric acid-anthrone method and measured at 620 nm. Sucrose concentration was determined using the phloroglucinol method and measured at 480 nm (Zhang, 2009). Takahashi's method was used for starch extraction (Takahashi *et al.*, 1995). The residue obtained after ethanol extraction was resuspended with 0.1 mol/l sodium acetate buffer (pH 4.8) and boiled for 20 min. The gelatinized starch was digested with amyloglucosidase for four hours at 37°C and boiled again to stop the enzymatic reaction. After cooling, the mixture was centrifuged, and the amount of soluble sugar in the supernatant was determined by anthrone colorimetry (Li *et al.*, 2010). The starch concentration was estimated by converting glucose to starch equivalents using a factor of 0.9.

2.8 Statistical Analysis

Statistical analyses were conducted with Statistical Product and Service Solutions (SPSS) for Windows, Version 16.0 (SPSS, Japan). Data were analyzed using analysis of variance (ANOVA), and the differences between means were tested using Tukey's Test ($P < 0.05$).

3. Results

3.1 The Growth of Non-heading Chinese Cabbage

The effects of different light sources on growth of non-heading Chinese cabbage seedlings under a PPFD of 80 μmol $m^{-2}s^{-1}$ (weak light) for 60 days varied significantly (Table 1). The fresh mass of shoots was higher in seedlings grown under blue + red, blue and red LEDs and lower under fluorescent lamps. The dry mass of shoots and those of fresh and dry roots were greatest in seedlings under red LEDs and lowest under fluorescent lamps, an indication that LEDs light sources are more suitable for the growth of non-heading Chinese cabbage than fluorescent lamps and that red LEDs benefit biomass accumulation in non-heading Chinese cabbage.

Different light sources had variable effects on growth of non-heading Chinese cabbage seedlings that were first grown under weak light for 30 days and then transferred to sunlight for 30 days (Table 2). The dry masses of shoots and roots were greatest in seedlings under B:R=1:8 LEDs and lowest under fluorescent lamps. The fresh mass of shoots and roots were greatest in seedlings under red LEDs and lowest under fluorescent lamps. This is an indication that B:R=1:8 LEDs benefit the accumulation of dry biomass. The after-effects of different light sources on non-heading Chinese cabbage seedlings were obvious.

Different light sources had variable effects on growth of non-heading Chinese cabbage seedlings before flowering (Table 3). The fresh mass of shoots was greatest in seedlings under blue LEDs, whereas the fresh and dry masses of roots were greatest in seedlings under red LEDs and lowest under fluorescent lamps. For the shoot dry mass, red LEDs had similar higher; while fluorescent lamps gave the least shoot dry mass than any of the lights sources examined.

3.2 The Concentrations of Pigments

The leaf pigments of non-heading Chinese cabbage seedlings varied in response to the weak light. The leaf pigments also varied when they were first grown at weak light and then transferred to sunlight. The concentrations of chlorophyll a, chlorophyll b, total chlorophyll and carotenoid were greatest in seedlings under blue LEDs (Figures 1a & b).

Different light sources had variable effects on the concentrations of pigments in non-heading Chinese cabbage seedlings before blooming. The concentrations of chlorophyll a, chlorophyll b and total chlorophyll were greatest in seedlings under blue LEDs and lowest in seedlings under fluorescent lamps (Figure c).

3.3 Vitamin C Concentration

The concentration of vitamin C was greatest in non-heading Chinese cabbage seedlings under blue plus red LEDs with weak light, followed by those under blue LEDs and lowest in seedlings under fluorescent lamps (Figure 2). The seedlings adapted to new illumination conditions with altered PPF levels. The concentration of

vitamin C was greatest in seedlings under blue LEDs and lowest in seedlings under fluorescent lamps with altered PPF levels.

3.4 Soluble Protein Concentration

The concentration of soluble protein was highest under red LEDs in seedlings with the weak light, followed by fluorescent lamps and blue LEDs and lowest under blue plus red LEDs (Figure 3). The seedlings adapted to new illumination conditions with altered PPF levels. The concentration of soluble protein was greatest in seedlings under blue LEDs and blue plus red LEDs with altered PPF levels.

