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Research on Quality Characteristic Using LED as Supplementary Lighting during Withering Process in Oolong Tea

Chen Shousong[1] Jin Xinyi[1,2] Lin Hongzheng[1,2] Yu Shaojuan[1] Zhou Ziwei[1] Sun Yun[1,2]
(1. *College of Horticulture, Fujian Agriculture and Forestry University, Fuzhou* 350002, *China*
2. *Key Laboratory of Tea Science, Fujian Province, Fuzhou* 350002, *China*)

Abstract: Solar withering is the first and essential processing during Oolong tea manufacturing, which can improve and develop a pleasant scent, especially for the floral fruity scent. The traditional technology employed hot air withering in rainy days, which lacks of light radiation, the quality of Oolong tea has no fruit floral odour and the taste is niffy green and astringency. In order to make up the light waves in rainy days or instability sunlight, an artificial light source could be considered for quality improvement during withering process in Oolong tea. In this study, solar, LED (red, yellow, blue) and dark treatments were projected for the test of physiological response, physicochemical, aroma, sensory evaluation and efficiency. Firstly, the constant temperature and humidity containing LED resource withering device for Oolong tea was developed, mainly including LED panel, air circulation channel, temperature/humidity transducer and uniform plate. The temperature/humidity transducer was applied to control the fixed conditions; Air circulation channel was projected as a medium to dehumidify and ensure the circulation of air in the box. Secondly, the test of physiological response indicated that fresh tea leaves plucking from tea plants had a limited capacity to absorb light, the net photosynthetic and transpiration rate of tea leaves increased at first and then decreased, reached peak at 10 ~ 15 min; However, the dark treatment remained negative value(-2.5 μmol/($m^2 \cdot s$)), mainly conduct respiration action, and when photo synthetically active radiation was 300 μmol/($m^2 \cdot s$), the time of withering by 30 min could be well. Thirdly, the test of biochemical component indicated that treatments exposed to different light significances increased the content of water extracts, amino acid, soluble sugar and flavones, boosted the conversion of polyphenol and decreased content of caffeine. Then, the volatile components of different treatments were assayed by chromatography − mass spectrometry detection (GC − MS). Principal component analysis method was used to evaluate the results. In contrast to dark treatment, the relative content of alpha-farnesene and nerolidol increased by 11.42% and 30.65%, respectively. The score of aroma quality exposed to solar was the highest, yellow and blue light had a bit better than red light, and dark treatment ranked the last. The sensory evaluation of quality in raw tea showed a similar trend to the results of principal component analysis. Moreover, based on light withering, the productive efficiency can be improved by 2.6 times, the grade of tea quality increased 1 ~ 2 levels, and the economic benefit enhanced by approximately 63%. In conclusion, light can regulate and improve the taste and volatiles of Oolong tea, selecting LED as an artificial light to substitute for solar withering could be a promising technology, especially for the standardization during Oolong tea manufacturing.

Key words: Oolong tea; light emitting diode; supplementary lighting and withering; quality; benefit

0 Introduction

Oolong tea is a type of special tea with high aroma, which belongs to a kind of semi-fermented tea and main products in Fujian, Guangdong and Taiwan Provinces. The natural floral fruity aroma and green leaves embroidered red shape are regarded as its quality characteristics[1]. The fine quality strongly relys on several environmental factors during Oolong tea manufacturing, including light, temperature, humidity and airflow[2-3]. Solar withering is the first and essential process, which can directly influence and determine the formation of aroma and taste flavor[4-5]. The rate of overcast and rainy weather occurred 50% ~

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Corresponding author: SUN Yun, Professor. E-mail: sunyun1125@126.com. Tel: +86-139-60826626.

80% during the fastigium of Oolong tea manufacturing, especially happened in high altitude mountain areas. So fine material without solar condition becomes a common problem in tea production regions. The traditional technology employed hot-air withering in rainy days which lacks of light radiation, thus the aroma of Oolong tea has little floral fruity scent and the taste is niffy green and astringency[6]. Several hundred millions Yuan of financial loss was caused by the bad weather during tea manufacturing annually.

Some relative researches about artificial light withering had been carried out. WANG et al.[7] and ZHANG et al.[8] sifted out several light wave bands from sunlight by filtering material, and the full spectrum was taken as control. The test showed that a better quality could be brought by yellow light (>520 nm) with 13 725 ~ 16 774 lx for 30 min light treatment and the accumulation of amino acid, soluble sugar and aroma could also be enhanced. Huang et al.[9] indicated that the content of catechin acid in black tea could be reduced by withering with red LED and the content of amino acid could be increased by withering with blue LED. In conclusion, the sensory quality under red and blue LED withering treatment is higher than that under indoor withering treatment. JIANG et al.[10] showed that fresh leaves of Maoxie was irradiated under UV - B for 2 h, and then the content of aroma could be enhanced. FAN et al.[11] employed iodine-tungsten lamp to irradiate fresh leaves, and the result showed that the score of aroma under light withering was higher than that using indoor withering. So far, most researches mainly focused on sole light withering, the research that how to combine LED with hot-air withering and obtain better quality of Oolong tea in rainy days has not yet been reported.

As a cold light source, LED has the advantages of widely optional central wavelength and narrow half-wave breadth, which can save 83% and 54% energy compared to fluorescent and incandescent lamp[12-13]. Furthermore, LED has more superiority on characteristic spectrum than the other lights, and it has been applied in facility agriculture of plant for supplementary light[14-15]. Based on the constant temperature and humidity containing LED resource withering device, taking fen-flavor Tieguanyin as research object, the solar, LED (red, yellow, blue) and dark treatments were projected for the test. Firstly, we analyzed the physiological response characteristic and rule on postharvest leaves, which are exposed to different wavelengths of LED, and the response capability was evaluated for confirming illumination time. Then, similar processing technical was used to make primary tea for analyzing the physicochemical, aroma, sensory evaluation and efficiency. This paper presents a comprehensive evaluation and verification on the effect of supplementary light withering in Oolong tea by LED, and provides a technical reference for the factorization and standardization during Oolong tea manufacturing.

1 Materials and methods

1.1 Materials

Plucking Tieguanyin (one bud and three leaves) as materials, moisture content of fresh leaves are (74.6 ± 1)%. The experiment site was located in natural protection area of Meihua mountain (altitude: 1 100 m) in Longyan City of Fujian Province.

1.2 Apparatus and instruments

1.2.1 Apparatus

The constant temperature and humidity containing LED resource withering equipment which mainly including box, LED panel, uniform plate, heat pump unit, humidifying unit, hydrofuge fan, air circulation channel, temperature/humidity transducer, and intelligence digital readout control system was developed by ourselves (Fig. 1). The boxes were installed three different wavelengths of LED which including red LED ((628 ± 10) nm), yellow LED ((595 ± 12) nm), blue LED((455 ± 10) nm) (those LEDs were made in Shenzhen City (Tuobang Co., Ltd.)). Illuminate distance(between luminous surface and fresh leaves) were adjusted to ensure uniform intensity under different wavelengths of LED. The wall of boxes were installed uniform plate which can remove the effect of boundary and control the light intensity reach a stable level at (300 ± 10) μmol/(m^2·s). The balance of temperature and humidity can be controlled by heat pump unit which can heat in spring and refrigerate in summer. Hydrofuge fan and air circulation channel were projected as a medium to dehumidify and the circulation of air in the boxes were checked.

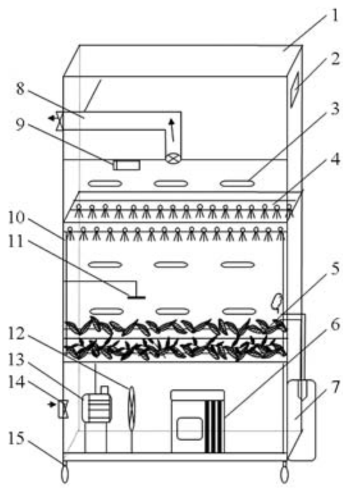

Fig. 1 Sketch diagram of constant temperature and humidity withering device by LED

1. Box 2. Controller 3. Hot air port 4. LED panel 5. Freshly leave 6. Refrigerating system 7. Humidifier 8. Air circulation channel 9. Humidity transducer 10. Uniform plate 11. Temperature transducer 12. Air inlet 13. Heater 14. Fan 15. Trundle

The postharvest leaves were tiled on cabient layers, which can respond to light and heat rapidly under condition of fixed environment, including temperature, humidity, airflow and light. Then photochemical reactions were motivated after absorbing and transmitting, and numerators were promoted by high-velocity motion and collision, stomatal conductance was enlarged, moisture of leaves were evaporated, then energy was released. The catalysis between precursor substances and relative oxydic and hydrolytic enzymes can promote the accumulation of primary and secondary metabolites. Because of minishing cell turgor and owner gravity, different leaf-position leaves were flagged and leading to phase shift after dehydration (Fig. 2).

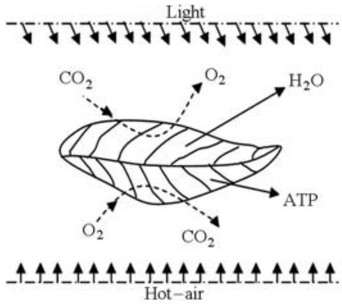

Fig. 2 Physiological change of tea leaves on light response

Others apparatus: several preliminary process devices in Oolong tea which were purchased from Fujian Jiayou Science & Technology Co., Ltd., China. For example, a minitype turn over device (Model 6CST-30), a fixation device (Model 6CST-90), a fast package device (Model 6CSBG-22), a panel package and malaxate device (Model 6CBRP-75), a bale breaking and sift powder device (Model 6CSST-80) and a dryer device (Model 6CH-54) were used for this work.

