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An *in vivo* study of the best light emitting diode (LED) systems for cut chrysanthemums

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Abstract: The cut chrysanthemum (*Chrysanthemum ×morifolium* Ramat.) is one of the most recognized cut flowers in the world. Light quality significantly affects the development and growth of plants. To conduct an in-depth investigation of the effects of light quality on the growth and development of cut chrysanthemums, seedlings of the cut chrysanthemum cultivar 'Riqietaohong' were cultured under four different light emitting diode (LED) systems: red (R), blue (B), red : blue = 2:1 (RB) and blue : red = 2:1 (BR). A fluorescent lamp was used for control group lighting. The Duncan multiple comparisons analysis showed that the B light promoted stem and leaf development of seedlings but inhibited photosynthesis. The R light stimulated their rooting but inhibited the accumulation of biomass. RB improved transpiration. Moreover, a comprehensive evaluation system that combined the analytic hierarchy process (AHP) method with the technique for order preference by similarity to an ideal solution (TOPSIS) method indicated that the photosynthesis index, transpiration index and biomass index were the most important indicators for the growth and development of cut chrysanthemums, and RB was the best LED system for cut chrysanthemums. The present study provides references for the lower energy consumption and industrial annual production of cut chrysanthemums.

Keywords: *Chrysanthemum ×morifolium*, Light emitting diode, Vegetative growth, Comprehensive evaluation system, Analytic hierarchy process, TOPSIS

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1 Introduction

The cut chrysanthemum (*Chrysanthemum ×morifolium* Ramat.) is one of the most recognized cut flowers in the world because of its annual yield in the hundreds of millions and its demand for use in flower arrangement drives production, which plays a key role in design and decoration [1]. However, promoting the quality of cut chrysanthemums is difficult in many countries at present, and a serious issue with cultivar deterioration has resulted in the poor uniformity of seedlings [2]. Moreover, the efficiency of the industrial annual production of cut chrysanthemums is restricted to a low level because of the deficiency in basic biological studies on the growth characteristics of cut chrysanthemums [2].

Light, the energy and signal source for the growth and development of all species on the Earth, is closely related to the morphogenesis and metabolism of animals and plants. In most of the environmental conditions that affect the growth of plants, light plays a leading role in all stages of plant growth and development, such as germination, stem growth, root and leaf development, phototropism, synthesis of chlorophyll, branching and floral induction, among others. The light-related parameters which affect plant growth include the intensity, photoperiod, light quality and orientation of illumination [3]. The importance of the photosynthetic photon flux (PPF) that affects the growth and photosynthesis of plantlets has already been demonstrated in many species [4-6]. However, light quality also plays an important role in morphogenesis and photosynthesis, influencing the way in which light is absorbed by chlorophyll [7].

With the development of electro-optical technology, light emitting diode (LED) systems can now be applied to agricultural fields. LEDs are created using semiconducting materials, such as gallium arsenide (GaAs), gallium phosphide (GaP) or gallium arsenide phosphide (GaAsP) [8]. Compared with traditional lamps, LED systems possess the advantages of high purity, high transfer efficiency of light to electricity, single waveband, less heat generation, smaller mass and volume, long life, and lower power requirements [7,9]. With the constant evolution of electro-optical technology, the cost performance of LEDs has improved rapidly, and they now meet important requirements for the application of this new light source on the improved success of crop breeding [10].

There are various studies on the effect of spectral quality from the application of LED systems to horticultural crop cultivars. The absorbed wavelength of visible light for plants is mainly concentrated in the blue to purple (400 to 510 nm) and red to orange (610 to 720 nm) ranges; thus, it is better to use red or blue light sources for plant cultivation [11]. For many genera and species (e.g., *Lilium* L., *Musa paradisiaca* L., *Eucalyptus citriodora* Hook. f., *Lactuca sativa* L., *Vitis vinifera* L., *Doritaenopsis* Hort., *Gossypium hirsutum* L. and *Chrysanthemum* L.), several eco-physiological studies have been reported that developed models proposing alternative hypotheses on different light qualities: (1) the red light elongates stems, expands leaf area and improves the net photosynthetic rate and the accumulation of photosynthate; (2) the blue light produces dwarf seedlings, increases the ratio of chlorophyll a to b and carotenoid content, increases the utilization of red-blue light, accelerates growth and development of crops, improves the utility rate of light power, improves photosynthetic rate and quality, and increases the biomass per unit area [7, 12-20]. The application of LED systems to the industrial annual production of *Triticum aestivum* L., *Vigna radiata* (L.) Wilczek and *Oryza sativa* L. have also been reported [21].

Although previous results have confirmed the physiological and morphological effects of light quality, these effects are quite different among various plant species. Accordingly, it is necessary to apply proper LED systems to achieve different purposes, e.g., promotion or inhibition of shoot and root growth, formation and growth of bulbs and control of flowering, among others. At present, studies on how the light quality affects the growth and development of cut chrysanthemums are very limited. Moreover, most previous studies were focused on the study of morphological indices, but we know little about the response mode of various physiological indices under different light qualities. Finally, because of the limitations of the mathematical analysis methods, evaluation results with strong subjectivity are always obtained when we estimate which type of light quality is the best. Therefore, a comprehensive scientific and objective evaluation system needs to be constructed to estimate the optimum light quality for high market demand of cut chrysanthemum cultivars.