3.5 Sugar and Starch Concentrations

The sugar and starch concentrations of seedlings varied in response to different weak lights. Both concentrations also varied when seedlings were first grown at weak light and then transferred to sunlight. The concentrations of sucrose and soluble sugar were greatest in seedlings under blue LEDs, followed by those under red LEDs and blue plus red LEDs and lowest in seedlings under fluorescent lamps (Figures 4a & b). The starch concentration was greatest in seedlings under red LEDs.

The sugar and starch concentrations of seedlings varied in response to different lights before blooming. The concentrations of sucrose, soluble sugar and starch were greatest in seedlings grown under red LEDs, followed by those under blue plus red LEDs and lowest in seedlings under fluorescent lamps (Figure 4c). These results revealed that red LEDs are the best light source for accumulation of sucrose, starch and soluble sugar in non-heading Chinese cabbage.

3.6 The Number of Flower Buds and the Duration of Flowering

Different light sources had variable effects on the development of flowers in non-heading Chinese cabbage seedlings from 90 to 120 days (Table 4). The number of open flowers was highest in seedlings under red LEDs and blue plus red LEDs and the number of flower buds was higher in seedlings under LEDs than in those under fluorescent lamps. The duration of flowering was longest in seedlings under red LEDs and blue plus red LEDs.

4. Discussion and Conclusion

4.1 Red LEDs Are the Best Light for Accumulation of Dry Mass and Photosynthates in Plants

The present study demonstrated that red LEDs benefits the dry biomass accumulation of non-heading Chinese cabbage (Tables 1, 2 &3). However, the present study are inconsistent with those previous studies (Brown *et al.*, 1995; Goins *et al.*, 1997; Okamoto *et al.*, 1997; Yorio *et al.*, 2001; Kim *et al.*, 2004; Avercheva *et al.*, 2009) that showed the best light sources for dry biomass accumulation are related to species or cultivars. LEDs lights show a significant superiority on plant growth and biomass. Red LEDs has variable effects on different plant species.

Light quality regulates the carbohydrate metabolism of higher plants, and carbohydrate content is increased under red light. The accumulation of starch in chloroplasts, which is enhanced by red light, may cause inhibition of photosynthesis (Kowallik *et al.*, 1982). Red light may inhibit the translocation process of photosynthates (Saebo *et al.*, 1995). The excess starch accumulation counters leaf photosynthesis (Bondada and Syvertsen, 2005). Red light enhances starch accumulation in *Glycine* and *Sorghum* species, the application of blue light sources is a means of studying the regulation of photosynthetic carbon metabolism in relation to plant growth (Britz and Sager, 1990). The present study, which is consistent with previous studies, reveal that the starch concentration is greatest in seedlings grown under red LEDs with altered PPFD levels (Figure 4) and red LEDs are advantageous to accumulation of starch in non-heading Chinese cabbage, moreover, the red LEDs benefits the accumulation of dry biomass in non-heading Chinese cabbage (Tables 1, 2 & 3). Red LEDs may promote accumulation of the photosynthetic products and the dry biomass but inhibit the translocation of photosynthetic products out of leaves; thus, the starch ultimately accumulated in leaves. Red LEDs may be used as the main light sources for reproductive growth of non-heading Chinese cabbage. In the artificial cultivation of plants, red LEDs may be the preferred light source, to get achieve a larger amount of dry matter and yield.

4.2 The Effects of Blue LEDs on the Accumulation of Chlorophylls and the Quality of Plants

The present results indicated that blue LEDs light is beneficial to pigment accumulation. The present results are consistent with previous studies (Senger, 1982; Saebo *et al.*, 1995; Tanaka *et al.*, 1998; Poudel *et al.*, 2008; Kurilcik *et al.*, 2008). Moreover, the blue LEDs play a key role in accumulation of chlorophylls.

The present results indicated that blue LEDs benefits vitamin C, sucrose and soluble sugar accumulation and nutritional quality of non-heading Chinese cabbage seedlings. LEDs light is beneficial to soluble protein accumulation and to nutritional quality of seedlings. The results in the present study demonstrate that blue LEDs benefits the accumulation of vitamin C and soluble protein, which are consistent with reports by Yang *et al.*

(2010) and Zhang *et al.* (2010). However, the soluble sugar concentration was greatest under blue LEDs (Figure 4), which is inconsistent with the results of Yang *et al.* (2010) and Zhang *et al.* (2010). Blue LEDs benefits the accumulation of nutritional substances, and these effects may correlate with plant species or cultivars. The nutritional quality of plants could be varied by selecting special light sources under controlled growth environments. For the purpose of improving nutritional quality of vegetables, blue LEDs should be chosen as the preferred light source in artificial cultivation and subsequent transplanting of plants.