1.2.2 Instruments

A portable photosynthetic system (Model CID-340, USA) was purchased from Shanghai Zequan Science & Technology Co., Ltd. A photosynthetically active radiation instrument (Model GLZ-B, China) developed by Zhejiang Tuopu Instrument Co., Ltd. was used. A rapidly moisture determinator (Model SFY-60, China) was purchased from Shenzhen Guanya Electronic & Technology Co., Ltd. A temperature and humidity recorder (Model S500-EX, China) was purchased from Shenzhen Huatu Measurement & Control Co., Ltd. Electronic balance (Model BAS124, Switzerland) developed by Mettler Co., Ltd. was used. The GC-MS instrument (Model 6890N-5975B, USA) developed by Agilent Science &Technology Co., Ltd. was used for this work. Several conventional detection instruments were also used as containers and determinators in this study.

1.3 Methods

1.3.1 Protocol

Projecting four treatments of light withering: solar withering (S), red LED (LR), yellow LED (LY), blue LED (LB) and taking dark withering as control (CK). The parameters of environment were set as follows: photosynthetically active radiation (PAR) was set at $(300 \pm 5)\ \mu mol/(m^2 \cdot s)$, temperature was set at 30℃, relative humidity was set at 60%, thickness of stalling leaves was set at 10 mm, and solar withering was conducting at 16:00 (PAR set at $(300 \pm 10)\ \mu mol/(m^2 \cdot s)$). Then, those leaves treated with light withering were transferred to normal temperature for indoor withering, and the finishing time of withering process was evaluated by dehydrating to 68%. Finally, primary tea was made by following technological process of fen-flavor Tieguanyin.

1.3.2 Treating and sampling

1.3.2.1 Sample preparation

Plucking one kilogram leaves (200 g per treatment, five treatments in total)→Light withering (exposed to light for 0.5 h, dark treatment (CK) for 0.5 h)→

Turn over under 20℃ (shaking and stalling for 10 h, three circulation)→Killing out under 230℃ for 2 min (little stab feeling)→Rolling (fast package and panel package add in malaxate, eight circulation)→Drying under 70℃ by hot air (1.5 h)→Primary tea.

1.3.2.2 Sampling methods

Portable photosynthetic system (CID-340, Zequan Co., Ltd., USA) was used to measure all samples during dark conditions for 5 min at first, and then turned to different light withering treatments. The light physiological response index of the third leaves were continuously measured per minute during treated with dark condition for 5 min and treated with dark and light conditions for 30min. Manufacturing of primary tea was followed technological process of fen-flavor Tieguanyin, and then those primary tea samples were frozen in refrigerator at −20℃. The samples were applied to biochemical, aroma components, and sensory quality evaluation analysis.

1.3.3 Indicators and methods

1.3.3.1 Physiological response

Open circuit mode was selected in photosynthetic measurement system, and the parameters of that mode were set as follows: leaf area was performed at 11.0 cm^2, pressure was performed at 101 kPa, air flow was performed at 0.30 L/min, flow velocity was performed at 0.18 mol/(m^2·s), concentration of air inlet CO_2 was performed at 0.09 %, and the data were obtained by the average of all data measured during one minute. The formula of net photosynthetic rate (P_n) was calculated as follows:

$$P_n = -W(c_o - c_i) = -2\,005.39\frac{Vp}{AT_a}(c_o - c_i) \tag{1}$$

in which V is volume velocity of flow, L/min; p is atomospheric pressure, MPa; A is leaf area, cm^2; T_a is air temperature, K; W is flow velocity, mol/(m^2·s); c_o、c_i is volume fraction of int(out) CO_2, %.

The formula of transpiration rate (E) was calculated as follows:

$$E = \frac{(h_{ro} - h_{ri})e_s W}{p - h_{ro}e_s} \times 10^3 \tag{2}$$

in which

$$e_s = 6.137\,53 \times 10^{-3} e^{T_a \frac{18.564 \frac{T_a}{254.4}}{T_a + 255.57}}$$

e_s is saturation vapour pressure at air temperature, MPa; h_{ro}、h_{ri} is relative humidity of air outlet(inlet), %.

1.3.3.2 Biochemical components

Content of aqueous extract refers to GB/T 8305—2002(full dose); Content of tea polyphenol refers to GB/T 8313—2012 (foline-phenol); Content of amino acid refers to GB/T 8314—2002 (ninhydrine); Content of caffeine refers to GB/T 8312—2002; Content of flavonoid refers to alchlor colormetry; Content of soluble sugar refers to anthrone colorimetry.

1.3.3.3 Aroma components

Fragrance was extracted by HS–SPME (Headspace solid phase microextraction). Ten grams of tea fanning were weighed up with 25 μL ethyl n-decanoate (2 mg/mL) as an internal standard and added in 100 mL boiled distilled water. Then the mixture was stirred on magnetic stirring apparatus at 450 r/min, and readsorpted for 40 min after drying at 50℃ for 5 min. Finally, the samples from previous step were sent to injection port of GC–MS(Gas chromatography-mass spectrometer) to desorb at 230℃ for 5 min. HP-5MS(30 m × 0.25 mm ID × 0.25 μm) was selected as chromatographic column. The carrier gas was 99.999% with high purity helium at a constant pressure mode. Temperature of injection port was set at 230℃. An Agilent 6890N-5975B autosampler was used with an injection volume of 1 μL in splitless mode. The temperature of GC transfer line were set at 250℃. The temperature of ion source was set to 230℃. EI was set as ionization mode and 70 eV was set as electron energy. The oven temperature of the first column was held at 50℃ for 2 min, and then ramped to 180℃ (5℃/min), and held for 2 min at the last temperature. The oven temperature of the second column was ramped to 230℃ (10℃/min), and held for 5 min at the last temperature. Finally, qualitative and quantitative analysis were conducted by database.

1.3.3.4 Sensory evaluation

According to GB/T 23776—2009, code evaluation was carried out by several professors. Five grams of tea fanning were weighed up with 110 mL of boiled water and were brewed three circulation for 2 min, 3 min, 5 min, respectively. Comprehensive assessment of sensory quality was based on weight function (aroma by 50% and taste by 50%) by hundred-mark system.

1.4 Data processing

Excel and SPSS 19.0 were used for data processing and principal component analysis.

2 Results and discussion

2.1 Characteristic of physiological response under different light treatments

The fresh tea leaves plucked from tea plants were still alive, which have a limited capacity to absorb light. Changing rule and physiology response characteristic of net photosynthetic and transpiration rate in different light supplemental treatments were performed as follows (Fig. 3):

It showed that net photosynthetic rate of all treated leaves basically stabilized at −2.5 μmol/(m^2·s) during dark conditions for 5 min at first (Fig. 3a). Then leaves could response to light rapidly when opened LED illuminants, and net photosynthetic rate tended to greater than 0 μmol/(m^2·s), including all kinds of light treatments. The net photosynthetic rate of tea leaves was increased at first and then decreased during light supplemental conditions for 30 min. Net photosynthetic rate with solar treatment reached peak at 15 min(8.89 μmol/(m^2·s)). And net photosynthetic rate with red LED, yellow LED, blue LED treatments reached peak at 10 ~ 15 min(5.32, 4.69, 6.65 μmol/(m^2·s)), respectively. However, dark treatment remained negative value (−2.5 μmol/(m^2·s)), which may due to that the fresh leaves mainly conduct respiration action.

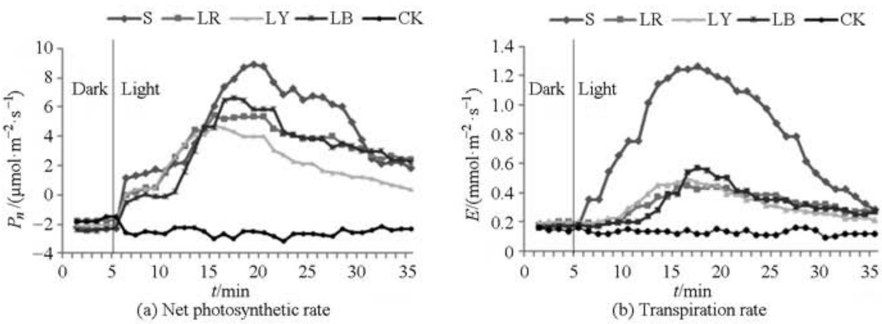

Fig. 3 Changing rule of net photosynthetic P_n and transpiration rate E of different treatment leaves

The changing rule of transpiration rate represented certainly discrepancy (Fig. 3b). It showed that transpiration rate of dark treatment was lower than all kinds of light treatments, which basically stabilized at 0.15 mmol/(m^2·s). The gaseous exchange between atmosphere and mesophyll cell decreased, and dehydration rate was slow. The rate of dehydration inordinately was promoted with the light withering treatments and the rate was increased at first and then decreased. The transpiration rate of leaves treated with solar, red LED, yellow LED and blue LED reached peak at 10 ~ 13 min(1.24, 0.45, 0.49, 0.55 mmol/(m^2·s)), respectively. In conclusion, stomatal conductance could be enlarged, leaves moisture lost rapidly and withering time could be shortened when fresh leaves exposed to light.

2.2 Changes of biochemical components under different light treatments

Quantity on transformation or accumulation of different chemical components was conclusive to evaluate the abundance of internal substances in tea, which influence the refresh, mellow and taste of primary tea.