In this context, the cut chrysanthemum cultivar ‘Riqietaohong’ was selected as material. The seedlings were cultured under four different light treatments, and a fluorescent lamp was used for the control group. To discuss the effects of different light qualities on the growth and development of seedlings, 20 indices that are closely related to the vegetative growth of crops were first selected for variance (ANOVA) and Duncan multiple comparisons analyses. Then, the analytic hierarchy process (AHP) method and the technique for order preference by similarity to an ideal solution (TOPSIS) method were combined to construct a comprehensive evaluation system. Using these methods as a basis, we calculated and analyzed the optimum LED system for the growth and development of the tested cultivar. All of the above analyses will provide a reference for lower energy consumption and optimized industrial annual production of cut chrysanthemums and the physiological research of other horticultural crops.

2 Experimental Procedures

2.1 Plant materials and LED systems

The cut chrysanthemum cultivar ‘Riqietaohong’ was used for this study. After the virus-free seedlings produced three to four leaves, the robust and uniform seedlings, which were cultured under fluorescent lamp (FL), were transferred to plugs (turf: vermiculite = 1:1, v/v) and were placed in growth chambers (intensity of illumination = 50 ± 5 μmol m^{-2} s^{-1}, photoperiod = 16 h in the daytime and 8 h at night, and temperature = 20 °C). The seedlings were then cultured under four different LED systems (Royal Dutch Philips Electronics Ltd., Amsterdam, Holland): red (R), blue (B), red : blue = 2:1 (RB) and blue : red = 2:1 (BR). The constant wavelengths of the red and blue light were 650 nm and 450 nm, respectively. A FL (PLS-13/2P, Foshan Electrical Lighting Co., Ltd., Foshan, China) was used for illuminating the control group. Because the different light devices were installed in the same growth chamber, to prevent light from one treatment contaminating light system for another treatment, black cloths were used to shade between different treatments. Twenty seedlings were treated under each light quality with three replicates in separate growth chambers under the same illumination intensity, photoperiod and temperature. The seedlings were watered at intervals of five days; no fertilization was applied.

2.2 Selection of indices and their measuring methods

After six weeks of treatment, 20 indices that are closely associated with the vegetative growth of crops were selected and measured. These indices were classified into six types: root morphological indices (the length and number of roots), stem morphological indices (the length and width of stem and the length of internodes), leaf morphological indices (the length, width, color, luster and smoothness of leaves and crown area) [22], biomass indices (the dry weight and fresh weight of seedling shoots), transpiration indices (the length, width, number and density of stomata) and photosynthesis indices (the contents of chlorophyll a, chlorophyll b and chlorophyll fluorescence indices) (Supplemental Table 1). The mean values of each index of all seedlings were used for statistical analysis.

2.3 ANOVA and Duncan multiple comparisons analyses

To determine the repeatability of the selected indices and the effects of different light qualities on each index, PASW Statistics 18.0 software (IBM, Armonk, NY, USA) was used for ANOVA and Duncan multiple comparisons analyses [23].

2.4 AHP method

First, "seedlings with good comprehensive growth status" [24] were considered as the aim layer (A), and six constraint layers (C) corresponding to the different types of indices were constructed using the expert opinion method: root morphological indices (C1), stem morphological indices (C2), leaf morphological indices (C3), biomass indices (C4), transpiration indices (C5) and photosynthesis

Table 1 3-way ANOVA of the selected quantitative indices.

Factor analyzed	Mean square					*F*-value				
	FL	B	R	BR	RB	FL	B	R	BR	RB
LR	245.44	159.60	136.89	144.00	229.02	2.47	3.64	3.21	3.88	3.26
NR	106.78	53.78	32.11	75.11	160.44	2.27	2.32	2.21	2.74	2.68
LS	28.71	30.56	27.17	30.69	35.05	42.38**	39.7**	41.66**	59.74**	62.03**
WS	5.52	6.09	4.43	4.53	4.85	0.49	0.43	0.46	0.47	0.43
LI1	0.02	0.05	0.02	0.05	0.02	1.07	1.73	1.66	1.09	1.26
LI2	0.05	0.11	0.06	0.08	0.06	0.16	0.14	0.17	0.13	0.14
LI3	0.09	0.13	0.09	0.08	0.09	1.23	1.26	1.38	1.29	1.33
LL	57.86	72.25	36.72	57.05	38.32	1.98	1.84	1.99	1.87	1.90
WL	49.89	71.97	37.25	49.42	30.95	2.01	2.13	2.34	3.17	2.41
CA	118.81	82.81	57.25	80.40	71.12	0.64	0.73	0.66	0.77	0.70
L^*	1179.01	1303.93	1290.25	1218.48	1231.54	80.01**	125.31***	72.69**	74.33**	114.26***
a^*	132.02	112.08	136.03	100.13	111.72	26.47*	35.26*	27.43*	62.58**	27.09*
b^*	199.66	174.42	199.94	146.17	139.08	0.24	0.36	0.20	0.37	0.22
FWS	8.65	6.19	1.78	4.26	4.48	1.39	1.25	1.47	1.36	0.99
DWS	0.08	0.09	0.02	0.04	0.06	1.33	1.24	1.24	1.26	0.98
LST	1392.28	1473.79	1075.84	1540.56	1206.64	33.22*	46.51*	62.31**	48.06*	51.31*
WST	837.14	1006.58	1331.52	952.75	837.14	46.95*	43.26*	58.91*	44.08*	62.99**
NST	336.11	400.25	400.25	256.00	544.44	2.73	2.85	2.96	3.13	3.24
DST	1103.22	1193.91	1193.91	764.10	1625.05	3.33	3.17	3.26	2.98	3.14
CCA	505671.11	195061.59	420230.94	272993.48	477619.21	0.65	0.73	0.66	0.60	0.70
CCB	1654624.86	636151.58	1376559.89	891081.46	1564000.36	0.67	0.66	0.84	0.91	0.62