4.3 Red LEDs Are the Best Light for Flowering

Spectral quality has a major influence on induction rate of flower bud and subsequent development. The numbers of *Cyclamen* flower buds and open flowers were highest in plants grown under a mixture of blue plus red LEDs (B:R=10) compared with fluorescent lamps and other light sources (Heo *et al.*, 2003). However, the development of visible flower buds in marigolds was about five times greater in fluorescent lamps than in blue or red LEDs (Heo *et al.*, 2002). Monochromatic blue light delayed flowering in *Arabidopsis* possibly by influencing cryptochromes (Mockler *et al.*, 1999). The present study showed that the number of flowers was highest in seedlings grown under red LEDs and blue plus red LEDs, and the number of flower buds was higher in seedlings grown under LEDs than fluorescent lamps (Table 4). Red LEDs and blue plus red LEDs are more suitable for flower opening in non-heading Chinese cabbage. The findings from the present study are consistent with those of Heo *et al.* (2003) and Mockler *et al.* (1999), but inconsistent with a report from Heo (2002). The shift in plants from vegetative growth to floral development is regulated by red-far-red light receptors (phytochromes) and blue-ultraviolet A light receptors (cryptochromes) (Guo *et al.*, 1998). The present study also showed that the concentrations of sucrose and starch were greatest in seedlings grown under red LEDs before blooming and red LEDs benefitted dry biomass accumulation in non-heading Chinese cabbage. The number of flower buds and open flowers and the duration of flowering may correlate with the dry biomass and photosynthates, it regulated by different light receptors.

In conclusion, dry biomass and starch of non-heading Chinese cabbage accumulate under red LEDs light sources. In addition, red LEDs also benefits the flower opening. The pigment and nutritional substances (vitamin C, soluble sugar and soluble protein) accumulate under blue LEDs light sources. Red LEDs should be selected as the preferred light source in the artificial cultivation and subsequent transplanting of plants to obtain a higher biomass and more flowers. By contrast, blue LEDs should be used as the preferred light source for higher nutritional quality to improve the growth and development of plants.

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Table 1. The effects of different lights on the mass of non-heading Chinese cabbage seedling growth under a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 60 days

Light treatment	Shoot fresh mass (g)	Shoot dry mass (g)	Root fresh mass (g)	Root dry mass (g)
FL	1.38b	0.23c	0.13d	0.02d
B+R	5.28a	0.53b	0.95b	0.11b
B	6.67a	0.49b	0.61c	0.08c
R	5.93a	0.73a	1.08a	0.14a

Different letters within the column indicate significant differences at P<0.05 according to Tukey's test.

Table 2. The effects of sunlight on the mass of non-heading Chinese cabbage seedlings that were first grown at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days and then transferred to sunlight for 30 days

Light treatment	Shoot fresh mass (g)	Shoot dry mass (g)	Root fresh mass (g)	Root dry mass (g)
FL	3.69c	0.33c	0.33c	0.04d
B+R	10.95b	0.96a	0.93b	0.15a
B	11.79b	0.75b	0.90b	0.10b
R	13.60a	0.80b	1.40a	0.06c

Different letters within the column indicate significant differences at P<0.05 according to Tukey's test.

Table 3. The effects of different lights on the mass of non-heading Chinese cabbage seedlings that were first grown at a PPFD level of 80 μmol $m^{-2}s^{-1}$ (weak light) for 30 days, then under sunlight for 30 days and, finally, under weak light at 61 days until flowering

Light treatment	Shoot fresh mass (g)	Shoot dry mass (g)	Root fresh mass (g)	Root dry mass (g)
FL	0.61c	0.04c	0.04c	0.01c
B+R	6.83b	0.71b	1.36b	0.18b
B	9.73a	0.76ab	1.21b	0.20b
R	6.57b	0.87a	1.71a	0.24a

Different letters within the column indicate significant differences at P<0.05 according to Tukey's test.