Compared to the control, the biochemical components showed significantly increased under different light treatments during withering process, including water extract, amino acid, soluble sugar, flavones (Tab. 1). All of them were benefit for the formation of refresh and mellow taste. The blue and red light treatments significantly promoted accumulation of the content of amino acid(1.86%) and soluble sugar (5.05%), respectively. Solar and yellow light treatments dramatically promoted accumulation of content of water extract. At the same time, macromolecular substances were transformed and reduced validly by different light treatments, which represent bitterness taste compounds such as tea polyphenols and caffeine. The above results showed that light treatments not only accelerating the course of water emission, but also promoting transformation and accumulation of small molecule substance, which eventually attribute to the extract velocity and durable brew in Tieguanyin primary tea.

Tab. 1 Biochemical components of Oolong tea in different treatments

Parameters	S	LR	LY	LB	CK
Water extracts/%	31.22 ± 1.61[a]	30.09 ± 1.74[c]	31.26 ± 1.11[a]	30.31 ± 1.38[b]	30.03 ± 1.25[d]
Polyphenols/%	12.35 ± 1.22[c]	12.20 ± 1.07[d]	12.42 ± 0.98[b]	12.39 ± 1.37[bc]	12.75 ± 1.42[a]
Amino acid/%	1.72 ± 0.18[bc]	1.70 ± 0.29[c]	1.75 ± 0.11[b]	1.86 ± 0.17[a]	1.62 ± 0.26[d]
Caffeine/%	2.56 ± 0.38[c]	2.57 ± 0.42[c]	2.50 ± 0.22[d]	2.62 ± 0.19[b]	2.68 ± 0.20[a]
Soluble sugar/%	4.96 ± 0.52[b]	5.05 ± 0.61[a]	4.92 ± 0.38[b]	4.96 ± 0.47[b]	4.84 ± 0.31[c]
Flavone/($mg \cdot g^{-1}$)	6.86 ± 0.79[a]	6.61 ± 0.68[c]	6.71 ± 0.54[b]	6.87 ± 0.62[a]	6.44 ± 0.55[d]

Note: The different upper case in the same row of samples treatment means significant difference at $p \leqslant 0.05$ levels. All the same as below.

2.3 Analysis of aroma components under different light treatments

Aroma factor in Oolong tea accounting for 35% among comprehensive factor of sensory evaluation, which is 5% higher than taste factor (30%). Although the relative content of volatile aroma components in tea is occupies 0.01% of dry weight, the major volatile aroma components have low threshold and determine the formation of floral fruity flavor in Oolong tea directly.

Tab. 2 Relative contents of main aroma component of Oolong tea in different treatments %

No.	Compounds	S	LR	LY	LB	CK
1	alpha. -Farnesene	30.23[b]	29.54[c]	30.10[b]	31.73[a]	28.10[d]
2	Nerolidol	26.65[a]	25.18[b]	26.86[a]	25.14[b]	20.40[c]
3	Indole	12.15	9.10	9.85	9.37	9.93
4	Hexanoic acid, 3-hexenyl ester, (Z)-	6.81	7.62	8.61	8.20	8.36
5	beta. -Ocimene	4.86	3.81	3.12	3.87	4.96
6	Butanoic acid, 3-hexenyl ester, (Z)-	4.25	5.87	5.66	5.71	9.09
7	cis-3-Hexenyl isovalerate	2.03	2.23	2.27	2.07	3.72
8	(Z,E)-. alpha. -Farnesene	1.74	1.35	1.31	1.26	1.21
9	Methyl salicylate	1.34	0.15	–	–	2.59
10	Hexanoic acid, hexyl ester	1.15	1.19	1.42	1.32	1.25
11	Benzeneacetaldehyde	0.91	0.91	0.78	0.93	0.92
12	beta. -Phenylethyl butyrate	0.59	0.40	0.56	0.48	0.14
13	(E) beta. -Farnesene	0.58	0.58	0.65	0.58	0.43
14	beta. -Ionone	0.54	0.42	0.43	0.42	0.34
15	Linalool	0.50	0.66	0.43	0.60	0.32

Note: " – " means non-detected.

It showed that there was no significant difference in varieties of the primary tea made by different light withering treatments (Tab. 2). The terpenes, alcohols and esters were regarded as the main volatile types, which make up more than 85% of the total aroma content; Where in the terpenes usually presenting delicate fragrance, and special floral and fruity-like scent, which contribute largely to the aroma of Oolong tea. The terpenes such as α-farnesene (floral-like odor) and nerolidol (floral-like, wood-like and fruity lily odor) as the main aroma-producing substance, which accounted for more than 50% of total aroma volatiles in the Tieguanyin primary tea.

The relative mass fraction of α-farnesene in different treatments with ascending order of sequentially was showed as follows: CK, LR, LY, S, LB; Dark treatment was the lowest (28.10%) and blue light treatment was the highest (31.73%). The relative mass fraction of nerolidol in different treatments with ascending order of sequentially was showed as follows: CK, LB, LR, S, LY; Dark treatment was also the lowest (20.40%) and yellow light treatment was the highest (26.86%). In conclusion, relative mass fraction of α- farnesene and nerolidol in primary tea under light treatments were significantly higher than CK condition, and their growth rateg were approximately 11.42% and 30.65%, respectively. Thus, supplemental light withering can largely contribute to transformation and accumulation of floral aroma components and enrich the flavor characteristics in Tieguanyin primary tea.

To comprehensively determine the aroma quality under different light treatments, HS-SPME and GC-MS were used to analyze fire different treatments. The result which contains 48 aroma components had been formed 5 × 48 matrix and were analyzed by SPSS 19.0 software using principal component analysis. Then, according to the principle eliminating of variables, minimum characteristic value principal component corresponding to the maximum feature vector and the other reports about main fragrance of Tieguanyin at home or abroad were synthesized together, and the top 15 main fragrance components of all treatments were analyzed and figured out. All those relative mass fraction of fragrance components were greater than 0.5% and reached the smelling threshold, which can meet and represent distinctive fragrance in quality characteristic of Tieguanyin primary tea.

Raw data of 15 fragrance components which mentioned above were re-analyzed using principal component assay, and principal components' characteristic value and cumulative contribution rate were accquired via standardization (Tab. 3).

Tab. 3 Characteristic value and cumulative contribution rate of principal component

Principle components	Eigennalue	Variance proportion/%	Cumulative proportion/%
F_1	8.298	55.322	55.322
F_2	4.706	31.373	86.695
F_3	1.348	8.989	95.684

The cumulative contribution rate of first 3 principal components reached 95.684%, and the variance contribution rate of F_1, F_2, F_3 reached 55.322%, 31.373%, 8.989%, respectively, and their characteristic root λ was greater than 1.000. Those data indicated that the first 3 principal components (F_1, F_2, F_3) contain most aroma information, thus it is reasonable to choose these components to explain and evaluate all information of aroma quality for all samples.

Tab. 4 Load matrix on principal component

Components	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
F_1	0.634	0.992	0.360	−0.419	−0.476	−0.961	−0.973	0.638	−0.688	0.070	−0.432	0.982	0.919	0.830	0.970
F_2	−0.266	−0.051	0.784	−0.809	0.850	−0.241	−0.073	0.753	0.590	−0.925	0.589	0.044	−0.389	0.524	0.181
F_3	−0.508	0.079	0.472	0.304	0.057	0.052	0.121	0.139	0.408	0.273	−0.668	0.179	−0.018	0.039	−0.092

As the Tab. 4 showed, three principal components (F_1, F_2, F_3) were transferred to fully reflect the integrated features of aroma quality in different treatments by analyzing 15 indicator variables. Three linear equations of principal components were calculated based on load matrixs of each corresponding principal component. The code of X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15} were represented relative mass fraction of α-farnesene, nerolidol, indole, hexanoic acid (3-hexenyl ester), β-ocimene, butanoic acid (3-hexenyl ester), cis-3-hexenyl isovalerate, (Z, E)-α-farnesene, methyl salicylate, hexanoic acid (hexyl ester), benzeneacetaldehyde, phenylethyl butyrate, (E)-β-farnesene, beta-ionone, linalool, respectively.

The relationship between the load factors of each principal component equation and corresponding indicators were analyzed. The result showed that cumulative contribution rate of the first principal component (F_1) reached 55.322%, representing more than half information of aroma in samples. The load factors of nerolidol and α-farnesene were 0.992 and 0.634, respectively, which were high-positive correlated with the principal component equation F_1. By contrast, the load factors of cis-3-hexenyl isovalerate, butanoic acid (3-hexenyl ester) and other compounds representing green and grassy fragrance were high-negative correlated with the principal component equation F_1.

Using variance contribution rates of different characteristic values as F_1, F_2, F_3 weighting factors, multiplying each principal component and corresponding weighting factor, and establishing comprehensive evaluation model: $F = 0.553F_1 +$

$0.314F_2 + 0.899F_3$. The scores of aroma quality under different light treatments were calculated by comprehensive evaluation function F and then sorted by score. According to the first principal component that had greatest variance contribution, the higher F value of comprehensive evaluation model equation, the better overall quality of aroma in primary tea (Tab. 5).

Tab. 5 Result of comprehensive evaluation on aroma quality

Treatment mode	F_1	F_2	F_3	F	Rank
S	39.70	−0.67	−4.13	21.37	1
LY	38.21	−7.29	−5.03	18.39	2
LB	36.90	−6.84	−6.49	17.67	3
LR	35.23	−5.84	−5.63	17.14	4
CK	22.60	−3.82	−3.27	11.01	5

According to principal component analysis, scores (F values) of integrated features of aroma quality in different treatments with ascending order of sequentially were showed as follows: CK, LR, LB, LY, S. Based on the thesis that "the higher F value, the better integrated quality of primary tea", the results showed that solar treatment had the best aroma quality, followed by yellow treatment, and dark treatment ranked last.