Length of roots (LR), number of roots (NR), length of stems (LS), width of stems (WS), length of the first internode (LI1), length of the second internode (LI2), length of the third internode (LI3), length of leaves (LL), width of leaves (WL), crown area (CA), value of brightness (*L*), value of chrominance component ranged from green to red (*a*), value of chrominance component ranged from blue to yellow (*b*), fresh weight of seedling shoots (FWS), dry weight of seedling shoots (DWS), length of stomata (LST), width of stomata (WST), number of unit-area stomata (NST), density of stomata (DST), content of chlorophyll a (CCA), content of chlorophyll b (CCB), fluorescent lamp (FL), blue light (B), red light (R), blue : red = 2:1 (BR), red : blue = 2:1 (RB). *, ** and *** represent significant at 0.05, 0.01 and 0.001 level, respectively.

indices (C6) [24]. Those indices without good repeatability and significance ($P < 0.05$), as indicated by the ANOVA and Duncan multiple comparisons analyses, were eliminated, and several index layers (P1 to Pn) were constructed based on the significant indices. Thus, a layered structural model for the comprehensive evaluation system that consisted of aim layer, constraint layers and index layers was constructed.

According to the membership function of each factor within the different layers, the judgment was quantified by using the "1-9 scale" method [25], and accordingly, seven judgment matrixes were calculated, including an Aim-Constraint-Layer judgment matrix and six Constraint-Index-Layer judgment matrixes.

YAAHP software (version 0.6, Xinshengyun Software Technique Co. Ltd., Beijing, China) was used to calculate the normalized eigenvectors and the maximum eigenvalues (λmax) of seven judgment matrixes. Then, the consistency check was conducted.

$$CI = (\lambda max - n) / (n - 1) \quad ①$$

$$CR = CI / RI \quad ②$$

In formula ①, CI, λmax and n represent the consistence index, the maximum eigenvalue and the number of indices, respectively. In formula ②, CR and RI represent the consistency ratio and the mean random consistency ratio [26], respectively. When $CR < 0.1$, the consistency check of the judgment matrix was qualified.

2.5 TOPSIS method

The decision matrix D was constructed based on the raw data:

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

In the matrix, x, m and n represent the score, the ordinal number of the scheme and the ordinal number of the index, respectively.

The decision matrix $D = (x_{ij})\, m_{\times} n$ was transformed to a standard matrix $R' = (r'_{ij})\, m_{\times} n$ using linear transformation. Then, it was further transformed to a standard decision matrix $R = (r_{ij})\, m_{\times} n$ using the normalization treatment:

$$r'_{ij} = x_{ij} / x_{\max}(j) \quad ③$$

$$r_{ij} = r'_{ij} / \sqrt{\sum_{i=1}^{m} (r'_{ij})^2} \; (i = 1, 2, \cdots, m; j = 1, 2, \cdots, n) \quad ④$$

In formula ③, $x_{\max}$, i and j represent the maximum value, the ordinal number of the scheme and the ordinal number of the index, respectively.

Finally, the weight coefficients of all indices obtained by the AHP method were multiplied with the standard decision matrix R to construct a weighted standard decision matrix $V = (v_{ij})\, m_{\times} n$:

$$V = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \cdots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \cdots & w_n r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \cdots & w_n r_{mn} \end{bmatrix}$$

The plus and minus ideal solutions were calculated according to the constructed weighted standard decision matrix V:

$$Sj^+ = \{ xj^+ \mid \max (x_{1j}, x_{2j}, \cdots, x_{nj}) \mid \}, \; j = 1, 2, \cdots, m \quad ⑤$$

$$Sj^- = \{ xj^+ \mid \min (x_{1j}, x_{2j}, \cdots, x_{nj}) \mid \}, \; j = 1, 2, \cdots, m \quad ⑥$$

In the formulas ⑤ and ⑥, Sj^+ and Sj^- represent the plus ideal solution and the minus ideal solution, respectively, whereas xj^+ represents the attribute value of each index within the weighted standard decision matrix V.

Supposing that the distance between the scheme Qi and the plus ideal solution Sj^+ is D_i^+, whereas the distance between the scheme Qi and the minus ideal solution Sj^- is D_i^-, then the following is true:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \omega_j^2 (x_{ij} - x_j +)^2} \quad ⑦$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} \omega_j^2 (x_{ij} - x_j -)^2} \quad ⑧$$

$$\omega_j = \frac{x_j}{\sum_{j=1}^{m} x_j} \quad ⑨$$

$$Z_i = \frac{D_i^-}{D_i^- + D_i^+}, \; i = 1, 2, \cdots, n \quad ⑩$$

When Qi converges toward Sj^+, accordingly, the Di converges toward 0 and Zi converges toward 1. Finally, the schemes were reordered according to the values of Zi. The larger the Zi value was, the better the scheme.