Table 4. The Number of flower buds and open flowers per plant in non-heading Chinese cabbage seedlings grew under different lights until flowering (90 -120 days)

Light treatment	Numbers of open Flowers				Numbers of flower buds			
	0 d	10d	20d	30 d	0d	10d	20d	30d
FL	0a	0b	5bc	8a	2a	4a	0b	0a
B+R	2a	5a	9ab	11a	3a	5a	2ab	2a
B	0a	0b	3c	9a	1a	7a	7a	2a
R	2a	5a	10a	11a	3a	5a	2ab	0a

Different letters within the column indicate significant differences at P<0.05 according to Tukey's test.

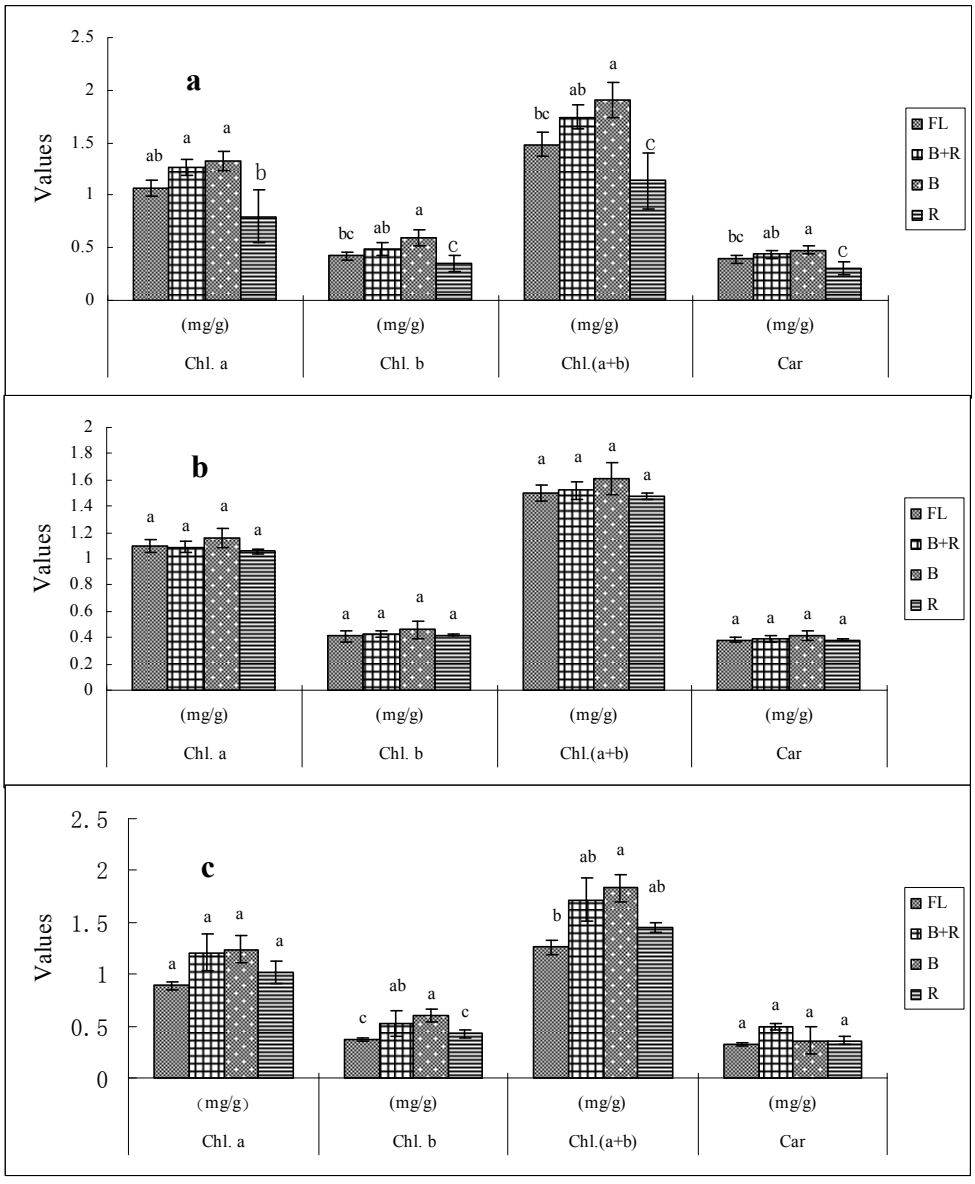

Figure 1. The effects of different lights on the pigment concentrations of non-heading Chinese cabbage seedlings with different PPFD levels, growth under LEDs and FL at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 60 days (a), initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days (b) and initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days and then weak light at 61 days until flowering (c)

Different letters within the column indicate significant differences at P<0.05 according to Tukey's test.