2.4 Sensory quality evaluation under different light treatments

Selecting aroma by 50% and taste by 50% as the indicators of sensory quality evaluation (Tab. 6). The primary tea of Oolong tea with solar treatment showed highest score (88.6) by comprehensive assessment of sensory evaluation. While yellow and blue LED treatments shared balance effect on quality, ranking second. In addition, score of dark treatment showed significantly lower than other light treatments ($p < 0.05$), and lack of obvious fragrance accompanied with green stuffy odor and slightly astringent taste. Sensory evaluation of aroma factor agreed well with the principal component analysis results. In sum, sensory quality of primary tea in Oolong tea produced by artificial lighting withering treatment was significantly higher than dark treatment.

Tab. 6 Result of sensory quality evaluation in raw tea

Treatment mode	Aroma		Taste		Comprehensive evaluation score
	Reviews	Score	Reviews	Score	
S	Floral fruit odor; Heavy, enduring	90.6	Mellow, fresh sweet	86.5	88.6^a
LY	Floral fruit odor; enduring	88.5	Mellow, fresh Slight sweet	84.7	86.6^b
LB	Floral fruit odor; enduring	87.3	Mellow, fresh Slight sweet	85.6	86.4^b
LR	Floral fruit odor; Slight	86.0	Slight mellow; Little bitter, astringent	82.1	84.1^c
CK	Gentle scent niffy, grassy	81.4	bitter, astringent grassy	79.2	80.3^d

2.5 Analysis of economic and efficiency

Withering using LED combined with hot-air has much superiority (Tab. 7). Compared to dark treatment, supplemental light withering can shorten 3 ~ 4 h of withering time and improve production efficiency by 2.6 times per batch. Additional value of primary tea can be significantly boosted applied with this new technology, and grade of quality can be enhanced, profits will be increased, and economic performance can be improved to 63%.

Tab. 7 Analysis on economy and efficiency

Withering mode	Withering time/h	Production efficiency/($kg \cdot h^{-1}$)	Energy cost/ ($Yuan \cdot kg^{-1}$)	Production cost/($Yuan \cdot kg^{-1}$)	Output value/ ($Yuan \cdot kg^{-1}$)	Profit/ ($Yuan \cdot kg^{-1}$)
LED and hot-air	1 − 2	13	8	18	45	27
Dark and hot-air	4 − 6	5	10	20	30	10

3 Conclusions

(1) Light using efficiency of tea leaves was not increase along with time extension. The net photosynthetic and transpiration rate of tea leaves exposed to different lights were increased at first and then decreased, reached peak at 10 ~ 15 min. Overall consideration on production cost, energy saving and capacity utilization of optical energy, fresh leaves exposed to light withering for 30 min could be well

when photo synthetically active radiation was 300 μmol/(m^2·s).

(2) Compared to the control, the biochemical components including water extract, amino acid, soluble sugar, flavones were increased under different light treatments and macromolecular substances, which represent bitterness taste compounds such as tea polyphenols and caffeine, were transformed and reduced validly. Especially, blue and red light treatments can significantly increased accumulation of the content of amino acid (1.86%) and soluble sugar (5.05%), respectively.

(3) Relative mass fraction of α-farnesene and nerolidol were significantly increased by 11.42% and 30.62%, respectively. Based on principal component analysis method, score of aroma quality exposed to solar was the highest, yellow and blue light treatment had a bit better than red light treatment, and dark treatment ranked the last. The sensory evaluation of quality in primary tea showed a similar trend to the results of principal component analysis.

(4) Contrast to dark light treatment, the withering time of Oolong tea can be shortened 3 ~ 4 h and production efficiency can be improved by 2.6 times per batch treated with supplemental light withering. About 1 ~ 2 grade level of quality in primary tea can also be enhanced and economic performance can be improved by 63%.

References

[1] CHEN Zongmao, YANG Yajun. Classic of tea[M]. Shanghai: Shanghai Culture Press, 2011: 565 – 573. (in Chinese)

[2] WANG Li, LIN Zhi, LÜ Haipeng, et al. Research progress in affecting factors of tea aroma[J]. Food Science, 2010, 31(15): 293 – 298. (in Chinese)

[3] CHEN Jibin, JIN Xinyi, HAO Zhilong, et al. Research of sunlight withering room and its withering effect on whitetea[J]. Transactions of the CSAE, 2012, 28(19): 171 – 177. (in Chinese)

[4] WAN Xiaochun, LI Daxiang, ZHANG Zhengzhu, et al. Research advance on tea biochemistry[J]. Journal of Tea Science, 2015, 35(1): 1 – 10. (in Chinese)

[5] WAN Xiaochun, XIA Tao. Secondary metabolism of tea plant[M]. Beijing: Science Press, 2015: 145 – 149. (in Chinese)

[6] LI Wencui, REN Guangxin, HE Xin. Status and improvements of the technology and equipment in tea leaf spreading and withering[J]. China Tea Processing, 2013(3): 44 – 48. (in Chinese)

[7] WANG Dengliang, ZHANG Lingzhi, MAO Minghui, et al. Effects of withered with different light-wave bands on qualities of Dancong tea[J]. Journal of Food Science and Biotechnology, 2006, 25(2): 56 – 59. (in Chinese)

[8] ZHANG Lingzhi, WANG Dengliang, MAO Minghui, et al. Effects of different light-intensity withering on quality of Dancong tea[J]. Food Science, 2005, 26(6): 185 – 188. (in Chinese)

[9] HUANG Fan, CHEN Lin, ZHOU Xiaofen, et al. Effect of red and blue light exposure during withering on amino acid and catechin contents of Congou black tea[J]. Fujian Journal of Agricultural Sciences, 2015, 30(5): 509 – 515. (in Chinese)

[10] JIANG J, YANG Y C, ZHANG G H, et al. Effect of ultra-violet B on release of volatiles in tea leaf[J]. International Journal of Food Properties, 2010, 13(3): 608 – 617.

[11] FAN Shisheng, JIN Xiu, YANG Qing, et al. Effects on main quality components and enzyme activity of tea leaves by artificial light withering[J]. Hubei Agricultural Sciences, 2012, 51(6): 1152 – 1155. (in Chinese)

[12] ZHANG Haihui, HU Jin, YANG Qing, et al. Realization of light quality adjustable precise light compensating method in greenhouse agriculture[J]. Transactions of the Chinese Society for Agricultural Machinery, 2012, 43(3): 181 – 186. (in Chinese)

[13] YANG Qichang, XU Zhigang, CHEN Hongda, et al. Application principle and technology progress in using light emitting diode (LED) light sources in modern agriculture[J]. Journal of Agricultural Science and Technology, 2011, 13(5): 37 – 43. (in Chinese)

[14] CUI Jin, XU Zhigang, DI Xiuru. Applications and prospects of light emitting diode in plant protected culture[J]. Transactions of the CSAE, 2008, 24(8): 249 – 253. (in Chinese)

[15] SHEN Baoying, DING Weimin, HUI Na, et al. Regulation of LED night lighting on growth and morphology of cucumber seedlings and process of night lighting[J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(6): 296 – 302. (in Chinese)

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乌龙茶 LED 补光萎凋品质特性研究

陈寿松[1]　金心怡[1,2]　林宏政[1,2]　俞少娟[1]　周子维[1]　孙　云[1,2]

(1.福建农林大学园艺学院，福州 350002；2.福建省茶学重点实验室，福州 350002)

摘要：光质是乌龙茶品质形成不可缺少的环境因素，为了明确 LED 补光萎凋对乌龙茶品质形成的影响，选取清香型铁观音为研究对象，以无光萎凋为对照，探明日光和 LED 红、黄、蓝光 4 个光照条件下采后茶鲜叶的生理响应能力以及铁观音毛茶生化、香气组分测定与感官品质评价。试验结果表明：离体叶对不同光质的生理响应在 10 ~ 15 min 时分别达到峰值，光照强度为 300 μmol/($m^2 \cdot s$)时，光照 30 min 可满足萎凋光环境技术参数。与无光处理相比，补光萎凋可显著提高铁观音毛茶的水浸出物、氨基酸、可溶性糖、黄酮等含量，促进了茶多酚转化并降低了咖啡碱含量；铁观音主要赋香成分 α-法呢烯和橙花叔醇的相对质量分数分别提高 11.42%、30.65%。主成分分析得出日光、LED 萎凋处理毛茶香气质量综合得分高于无光萎凋处理，LED 黄、蓝光萎凋处理香气质量综合评价略优于 LED 红光萎凋，并与各处理毛茶品质感官审评结果表现一致，补光萎凋技术可使经济效益提高 63%。

关键词：乌龙茶；LED；补光萎凋；品质；效益

中图分类号：S571.1；TS272.4　　**文献标识码**：A　　**文章编号**：1000-1298(2016)07-0282-08

Research on Quality Characteristic Using LED as Supplementary Lighting during Withering Process in Oolong Tea

Chen Shousong[1]　Jin Xinyi[1,2]　Lin Hongzheng[1,2]　Yu Shaojuan[1]　Zhou Ziwei[1]　Sun Yun[1,2]