3 Results

3.1 Repeatability of the selected indices

Only stable data with good repeatability can be used for the Duncan multiple comparisons analysis. Therefore, we first conducted a 3-way ANOVA taking the selected indices as factors. The results showed that the length of stem, color indices of L^* and a^* values of the leaf color and length and width of stomata showed significant or very significant differences at p-level 0.05, 0.01 or 0.001 among the three repeats in spite of light qualities, indicating that the repeatability of these five indices was very poor, therefore suggesting they could not be used for the Duncan multiple comparisons analysis thereafter. On the contrary, the other indices showed strong repeatability, and were accordingly reserved for further analyses (Table 1). Moreover, because the qualitative characters could not be analyzed by ANOVA, the luster and smoothness of leaf surface were directly used for the Duncan multiple comparisons analysis after being evaluated.

3.2 The effects of different light quality types on seedling growth

The different light quality types significantly affected the growth status and the form of seedlings in different ways. Compared to FL, the mean values of LR and NR were respectively 20.24% and 45.11% lower under B light. The mean values of the two indices for BR and RB light were also lower than that of the values for FL. In contrast, under R light, they increased 3.14% and 22.65%, respectively. The mean value of WS was 4.86% greater under B light than FL, whereas under other light quality types, the mean values of this index were lower than that of FL. Moreover, the mean value of LI1 increased 43.48% under BR light, while for LI2 and LI3, the mean values increased 30.30% and 16.67% under B light, respectively (Table 2).

The results also indicated that the leaf morphological indices were significantly affected by different light quality types. For instance, the mean values of WL was 16.74% greater under B light than FL. The mean values of CA all decreased under the four LED systems. The effect of different LED systems on the leaf color mainly manifested in terms of differences in the *b** value. Compared to FL, the effect of R light on this index was not significant, whereas the mean values were decreased under other light quality types, but the differences between RB and BR light were not significant. The effects of the four LED systems on the luster and smoothness of the leaves were not significant (Table 2, Figure 1).

Table 2 Duncan multiple comparisons analysis of the indices with good repeatability.

LQ	LR	NR	WS	LI1	LI2	LI3
FL	14.67 ± 2.59 b	10.33 ± 2.89 bc	2.35 ± 0.19 bc	0.13 ± 0.05 ab	0.23 ± 0.05 a	0.30 ± 0.08 a
B	11.70 ± 0.40 a	5.67 ± 0.58 a	2.47 ± 0.30 c	0.22 ± 0.08 ab	0.33 ± 0.06 c	0.36 ± 0.08 b
R	15.13 ± 2.37 ab	12.67 ± 2.31 c	2.11 ± 0.30 a	0.12 ± 0.04 a	0.24 ± 0.06 ab	0.29 ± 0.06 a
BR	12.00 ± 1.47 ab	8.67 ± 1.16 ab	2.13 ± 0.26 a	0.23 ± 0.30 b	0.27 ± 0.06 b	0.29 ± 0.06 a
RB	12.63 ± 1.96 ab	7.33 ± 0.58 ab	2.20 ± 0.28 ab	0.15 ± 0.04 ab	0.25 ± 0.06 ab	0.31 ± 0.06 a

LQ	LL	WL	CA	LLS	SLS	*b**
FL	7.61 ± 0.64 b	7.06 ± 0.32 b	10.90 ± 0.75 b	2.33 ± 1.15	1.67 ± 0.58	14.13 ± 0.57 b
B	8.50 ± 0.80 b	8.48 ± 0.28 c	7.57 ± 0.81 a	2.00 ± 1.00	1.67 ± 0.58	13.21 ± 0.63 ab
R	6.06 ± 0.50 a	6.10 ± 0.74 a	8.43 ± 0.29 a	2.00 ± 1.00	1.67 ± 0.58	14.14 ± 0.62 b
BR	7.55 ± 0.46 b	7.03 ± 0.45 b	9.00 ± 0.59 a	2.00 ± 1.00	1.67 ± 0.58	12.09 ± 0.07 a
RB	6.19 ± 0.17 a	5.56 ±0.27 a	9.10 ± 1.21 a	2.67 ± 0.58	1.00 ± 0.00	11.79 ± 0.77 a

LQ	FWS	DWS	NST	DST	CCA	CCB
FL	2.94 ± 0.77 c	0.29 ± 0.06 c	18.33 ± 2.08 ab	32.00 ± 3.61 ab	711.11 ± 21.67 b	1286.32 ± 39.19 b
B	2.48 ± 0.48 bc	0.28 ± 0.06 c	20.00 ± 3.00 ab	34.67 ± 5.51 ab	441.66 ± 40.55 a	797.59 ± 73.65 a
R	1.33 ± 0.23 a	0.13 ± 0.02 a	20.00 ± 6.08 ab	34.67 ± 10.69 ab	648.25 ± 193.90 b	1173.27 ± 353.87 b
BR	2.06 ± 0.16 ab	0.20 ± 0.03 ab	16.00 ± 2.64 a	27.33 ± 4.73 a	522.49 ± 72.06 a	943.97 ± 131.00 a
RB	2.12 ± 0.14 ab	0.25 ± 0.03 bc	23.33 ± 0.58 b	40.33 ± 0.58 b	691.10 ± 87.33 b	1250.60 ± 160.68 b