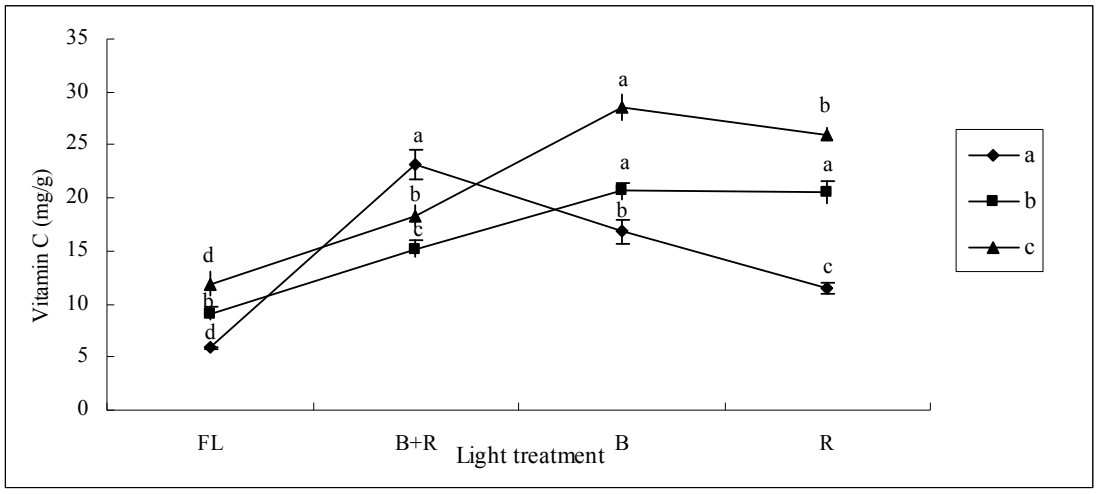

Figure 2. The effects of different lights on the vitamin C concentration of non-heading Chinese cabbage seedlings with different PPFD levels, growth under LEDs and FL at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 60 days (a), initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days (b) and initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days and then weak light at 61 days until flowering (c)

Different letters within the column indicate significant differences at $P<0.05$ according to Tukey's test.

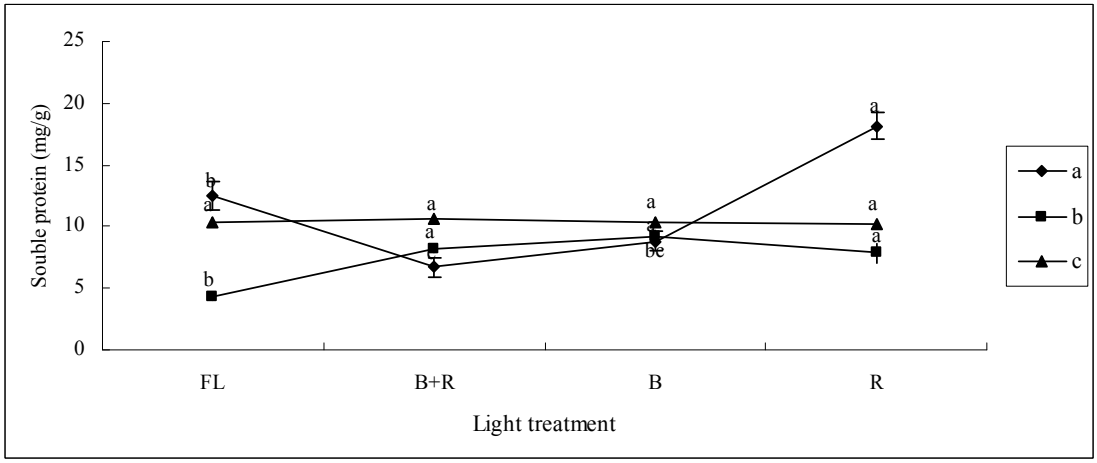

Figure 3. The effects of different lights on the soluble protein concentration of non-heading Chinese cabbage seedlings with different PPFD levels, growth under LEDs and FL at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 60 days (a), initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days (b) and initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days and then weak light at 61 days until flowering (c)

Different letters within the column indicate significant differences at $P<0.05$ according to Tukey's test.