(1. *College of Horticulture*, *Fujian Agriculture and Forestry University*, *Fuzhou* 350002, *China*
2. *Key Laboratory of Tea Science*, *Fujian Province*, *Fuzhou* 350002, *China*)

Abstract: Solar withering is the first and essential processing during Oolong tea manufacturing, which can improve and develop a pleasant scent, especially for the floral fruity scent. The traditional technology employed hot air withering in rainy days, which lacks of light radiation, the quality of Oolong tea has no fruit floral odour and the taste is niffy green and astringency. In order to make up the light waves in rainy days or instability sunlight, an artificial light source could be considered for quality improvement during withering process in Oolong tea. In this study, solar, LED (red, yellow, blue) and dark treatments were projected for the test of physiological response, physicochemical, aroma, sensory evaluation and efficiency. Firstly, the constant temperature and humidity containing LED resource withering device for Oolong tea was developed, mainly including LED panel, air circulation channel, temperature/humidity transducer and uniform plate. The temperature/humidity transducer was applied to control the fixed conditions; Air circulation channel was projected as a medium to dehumidify and ensure the circulation of air in the box. Secondly, the test of physiological response indicated that fresh tea leaves plucking from tea plants had a limited capacity to absorb light, the net photosynthetic and transpiration rate of tea leaves increased at first and then decreased, reached peak at 10 ~ 15 min; However, the dark treatment remained negative value (−2.5 μmol/($m^2 \cdot s$)), mainly conduct respiration action, and when photo synthetically active radiation was 300 μmol/($m^2 \cdot s$), the time of withering by 30 min could be well.

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作者简介：陈寿松(1987—)，男，博士生，主要从事茶叶加工与加工工程研究，E-mail：css7788531@163.com

通信作者：孙云(1964—)，女，教授，博士生导师，主要从事茶叶加工与品质研究，E-mail：sunyun1125@126.com

Thirdly, the test of biochemical component indicated that treatments exposed to different light significances increased the content of water extracts, amino acid, soluble sugar and flavones, boosted the conversion of polyphenol and decreased content of caffeine. Then, the volatile components of different treatments were assayed by chromatography - mass spectrometry detection (GC - MS). Principal component analysis method was used to evaluate the results. In contrast to dark treatment, the relative content of alpha-farnesene and nerolidol increased by 11.42% and 30.65%, respectively. The score of aroma quality exposed to solar was the highest, yellow and blue light had a bit better than red light, and dark treatment ranked the last. The sensory evaluation of quality in raw tea showed a similar trend to the results of principal component analysis. Moreover, based on light withering, the productive efficiency can be improved by 2.6 times, the grade of tea quality increased 1 ~ 2 levels, and the economic benefit enhanced by approximately 63%. In conclusion, light can regulate and improve the taste and volatiles of Oolong tea, selecting LED as an artificial light to substitute for solar withering could be a promising technology, especially for the standardization during Oolong tea manufacturing.

Key words: Oolong tea; light emitting diode; supplementary lighting and withering; quality; benefit

引言

乌龙茶(Oolong tea)是我国特有的一种高香型特种茶,属于半发酵茶类,具有独特的天然花果香和绿叶红镶边的品质特征,主产于福建、广东、台湾等省[1]。鲜叶加工过程优良品质的形成紧密依赖于良好的“光、温、湿、风”等自然环境因子[2-3],日光萎凋是乌龙茶初加工不可或缺的首道工序,是直接影响并决定着成品茶形成高香、味醇品质的关键因子[4-5]。乌龙茶春季生产正值南方梅雨季节,50% ~ 80% 时间处于阴雨潮湿天气,特别是高山茶区更是浓雾笼罩,原料好而日晒条件差成为高山茶区的共同问题。目前生产上一般采用加温除湿设备进行热风萎凋,但由于热风萎凋缺乏光的诱导,影响青叶内含物转化,影响乌龙茶花果香品质,毛茶往往香气低闷,滋味淡薄青涩[6],每年因天气原因导致乌龙茶经济损失数亿元。

关于人工光源萎凋方面的研究,王登良等[7-8]以全光谱为对照,采用滤光材料从太阳光中分出不同波段光谱进行乌龙茶晒青试验,提出光照强度为 13 725 ~ 16 774 lx、波长大于 520 nm 的黄光波段照射 30 min 对乌龙茶品质提高较好,可促进氨基酸、可溶性糖含量及其香气成分的积累;黄藩等[9]开展 LED 纯光照萎凋试验,认为 LED 红光萎凋可以降低红茶儿茶素含量,LED 蓝光萎凋可以提高氨基酸含量,红光和蓝光萎凋所制成红茶感官品质均高于无光组;JIANG 等[10]采用 3.0 mmol/(m^2·s)的紫外线 UV - B 照射毛蟹品种鲜叶,2 h 后香气含量显著提高;范仕胜等[11]采用碘钨灯光照萎凋鲜叶,试验结果表明室内萎凋的香气得分明显低于光照处理。但迄今为止,前人研究大多仍局限于纯光照萎凋,如何在现行的热风萎凋基础上配合节能、高效、环保、稳定的 LED 补光技术,使乌龙茶在阴雨天也能达到日光萎凋的优异品质,这方面研究尚未见报道。

LED 是一种冷光源,具有中心波长选择性强、光谱半波宽度窄等优点;较荧光灯节能 83%,较白炽灯节能 54%[12-13]。特别是基于 LED 开展植物特征光谱的研究较其它光源存在更多的优越性,已在许多设施农业的植物补光领域得到推广应用[14-15]。因此,基于自主研制的调温排湿 LED 光萎凋系统装置开展试验,以清香型铁观音为研究对象,设计日光、不同波长 LED 光源等光环境因素,以无光萎凋为对照,通过研究分析采后铁观音茶鲜叶对不同波长 LED 光源的光生理响应特性及规律,评估离体叶对光的响应能力以期初步确定出光照时间,同时经过相同加工工艺制成铁观音毛茶并进行生化成分测定、气相色谱-质谱联用(Gas chromatography - mass spectrometer,GC - MS)香气测定、感官品质审评以及经济效益分析,综合评价和探明人工光源 LED 应用于乌龙茶补光萎凋的效果,以期为乌龙茶全天候工厂化、标准化补光萎凋生产提供技术参考。

1　材料与方法

1.1　试验材料

采摘铁观音(标准开面三叶)为供试材料,鲜叶含水率为(74.6 ±1)%。

试验地点:福建省云雾香茶叶发展有限公司,地处海拔高度 1 100 m 的梅花山自然保护区。

1.2　试验装置与仪器

1.2.1　试验装置

自主研制乌龙茶调温排湿 LED 光补偿萎凋装

置(Oolong tea LED withering equipment,OLW),简称"LED 光萎凋装置",主要由箱体、LED 灯源、匀光板、热泵机组、增湿装置、排湿风扇、气流循环通道、温湿度传感系统、智能数显控制系统等构成(见图 1)。调温排湿箱各安装 3 种波长 LED 灯源(红光(628 ± 10) nm、黄光(595 ± 12) nm、蓝光(455 ± 10) nm,深圳拓邦股份有限公司),调节 LED 灯照射高度(发光面与鲜叶之间距离),保证鲜叶在不同波长 LED 灯照射下的光强达到一致;箱体四壁安装匀光板,以消除光边界效应,控制各点光强在(300 ± 10) μmol/(m^2·s);热泵机组春季制热夏季制冷,控制萎凋温湿度;排湿风扇和气流循环通道及时排除萎凋过程的水蒸气。

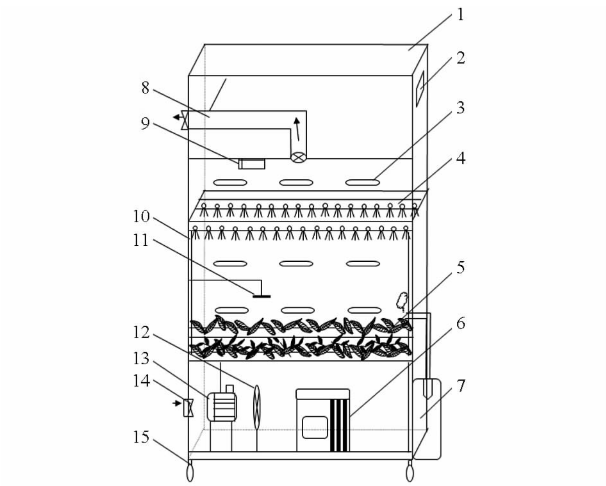


图 1 调温排湿 LED 光萎凋装置结构示意图

Fig. 1 Sketch diagram of constant temperature and humidity withering device by LED

1. 箱体 2. 控制器 3. 热风口 4. LED 灯板 5. 鲜叶 6. 制冷系统 7. 增湿装置 8. 气流循环通道 9. 湿度传感器 10. 匀光板 11. 温度传感器 12. 进风口 13. 加热器 14. 风机 15. 脚轮

鲜叶光响应原理:采收后的茶鲜叶薄层平铺箱体层架上,在一定的温、湿、风和光环境条件下,短时间内可对光、热效应产生响应作用,吸收、传递和激发光化学反应,促使叶内分子高速运动碰撞,气孔导度增大,叶内水分蒸发和能量释放,各种前体物质与相关氧化水解酶发生催化作用,促进在制叶初生、次生代谢产物积累;叶片失水后细胞膨压 T 减小和重力 G 等共同作用,使不同叶位的叶片萎蔫并发生叶相位移(见图 2)。