Light quality (LQ), length of roots (LR), number of roots (NR), width of stems (WS), length of the first internode (LI1), length of the second internode (LI2), length of the third internode (LI3), length of leaves (LL), width of leaves (WL), crown area (CA), luster of leaf surface (LLS), smoothness of leaf surface (SLS), value of chrominance component ranged from blue to yellow (*b*), fresh weight of seedling shoots (FWS), dry weight of seedling shoots (DWS), number of unit-area stomata (NST), density of stomata (DST), content of chlorophyll a (CCA), content of chlorophyll b (CCB), fluorescent lamp (FL), blue light (B), red light (R), blue : red = 2:1 (BR), red : blue = 2:1 (RB). Data in the table are the mean value ± standard deviation and different letters following the mean values represent significant difference at $P < 0.05$ between treatments. Twenty seedlings were treated under each light quality with three repeats in separate growth chambers under the same illumination intensity, photoperiod and temperature.

As shown in Table 2, compared to FL, the mean values of FWS and DWS all decreased under the four LED systems, and the mean values of the R treatment were significantly lower than that of the FL, indicating that the red light inhibited the accumulation of biomass of seedlings.

For the morphology of stomata, the mean values of NST and DST were 12.71% and 14.59% lower under BR light than FL, respectively, whereas RB light produced opposite results (Table 2, Figure 2). The above results indicate that the light of red : blue = 2 : 1 was good for the transpiration of the seedlings.

As shown in Table 2, the mean values of CCA and CCB were all significantly decreased under B and BR light, compared to FL, whereas the effects of R and RB light on these two indices were not significant, indicating that the blue light inhibited the photosynthesis of seedlings. As seen in Figure 3, the different LED systems did not obviously affect the chlorophyll fluorescence indices (CFI).

Based on the above results, we concluded that the blue light improved the growth and development of the stem and leaves of seedlings but inhibited their photosynthesis. The red light stimulated rooting of seedlings but inhibited their accumulation of biomass, which also resulted in leaf color blue shifting according to the change of b^* value. A red : blue = 2:1 ratio was good for seedling transpiration.

3.3 The computation of weight values of the indices

As mentioned above, the effects of different LED systems on the LLS and SLS were not significant. These values were accordingly eliminated, and a layered structure model that consisted of an aim layer (seedlings with good comprehensive growth status), constraint layers (root morphological indices, stem morphological indices, leaf morphological indices, biomass indices, transpiration indices and photosynthesis indices) and index layers (16 indices with significant differences) was constructed.

The consistency check of the seven decision matrixes that reflected the comprehensive growth status of seedlings was conducted according to formulas ① and ②. The results indicated that all of the *CR* values of these seven decision matrixes were smaller than 0.1, indicating that the matrixes possessed satisfactory consistency (Supplemental Table 2).

To reflect the effects of different indices on the aim layer, the weight values of C to A, P to C and P to A were summarized and reordered. According to the results, the ranking of effect degrees of different types of indices was as follows: photosynthesis indices (0.3434) > transpiration indices (0.2530) > leaf morphological indices (0.2420) > biomass indices (0.0750) > stem morphological indices (0.0506) > root morphological indices (0.0300). The sum of the weight values of the

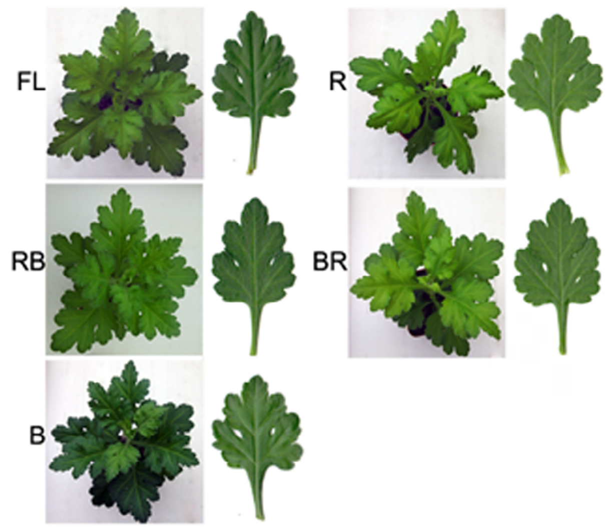

Figure 1 The overall forms and leaf morphology of seedlings under different LED systems. Fluorescent lamp (FL), blue light (B), red light (R), blue : red = 2:1 (BR), red : blue = 2:1 (RB). The leaves were taken from equivalent locations from each seedling.