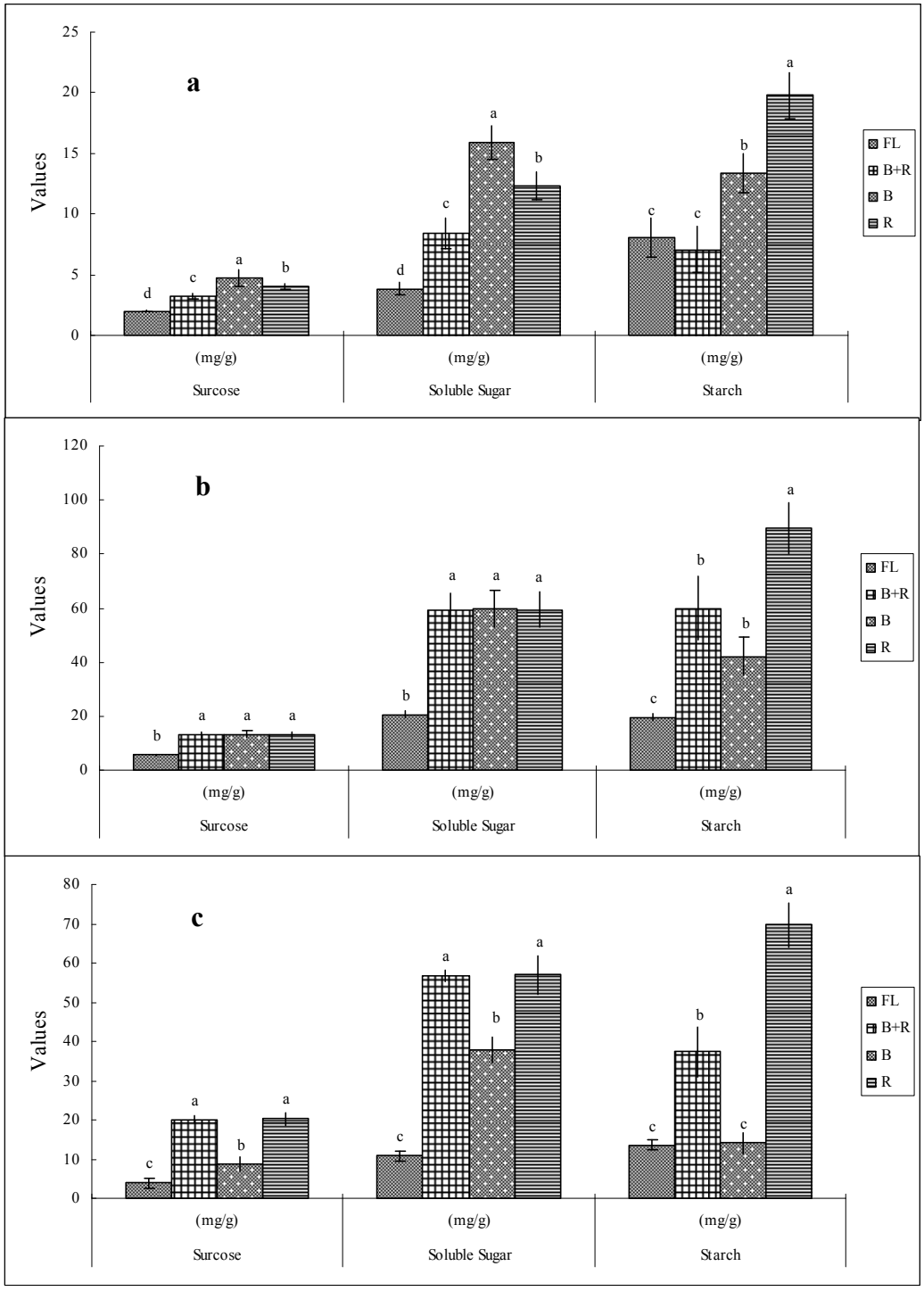

Figure 4. The effects of different lights on the photosynthesis production of non-heading Chinese cabbage seedlings with different PPFD levels, growth under LEDs and FL at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 60 days (a), initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days (b) and initial growth at a PPFD level of 80 μmol $m^{-2}s^{-1}$ for 30 days followed by sunlight for 30 days and then weak light at 61 days until flowering (c)

Different letters within the column indicate significant differences at $P<0.05$ according to Tukey's test.