其它试验装置为乌龙茶初加工成套设备,包括 6CST－30 型小型摇青机、6CST－90 型茶叶杀青机、6CSBG－22 型茶叶速包球茶机、6CBRP－75 型茶叶平板包揉机、6CSST－80 型茶叶松包筛末机和 6CH－54 型茶叶烘干机。

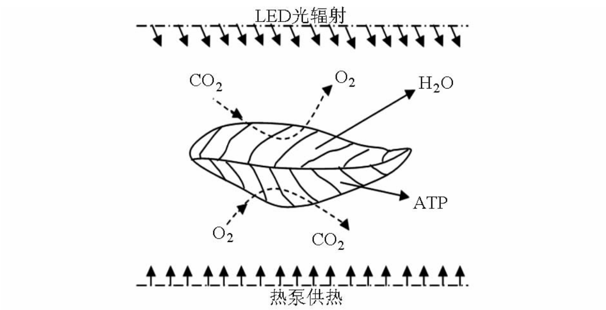


图 2 叶片光响应的生理变化

Fig. 2 Physiological change of tea leaves on light response

1.2.2 试验仪器

CID－340 超轻型便携式光合测定仪(USA),上海泽泉科技有限公司;GLZ－B 型托普仪,浙江托普仪器有限公司;SFY－60 型红外线快速水分测定仪,深圳市冠亚电子科技有限公司;S500－EX 型温湿度记录仪,深圳华图测控有限公司;BAS124S 型电子天平(精度:0.000 1 g),梅特勒-托利多仪器有限公司;Agilent 6890N－5975B 型气相色谱-质谱联用仪,安捷伦科技有限公司;其他常规检测仪器等。

1.3 试验方法

1.3.1 试验方案设计

设计 4 种不同光照萎凋处理:LED 红光(LR)、黄光(LY)、蓝光(LB)、日光(S),以无光处理为对照(CK),调温排湿乌龙茶 LED 光萎凋装置的控制条件为:光合有效辐射(300 ± 5) μmol/(m^2·s),温度 30℃,相对湿度 60%,摊叶厚度 10 mm,日光萎凋在晴天 16:00 进行((300 ± 10) μmol/(m^2·s)),光照萎凋后即放入常温室内继续萎凋,萎凋程度以样品失水至 68% 结束,并按照清香型铁观音工艺流程加工制成毛茶。

1.3.2 样品处理与取样

1.3.2.1 样品处理

采收鲜叶 1 kg,每个处理平均 200 g,共计 5 份→光照萎凋(各处理光照 0.5 h,CK 不照光)→空调 20℃做青(3 摇 3 晾,历时 10 h)→230℃杀青 2 min,青叶略有刺手感→包揉(速包 + 平板包揉,反复 8 次)→热风 70℃干燥(历时 1.5 h)→毛茶。

1.3.2.2 取样方法

光照前 5 min 暗处理阶段即开始采用 CID－340 型便携式光合系统测定,所测叶梢部位为第 3 片完全展开叶片,每隔 1 min 连续测量鲜叶在无光照 5 min中和有光照 30 min 过程中的光生理响应指标。按照工艺流程制作铁观音毛茶样品,足干后贮存在 －20℃冰箱内,样品备用于生化成分、香气组分测定及感官品质审评。

1.3.3　测定项目与方法

1.3.3.1　净光合速率 P_n 和蒸腾速率 E 生理响应

选择开路 Open 光合测量系统，叶室面积为 11.0 cm^2，大气压强 101 kPa，空气流量 0.30 L/min，流速为 0.18 mol/(m^2·s)，进气口 CO_2 体积分数为 0.09%，每隔 1 min 采集 1 个平均数据。其中，开路光合测量系统的净光合速率 P_n(μmol/(m^2·s))为

$$P_n = -W(c_o - c_i) = -2\,005.39\frac{Vp}{AT_a}(c_o - c_i) \quad (1)$$

式中　V——体积流速，L/min

p——大气压力，MPa

A——叶面积，cm^2

T_a——空气热力学温度，K

W——流速，mol/(m^2·s)

c_o、c_i——出、进气口的 CO_2 体积分数，%

蒸腾速率 E(mmol/(m^2·s))为

$$E = \frac{(h_{ro} - h_{ri})e_s W}{p - h_{ro}e_s} \times 10^3 \quad (2)$$

其中　$e_s = 6.137\,53 \times 10^{-3} e^{T_a \frac{18.564 \frac{T_a}{254.4}}{T_a + 255.57}}$

式中　e_s——空气温度下的饱和水汽压，MPa

h_{ro}、h_{ri}——出、进气口的相对湿度，%

1.3.3.2　生化成分测定

水浸出物含量参照 GB/T 8305—2002(全量法)测定；茶多酚含量参照 GB/T 8313—2012(福林酚试剂比色法)测定；游离氨基酸含量参照 GB/T 8314—2002(茚三酮比色法)测定；咖啡碱含量参照 GB/T 8312—2002 紫外分光光度法测定；黄酮类化合物含量参照三氯化铝比色法测定；可溶性糖含量参照蒽酮比色法测定。

1.3.3.3　香气组分测定

采用 HS－SPME 提取香气：称取 10.0 g 磨碎茶样加入 2 mg/mL 癸酸乙酯(内标)25 μL，100 mL 沸腾蒸馏水，放于磁力搅拌器上(转速 450 r/min)，在 50℃干燥箱中平衡 5 min 后再吸附 40 min，最后在 GC－MS 进样口于 230℃下解吸 5 min。

GC－MS 条件：色谱柱：HP－5MS(30 m×0.25 mm ID×0.25 μm 膜厚)；载气为高纯氦气，99.999%；进样口温度：230℃；脉冲不分流，进样 1 μL，柱流速：1 mL/min；色谱-质谱接口温度：250℃。离子源温度：230℃；离子化方式：EI；电子能量：70 eV；程序升温参数：50℃保持 2 min，以 5℃/min 升至 180℃，保持 2 min，再以 10℃/min 升到 230℃，保持 5 min，最后进行定性和定量分析。

1.3.3.4　毛茶感官审评

按照 GB/T 23776—2009 茶叶感官审评方法聘请专家进行编号审评，采用 5 g 茶样、110 mL 沸水冲泡 3 次(2、3、5 min)，以百分制为总分，并按照权重(香气 50%＋滋味 50%)综合评定感官品质。

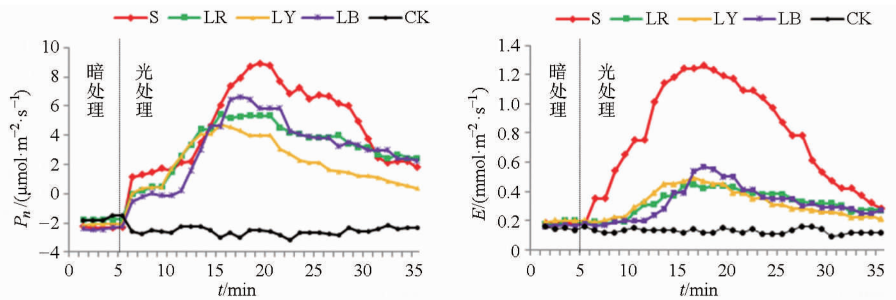
1.4　数据处理方法

采用 Microsoft Office Excel 及 SPSS 19.0 统计软件进行数据处理和主成分分析。

2　结果与分析

2.1　不同补光萎凋的青叶生理响应特性

离体茶鲜叶从茶树母体上采摘后，仍然保持着活体状态，不同补光萎凋处理青叶的生理响应特性及其变化规律见图 3。图中 t 为时间。



(a) 净光合速率　　(b) 蒸腾速率

图 3　不同处理青叶的 P_n 和 E 变化规律

Fig. 3　Changing rule of net photosynthetic P_n and transpiration rate E of different treatment leaves

由图 3a 可知，暗处理不照光 5 min 内，不同处理青叶净光合速率 P_n 稳定在 －2.5 μmol/(m^2·s)，开启 LED 光源，日光 S、红光 LR、黄光 LY、蓝光 LB 处理青叶在短时间内迅速对光产生响应作用，净光合速率 P_n 趋向并且大于 0 μmol/(m^2·s)。补光萎凋 30 min 内青叶的光响应变化规律总体呈现了先升高后降低的“∩单峰型”趋势，日光 S 萎凋处理在光照 15 min 达到了峰值(8.89 μmol/(m^2·s))，红光 LR、黄光 LY、蓝光 LB 萎凋处理分别在光萎凋 10～15 min 达到了峰值(5.32、4.69、6.65 μmol/(m^2·s))，无光 CK 萎凋处理青叶 P_n 在 30 min 内基本稳定在 －2.5 μmol/(m^2·s)，主要以呼吸作用消耗有机物为

主要生理方式。

不同补光萎凋环境下青叶蒸腾速率 E 的变化也存在一定差异。由图3b可知,无光CK萎凋处理较其它光萎凋处理相比,青叶的蒸腾速率 E 基本稳定在0.15 mmol/(m^2·s),明显低于其他光照处理,并持续保持最低水平,减少了大气与叶肉细胞的气体交换,失水速率最缓慢。光照萎凋在不同程度上促进了青叶的失水速率,总体也呈现了先升高后降低的"∩单峰型"变化趋势,日光S、红光LR、黄光LY、蓝光LB萎凋处理在光照10~13 min达到了峰值(1.24、0.45、0.49、0.55 mmol/(m^2·s)),促使其气孔导度增大,叶内水分快速散失,导致萎凋时间缩短。