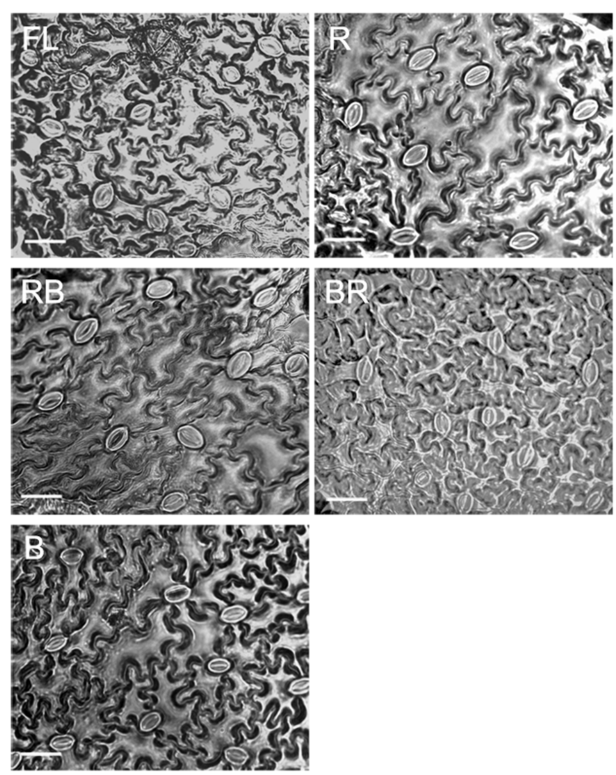

Figure 2 The stomatal forms of seedlings under different LED systems. Fluorescent lamp (FL), blue light (B), red light (R), blue : red = 2:1 (BR), red : blue = 2:1 (RB). Bars = 40 μm.

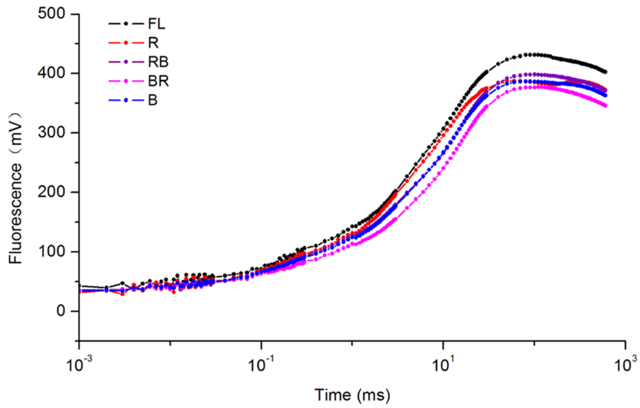

Figure 3 The chlorophyll fluorescence-induced dynamic curve of seedlings under different LED systems. The X-axis and Y-axis represent time and intensity of fluorescence, respectively. Fluorescent lamp (FL), blue light (B), red light (R), blue : red = 2:1 (BR), red : blue = 2:1 (RB).

top five indices reached 77.18% of the total weight value, which could reflect the comprehensive growth status of seedlings to a large extent. These indices were as follows: CCB (0.3005) > NST (0.1265) > DST (0.1265) > CA (0.0934) > LL (0.0710) > WL (0.0539) (Table 3). These results indicate that the above six indices affected the comprehensive growth status of seedlings to a large extent and should be considered as the most important indices for the cut chrysanthemum production.

3.4 The construction of a comprehensive evaluation system for the best LED system

The decision matrix was initially constructed based on the raw data, and the weighted standard decision matrix for different LED systems, and was further constructed based on the 16 indices. Finally, a comprehensive evaluation system for the screening of the best LED system was successfully constructed (Table 4). The evaluation results indicated that the best LED system for cut chrysanthemums was the RB system, with a relative approach degree of 0.7577. The second and third-ranking light quality types were BR (0.7488) and B (0.5950), respectively, whereas R (0.3069) and FL (0.2968) light were not suitable for the growth of cut chrysanthemums.

Table 3 The weight values of each layer in the AHP analysis.

Weight value of C to A		P	Weight value of P to C	Weight value of P to A	Ranking
C1	0.0300	P1	0.8333	0.0250	8
		P2	0.1667	0.0050	11
C2	0.0566	P3	0.0455	0.0026	12
		P4	0.3182	0.0180	10
		P5	0.3182	0.0180	10
		P6	0.3182	0.0180	10
C3	0.2420	P7	0.2933	0.0710	4
		P8	0.2229	0.0539	5
		P9	0.3860	0.0934	3
		P10	0.0978	0.0237	9
C4	0.0750	P11	0.5000	0.0375	7
		P12	0.5000	0.0375	7
C5	0.2530	P13	0.5000	0.1265	2
		P14	0.5000	0.1265	2
C6	0.3434	P15	0.1250	0.0429	6
		P16	0.8750	0.3005	1

Aim layer (A), constraint layer (C), index layer (P), root morphological indices (C1), stem morphological indices (C2), leaf morphological indices (C3), biomass indices (C4), transpiration indices (C5), photosynthesis indices (C6), length of roots (P1), number of roots (P2), width of stems (P3), length of the first internode (P4), length of the second internode (P5), length of the third internode (P6), length of leaves (P7), width of leaves (P8), crown area (P9),value of chrominance component ranged from blue to yellow (P10), dry weight of seedlings (P11), fresh weight of seedlings (P12), number of unit-area stomata (P13), density of stomata (P14), content of chlorophyll a (P15), content of chlorophyll b (P16).

Table 4 The weighted standard decision matrix of the 16 repeatable indices, ideal solutions and relative approach degrees of each light quality.

LQ	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
FL	0.0099	0.0021	0.0011	0.0104	0.0083	0.0075	0.0331	0.0245	0.0413	0.0090
B	0.0097	0.0014	0.0011	0.0057	0.0072	0.0076	0.0266	0.0213	0.0349	0.0112
R	0.0104	0.0017	0.0013	0.0099	0.0098	0.0093	0.0373	0.0295	0.0420	0.0076
BR	0.0129	0.0025	0.0012	0.0061	0.0071	0.0078	0.0334	0.0246	0.0503	0.0123
RB	0.0125	0.0031	0.0011	0.0070	0.0076	0.0079	0.0271	0.0194	0.0389	0.0120
Sj^+	0.0129	0.0031	0.0013	0.0104	0.0098	0.0093	0.0373	0.0295	0.0503	0.0123
Sj^-	0.0097	0.0014	0.0011	0.0057	0.0071	0.0075	0.0266	0.0194	0.0349	0.0076

LQ	P11	P12	P13	P14	P15	P16	Dj^+	Dj^-	Zi	Ranking
FL	0.0154	0.0141	0.0460	0.0460	0.0164	0.1146	0.0537	0.0227	0.2968	5
B	0.0099	0.0092	0.0575	0.0575	0.0203	0.1425	0.0334	0.0490	0.5950	3
R	0.0185	0.0205	0.0575	0.0575	0.0138	0.0969	0.0624	0.0276	0.3069	4
BR	0.0219	0.0200	0.0527	0.0527	0.0223	0.1562	0.0220	0.0655	0.7488	2
RB	0.0158	0.0173	0.0671	0.0671	0.0217	0.1519	0.0205	0.0642	0.7577	1
Sj^+	0.0219	0.0205	0.0671	0.0671	0.0223	0.1562				
Sj^-	0.0099	0.0092	0.0460	0.0460	0.0138	0.0969				

Light quality (LQ), length of roots (P1), number of roots (P2), width of stems (P3), length of the first internode (P4), length of the second internode (P5), length of the third internode (P6), length of leaves (P7), width of leaves (P8), crown area (P9),value of chrominance component ranged from blue to yellow (P10), dry weight of seedlings (P11), fresh weight of seedlings (P12), number of unit-area stomata (P13), density of stomata (P14), content of chlorophyll a (P15), content of chlorophyll b (P16), plus ideal solution (Sj^+), minus ideal solution (Sj^-), distance between the Pi to the plus ideal solution (Dj^+), distance between the Pi to the minus ideal solution (Dj^-), relative approach degree (Zi), fluorescent lamp (FL), blue light (B), red light (R), blue : red = 2:1 (BR), red : blue = 2:1 (RB).

4 Discussion

In the present study, we conducted an in-depth investigation of the effects of light quality on the growth and development of cut chrysanthemums, and then screened for the best LED system for cut chrysanthemums after combining the AHP with the TOPSIS method. The construction of a comprehensive evaluation system for the light quality was successful, and the effect of LED systems on the growth and development of chrysanthemum was significant.

4.1 The construction of comprehensive evaluation system

Fuzzy mathematics is one of the powerful mathematical tools for resolving unclear or fuzzy practical problems [27]. Fuzzy systematic theory constitutes the original form of speculative mathematics, which has been successfully applied to many aspects of agricultural comprehensive evaluation system [28]. One of the basic mathematical methods of fuzzy mathematics is called the fuzzy comprehensive evaluation method, which describes the fuzzy boundary according to membership grades [29]. Describing “black or white” objective facts is difficult because of the complexity, hierarchy and fuzziness of evaluation factors, which are difficult to measure or describe using the classical mathematical models [30]. In contrast, the fuzzy comprehensive evaluation method, based on the fuzzy set, is able to resolve this problem by evaluating the membership grades of different indices comprehensively and dividing targets into different regions to simplify the fuzziness of the evaluation criteria and influencing factors [31]. For example, the Duncan multiple comparisons analysis of the present study indicated that the blue light promoted the stem and leaf development of seedlings but inhibited their photosynthesis, making it difficult to evaluate the advantages and disadvantages of blue light for the growth of seedlings without an objective comprehensive evaluation system.

In addition to the AHP and TOPSIS methods used in the present study, the frequently used mathematical methods in agricultural comprehensive evaluation systems also include principal component analysis (PCA), gray relational analysis (GRA) and the entropy weight (EW) method. Xu *et al.* constructed a multiple-objective (coal consumption, water consumption, and pollutant and greenhouse gases emissions) comprehensive evaluation system for coal-fired power plants using the AHP and GRA methods [32]. Cao *et al.* also used these two methods and constructed a comprehensive evaluation system for the green supply chain of fresh food by taking all of the links in the fresh food supply chain as evaluation factors [33]. Wang and Zhao investigated the interaction of different power plant indices and successfully constructed a comprehensive evaluation system for energy plant security [34]. Thus it can be seen that these mathematical methods have been widely used for the construction of industrial comprehensive evaluation systems. However, at present, the application of comprehensive evaluation systems to the agriculture field has been restricted to the evaluation of field crops and new energy plants, but has been rarely applied to ornamental horticulture.

In the present study, the weight values of indices that displayed significant differences as determined by a Duncan multiple comparisons analysis were calculated using the AHP method, and then the performance of different LED systems was reordered according to the relative approach degree of TOPSIS method. Finally, the best LED system for the growth of cut chrysanthemums was determined. This comprehensive system scientifically and objectively evaluated the interaction of complicated factors, avoided subjectivity, fuzziness of natural-language-based description and the limitations of single mathematical methods. Thus, the evaluation result was more accurate and reliable.