2.2 不同补光萎凋对铁观音毛茶生化成分影响

评价茶叶内含物质的丰度主要取决于不同生化成分转化与积累的多少,从而直接影响着毛茶不同程度的鲜爽、醇厚、回甘口感。不同光萎凋处理铁观音毛茶的生化成分含量见表1。

表1 不同处理铁观音毛茶生化成分含量

Tab.1 Biochemical component of Oolong tea in different treatments

参数	S	LR	LY	LB	CK
水浸出物质量分数/%	31.22±1.61^a	30.09±1.74^c	31.26±1.11^a	30.31±1.38^b	30.03±1.25^d
茶多酚质量分数/%	12.35±1.22^c	12.20±1.07^d	12.42±0.98^b	12.39±1.37^{bc}	12.75±1.42^a
氨基酸质量分数/%	1.72±0.18^{bc}	1.70±0.29^c	1.75±0.11^b	1.86±0.17^a	1.62±0.26^d
咖啡碱质量分数/%	2.56±0.38^c	2.57±0.42^c	2.50±0.22^d	2.62±0.19^b	2.68±0.20^a
可溶性糖质量分数/%	4.96±0.52^b	5.05±0.61^a	4.92±0.38^b	4.96±0.47^b	4.84±0.31^c
黄酮质量比/(mg·g^{-1})	6.86±0.79^a	6.61±0.68^c	6.71±0.54^b	6.87±0.62^a	6.44±0.55^d

注:不同处理多重显著性分析采用不同小写字母(p≤0.05)表示,下同。

由表1可知,与无光CK处理相比,光照处理显著提高了铁观音毛茶的水浸出物、氨基酸、可溶性糖、黄酮等生化成分含量,不同程度地促进了鲜爽醇厚甘甜风味的形成,尤其是蓝光LB处理显著促进了氨基酸内含物的积累(1.86%),红光LR处理显著促进了可溶性糖含量的积累(5.05%),日光S处理、黄光LY处理显著促进了水浸出物含量的积累;同时,呈现苦涩味的大分子内含物质茶多酚和咖啡碱含量经过光辐射萎凋后也得到了有效转化与降低。补光萎凋处理不仅加速了萎凋失水进程,同时促进了小分子内含物质完成转化并获得积累,最终有效保证了铁观音毛茶的浸出速率和耐冲泡程度。

2.3 不同补光萎凋对铁观音毛茶香气组分影响

乌龙茶中的香气因子占其感官审评综合因子35%的权重,较滋味因子高5%,虽然茶叶挥发性香气组分的相对含量仅占干重的0.01%,但是大部分香气组分的香味阈值低,直接决定和形成了乌龙茶独特的兰花、果香风味特征。不同LED光质萎凋铁观音制成的毛茶主要香气组分相对质量分数见表2。

由表2可知,不同补光萎凋处理制成的铁观音毛茶香气种类差异不大,以萜烯类、醇类、酯类为主要香气类型,占毛茶总香气含量的85%以上,其中萜烯类化合物通常表现为清香并呈现特殊的花、果香,对乌龙茶香气形成贡献较大。香气组分以α-法呢烯(花香)和橙花叔醇(花香、木花香和水果百合香韵)为主要呈香物质,共占铁观音毛茶全部香气相对质量分数的50%以上。

表2 不同处理铁观音毛茶主要香气组分相对质量分数

Tab.2 Relative contents of main aroma component of Oolong tea in different treatments %

序号	化合物	S	LR	LY	LB	CK
1	α-法呢烯	30.23^b	29.54^c	30.10^b	31.73^a	28.10^d
2	橙花叔醇	26.65^a	25.18^b	26.86^a	25.14^b	20.40^c
3	吲哚	12.15	9.10	9.85	9.37	9.93
4	己酸叶醇酯	6.81	7.62	8.61	8.20	8.36
5	β-罗勒烯	4.86	3.81	3.12	3.87	4.96
6	顺-3-己烯基丁酯	4.25	5.87	5.66	5.71	9.09
7	异戊酸叶醇酯	2.03	2.23	2.27	2.07	3.72
8	(Z,E)-α-法呢烯	1.74	1.35	1.31	1.26	1.21
9	水杨酸甲酯	1.34	0.15			2.59
10	己酸己酯	1.15	1.19	1.42	1.32	1.25
11	苯乙醛	0.91	0.91	0.78	0.93	0.92
12	β-丁酸苯乙酯	0.59	0.40	0.56	0.48	0.14
13	(E)-β-法呢烯	0.58	0.58	0.65	0.58	0.43
14	β-紫罗酮	0.54	0.42	0.43	0.42	0.34
15	芳樟醇	0.50	0.66	0.43	0.60	0.32

不同处理的铁观音毛茶α-法呢烯相对质量分数由小到大依次为:CK、LR、LY、S、LB,无光CK处理相对质量分数最低(28.10%),蓝光LB处理相对质量分数最高(31.73%)。不同处理的橙花叔醇相对质量分数由小到大依次为:CK、LB、LR、S、LY,无光CK处理相对质量分数最低(20.40%),黄光LY处理相对质量分数最高(26.86%)。光照处理后毛茶的α-法呢烯和橙花叔醇的相对质量分数显著高于无光CK萎凋处理,其增长率分别达11.42%和30.65%左右。因此可以看出,补光萎凋处理在很大程度上促进了铁观音毛茶花果香气组分的转化与积

累，从而丰富了铁观音风味品质特征。

为了综合评价不同补光萎凋处理铁观音毛茶的香气品质，根据顶空固相微萃取 HS - SPME 结合 GC - MS 分析得到 5 个不同处理共检测出 48 种香气成分，构成 5×48 的矩阵，利用 SPSS 19.0 软件进行主成分分析，按照剔除最小特征值主成分对应最大特征向量的变量原则，并结合国内外关于铁观音主要香气成分的研究报道，得出不同处理铁观音毛茶检测出相对质量分数排名前 15 位的主要香气组分，所有香气成分的相对质量分数都大于 0.5%，检测出的 15 个香气组分达到嗅觉阈值，并完全满足和代表铁观音特有的香气品质特征。

对 15 种香气组分相对质量分数的原始数据重新进行主成分分析，标准化处理后得到各主成分的特征值和累计贡献率，见表 3。

前 3 个主成分分量的累计贡献率达到 95.684%，主成分 F_1、F_2、F_3 的方差贡献率分别为 55.322%、31.373%、8.989%，并且前 3 个因子的特征根 $\lambda > 1.000$，F_1、F_2、F_3 分量已包含铁观音毛茶香气的绝大部分信息，因此选择前 3 个因子 F_1、F_2、F_3 进行主成分分析能够充分解释和评价不同处理铁观音毛茶香气质量的全部信息。

表 3　主成分特征值与累计贡献率

Tab. 3　Characteristic value and cumulative contribution rate of principal component

主成分	特征值	方差贡献率/%	累计贡献率/%
F_1	8.298	55.322	55.322
F_2	4.706	31.373	86.695
F_3	1.348	8.989	95.684

由表 4 可知，通过对 15 个指标变量进行分析处理后，转换为 3 个主成分 F_1、F_2、F_3，全面反映不同处理铁观音毛茶香气质量的综合特征。根据各主成分对应的载荷矩阵得出 3 个主成分线性组合方程，其中 X_1、X_2、X_3、X_4、X_5、X_6、X_7、X_8、X_9、X_{10}、X_{11}、X_{12}、X_{13}、X_{14}、X_{15} 分别代表着铁观音香气成分的 α-法呢烯、橙花叔醇、吲哚、己酸叶醇酯、β-罗勒烯、顺-3-己烯基丁酯、异戊酸叶醇酯、(Z,E)-α-法呢烯、水杨酸甲酯、己酸己酯、苯乙醛、β-丁酸苯乙酯、(E)-β-法呢烯、β-紫罗酮、芳樟醇等相对质量分数。

表 4　主成分对应的载荷矩阵

Tab. 4　Load matrix on principal component

主成分	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
F_1	0.634	0.992	0.360	-0.419	-0.476	-0.961	-0.973	0.638	-0.688	0.070	-0.432	0.982	0.919	0.830	0.970
F_2	-0.266	-0.051	0.784	-0.809	0.850	-0.241	-0.073	0.753	0.590	-0.925	0.589	0.044	-0.389	0.524	0.181
F_3	-0.508	0.079	0.472	0.304	0.057	0.052	0.121	0.139	0.408	0.273	-0.668	0.179	-0.018	0.039	-0.092

通过分析各主成分方程载荷系数与对应指标之间的关系可知，第 1 主成分（F_1）的累计贡献率达到了 55.322%，代表了一半以上香气信息，并且铁观音呈花果香味的主香成分橙花叔醇和 α-法呢烯的载荷系数分别为 0.992 和 0.634，与主成分方程 F_1 呈高度正相关，而呈青香味的异戊酸叶醇酯、顺-3-己烯基丁酯等成分载荷系数与主成分方程 F_1 呈高度负相关。

以不同特征值的方差贡献率作 F_1、F_2、F_3 的加权系数，由各主成分和对应的不同特征值的方差贡献率为权重相乘再求和建立综合评价模型：$F = 0.553F_1 + 0.314F_2 + 0.899F_3$，由综合评价函数 F 计算不同处理的铁观音毛茶香气得分并按大小排序，同时根据方差贡献率最大的第 1 主成分分析可知，综合评价模型方程的 F 越大，毛茶的香气综合质量越好。综合评价结果见表 5。

通过主成分综合分析指出不同补光萎凋处理铁观音毛茶的香气质量综合得分 F 由低到高依次为：CK、LR、LB、LY、S，由于 F 越大，毛茶的香气综合质量越好，因此可知日光 S 处理毛茶香气质量最好，黄光 LY 处理次之，无光 CK 处理最低。