4.2 The effect of LED systems on the growth and development of plants

The Duncan multiple comparisons analysis is a powerful tool for analyzing the effects of different variables on the aim factors [23]. According to the Duncan multiple comparisons analysis of the present study, the blue light promoted the stem and leaf development of seedlings but inhibited their photosynthesis. One theoretical explanation for this would be that the matching wavelengths of blue LEDs to plant photoreceptors influence plant morphogenesis and results in optimum responses [35-37], and that monochromatic blue LEDs with narrow peak emissions may cause an imbalance of the distribution of light energy between the photosystems I and II, and thus be responsible for a reduction in net photosynthesis [38].

Moreover, we also found that the red light stimulated rooting but inhibited the accumulation of biomass of seedlings. Although the effectiveness of red light on rooting from shoots is dependent on genotype and the concentration of rooting compounds [19], light quality appears to be critical to the goal of promoting faster rooting under a shorter culture period, thereby increasing the efficiency while reducing the cost. It is reasonable to expect that, in the future, an LED irradiation system could also be used in the rooting stage of micropropagation to obtain better results.

Finally, the Duncan multiple comparisons analysis indicated that the red : blue = 2:1 system was good for plant transpiration. Stomatal size of *Salvia* Linn. was found to be smaller under blue LEDs than other light treatments, but no significant difference in stomatal size was observed in marigold [39]. The importance of blue light in stomatal opening has already been emphasized [40]. It has been proposed that blue light received by phototropins activates a signaling cascade, resulting in fast stomata opening under a red light background [20]. However, the effect of light quality on stomatal characteristics has not yet been clearly determined, and differential stomatal behavior could be related to photosynthetic activity and plant growth.

The AHP-TOPSIS comprehensive evaluation system analysis of the present study indicated that the red : blue = 2:1 system was the best LED system for the growth of cut chrysanthemums. The results we obtained are consistent with many studies. For instance, Nhut *et al.* analyzed the growth and fresh weight of *Musa paradisiaca* seedlings using five types of LED systems and found that 80% red : 20% blue was the best light quality [12]. Lian *et al.* compared the regeneration rate and biomass of *Lilium* species using three types of light qualities [41]. Their results indicated that red : blue = 1:1 was the best LED system. A study by Nhut *et al.* demonstrated that seedlings of *Fragaria ×ananassa* Duchesne under 70% red : 30% blue light quality reached the best growth status [42]. In a study of chrysanthemums, Kim *et al.* analyzed the length of stem, length of internodes, dry weight, fresh weight, leaf area, chlorophyll content, number and size of stomata and photosynthetic rate of chrysanthemum seedlings using six types of LED systems, and found that red : blue = 1:1 was the best light quality [7]. Although the ratios of red to blue light were different, the results of the above studies are consistent with the present study in that LED systems combining red and blue light best facilitated the growth and development of plants. Moreover, there were also several other findings that are partially consistent with the present study, such as the finding that blue light promoted the growth rate of *Zantedeschia jucunda* Letty, *Chrysanthemum* L. and *Dendrobium officinale* Kimura et Migo [43-45], and the finding that red light stimulated the rooting of *Pinus* L., *Tripterospermum japonicum* (Sieb.et Zucc.) Maxim. and *Gossypium hirsutum* [20, 46, 47].

However, the results of the present study are also inconsistent with some studies. Tanaka *et al*. analyzed the growth of leaves, chlorophyll content and weight of roots and stems of *Cymbidium* L. species using two types of LED systems, and found that red light promoted the growth of leaves but inhibited the accumulation of chlorophyll content, whereas the opposite result was observed for blue light [48]. Heo *et al*. found that red light promoted the growth of the stems of *Vitis berlandieri* × *V. riparia* cultivar 'Teleki 5BB7' [49]. The above results were rather different than the results of the present study, thus indicating that responses to light quality vary according to plant species, developmental stage of the plant, and environmental conditions such as PPF [44], medium composition [50], and ventilation [51]. Therefore, further studies are necessary for the elucidation of the influence of light, which may facilitate the establishment of artificial propagation methods in an efficient manner.

Interestingly, we also observed that the inflorescence of seedlings was significantly affected by different light qualities. The inflorescence of seedlings cultured under blue light was earlier than with the other types. The effects of LEDs on inflorescence development *in vitro* were investigated by Dewir *et al*. in photoperiodically day-neutral *Euphorbia milii* Des Moul. There were significant differences in flowering response between fluorescent and LED treatments. Blue, red : far-red and blue : far-red LEDs stimulated flowering *in vitro*, whereas red LEDs reduced the flowering percentage. Furthermore, red, blue, and blue : far-red delayed the flowering response. The highest flowering percentage (90%), number of inflorescences per plantlet, percentage of mature inflorescences, and early flowering were observed under fluorescent light [52]. The findings indicate that the potential role of LEDs in the flowering process of a day-neutral plant that does not require external signals for flower induction, which may be explained by a theory proposed by Li *et al*. that the expression of downstream genes that regulate flowering were activated because of the expression of light receptor genes activated by the blue light [53]. However, this mechanism requires further verification.

5 Conclusion

LED systems combining red and blue light for the growth and development of most plant species have been well studied. This has been further demonstrated in the present study, which partially reflected the previous proposed hypotheses on different light qualities. A red : blue = 2 : 1 was the best LED system for the growth and development of cut chrysanthemums. All of the analyses in the present study provide a reference for the industrial annual production of cut chrysanthemums and the physiological research of other horticultural crops. Moreover, due to the energy-saving advantage of LED systems, lower energy consumption on ornamental plants production also can be realized in the near future.

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