表 5　香气质量综合评价结果

Tab. 5　Result of comprehensive evaluation on aroma quality

处理方式	F_1	F_2	F_3	F	排序
S	39.70	-0.67	-4.13	21.37	1
LY	38.21	-7.29	-5.03	18.39	2
LB	36.90	-6.84	-6.49	17.67	3
LR	35.23	-5.84	-5.63	17.14	4
CK	22.60	-3.82	-3.27	11.01	5

2.4　不同补光萎凋对铁观音毛茶感官品质评价

不同补光萎凋处理所制铁观音毛茶感官审评结果见表 6。

以香气 50%、滋味 50% 为感官品质评价指标（见表 6），日光 S 萎凋处理所制铁观音毛茶感官评价最高，综合评价得分达到 88.6，黄光 LY、蓝光 LB 处理品质相当，无光 CK 处理无明显香气并夹杂青闷味、滋味略青涩，显著低于其余光照处理得分（$p < 0.05$），香气因子的感官评价与各处理香气组

分的主成分分析结果相吻合,补光萎凋处理铁观音毛茶感官品质都显著高于无光CK处理。

2.5 经济效益分析

乌龙茶在热风萎凋基础上,结合LED补光萎凋具有诸多优越性(见表7),与传统热风无光萎凋相比,每批次的萎凋用时可缩短3~4 h,生产效率提高2.6倍;从品质及经济效益方面分析,应用该项新技术可显著提高铁观音毛茶的附加值,可提高1~2个品质等级,增加创收17元/kg,经济效益提高63%。

表6 毛茶感官品质审评结果

Tab.6 Result of sensory quality evaluation on raw tea

处理方式	香气		滋味		综合评价得分
	评语	得分	评语	得分	
S	花果香显;馥郁持久	90.6	醇厚鲜爽;回甘好	86.5	88.6[a]
LY	花果香较显;持久	88.5	醇厚较鲜爽;略回甘	84.7	86.6[b]
LB	花果香较显;持久	87.3	醇厚鲜爽;略回甘	85.6	86.4[b]
LR	花果香尚显	86.0	醇和略苦涩;略回甘	82.1	84.1[c]
CK	香气平和;带青闷味	81.4	醇和苦涩;略带青味	79.2	80.3[d]

表7 经济效益分析

Tab.7 Analysis on economic and efficiency

萎凋方式	萎凋用时/h	生产效率/($kg\cdot h^{-1}$)	能耗成本/(元$\cdot kg^{-1}$)	生产成本/(元$\cdot kg^{-1}$)	产值/(元$\cdot kg^{-1}$)	利润/(元$\cdot kg^{-1}$)
LED+热风	1~2	13	8	18	45	27
无光+热风	4~6	5	10	20	30	10

3 结论

(1)通过光生理响应特性及其变化规律的试验研究发现:叶片光能利用效率并不随光照时间延长而升高,离体叶对不同光质的生理响应在10~15 min时达到峰值,然后逐渐下降。综合考虑生产成本、节约能源以及叶片利用光能能力等,萎凋光照强度为300 μmol/($m^2\cdot s$)时,光照30 min可满足铁观音鲜叶萎凋的补光环境技术参数。

(2)与无光萎凋相比,补光萎凋提高了铁观音毛茶的水浸出物、氨基酸、可溶性糖、黄酮等含量,促进了茶多酚转化并降低了咖啡碱含量,不仅加速了萎凋失水进程,而且不同程度地减少了苦涩味、促进了鲜爽醇厚甘甜风味的形成。尤其是蓝光LB处理显著促进了氨基酸内含物的积累(1.86%),红光LR处理显著促进了可溶性糖含量的积累(5.05%)。

(3)基于GC-MS和主成分分析各处理的香气组分表明,LED和日光萎凋相较无光萎凋显著提高了铁观音毛茶的主要赋香物质α-法呢烯和橙花叔醇的相对质量分数,两者的增长率分别为11.42%、30.65%。通过主成分分析表明,日光、LED萎凋处理的综合得分都高于无光萎凋处理,香气质量较高,LED黄、蓝光萎凋处理香气质量综合评价略优于LED红光萎凋,与各处理毛茶香气感官审评结果表现一致。

(4)乌龙茶LED光萎凋技术方法与传统采用热风无光萎凋方式相比,可缩短萎凋用时3~4 h,提高生产效率2.6倍;所制毛茶品质可提高1~2个等级,经济效益提高63%。

参 考 文 献

1 陈宗懋,杨亚军.中国茶经[M].上海:上海文化出版社,2011:565-573.

2 王力,林智,吕海鹏,等.茶叶香气影响因子的研究进展[J].食品科学,2010,31(15):293-298.
WANG Li, LIN Zhi, LÜ Haipeng, et al. Research progress in affecting factors of tea aroma[J]. Food Science, 2010,31(15):293-298. (in Chinese)

3 陈济斌,金心怡,郝志龙,等.节能日光萎凋设施及其对白茶萎凋效果研究[J].农业工程学报,2012,28(19):171-177.
CHEN Jibin, JIN Xinyi, HAO Zhilong, et al. Research of sunlight withering room and its withering effect on whitetea[J]. Transactions of the CSAE,2012,28(19):171-177. (in Chinese)

4 宛晓春,李大祥,张正竹,等.茶叶生物化学研究进展[J].茶叶科学,2015,35(1):1-10.
WAN Xiaochun, LI Daxiang, ZHANG Zhengzhu, et al. Research advance on tea biochemistry[J]. Journal of Tea Science,2015,35(1):1-10. (in Chinese)

5 宛晓春,夏涛.茶树次生代谢[M].北京:科学出版社,2015:145-149.

6 李文萃，任广鑫，何鑫. 茶鲜叶摊放与萎凋技术及设备应用现状与改进[J]. 中国茶叶加工，2013(3)：44－48.
LI Wencui, REN Guangxin, HE Xin. Status and improvements of the technology and equipment in tea leaf spreading and withering [J]. China Tea Processing，2013(3)：44－48. (in Chinese)
7 王登良，张灵枝，毛明辉，等. 不同光波晒青对单枞茶品质的影响[J]. 食品生物技术学报，2006，25(2)：56－59.
WANG Dengliang，ZHANG Lingzhi，MAO Minghui, et al. Effects of withered with different light-wave bands on qualities of Dancong tea[J]. Journal of Food Science and Biotechnology，2006，25(2)：56－59. (in Chinese)
8 张灵枝，王登良，毛明辉，等. 不同光照强度晒青对单枞茶品质的影响[J]. 食品科学，2005，26(6)：185－188.
ZHANG Lingzhi，WANG Dengliang，MAO Minghui, et al. Effects of different light-intensity withering on quality of Dancong tea[J]. Food Science，2005，26(6)：185－188. (in Chinese)
9 黄藩，陈琳，周小芬，等. 蓝光、红光对工夫红茶萎凋中鲜叶氨基酸和儿茶素组分含量的影响[J]. 福建农业学报，2015，30(5)：509－515.
HUANG Fan，CHEN Lin，ZHOU Xiaofen, et al. Effect of red and blue light exposure during withering on amino acid and catechin contents of Congou black tea[J]. Fujian Journal of Agricultural Sciences, 2015，30(5)：509－515. (in Chinese)
10 JIANG J，YANG Y C，ZHANG G H, et al. Effect of ultra-violet B on release of volatiles in tea leaf[J]. International Journal of Food Properties，2010，13(3)：608－617.
11 范仕胜，晋秀，杨清，等. 人工光照萎凋对茶叶主要品质成分与酶活性的影响[J]. 湖北农业科学，2012，51(6)：1152－1155.
FAN Shisheng, JIN Xiu，YANG Qing, et al. Effects on main quality components and enzyme activity of tea leaves by artificial light withering[J]. Hubei Agricultural Sciences，2012，51(6)：1152－1155. (in Chinese)
12 张海辉，胡瑾，杨青，等. 设施农业可调光质精确补光系统[J]. 农业机械学报，2012，43(3)：181－186.
ZHANG Haihui, HU Jin, YANG Qing, et al. Realization of light quality adjustable precise light compensating method in greenhouse agriculture[J]. Transactions of the Chinese Society for Agricultural Machinery，2012，43(3)：181－186. (in Chinese)
13 杨其长，徐志刚，陈弘达，等. LED 光源在现代农业的应用原理与技术进展[J]. 中国农业科技导报，2011，13(5)：37－43.
YANG Qichang, XU Zhigang, CHEN Hongda, et al. Application principle and technology progress in using light emitting diode (LED) light sources in modern agriculture[J]. Journal of Agricultural Science and Technology, 2011，13(5)：37－43. (in Chinese)
14 崔瑾，徐志刚，邸秀茹. LED 在植物设施栽培中的应用和前景[J]. 农业工程学报，2008，24(8)：249－253
CUI Jin，XU Zhigang，DI Xiuru. Applications and prospects of light emitting diode in plant protected culture[J]. Transactions of the CSAE，2008，24(8)：249－253. (in Chinese)
15 申宝营，丁为民，惠娜，等. 夜间补光对黄瓜幼苗形态的调节与补光方式的确定[J]. 农业机械学报，2014，45(6)：296－302.
SHEN Baoying, DING Weimin，HUI Na, et al. Regulation of LED night lighting on growth and morphology of cucumber seedlings and process of night lighting[J]. Transactions of the Chinese Society for Agricultural Machinery，2014，45(6)：296－302. (in Chinese)