Effects of short light/dark cycles on photosynthetic pathway switching and growth of medicinal *Dendrobium officinale* in aeroponic cultivation

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Abstract: *Dendrobium officinale* has high medicinal value but grows slowly in natural environment due to its special CAM photosynthetic pathway. In this study, *D. officinale were grown aeroponically* with light/dark cycles of 12 h/12 h, 4 h/4 h, and 2 h/2 h for 150 d. The photosynthetic electron transfer characteristics, photosynthetic CO_2 fixation pathways, and accumulations of biomass and soluble polysaccharides in *D. officinale* leaves were studied. The results showed that the photosynthetic apparatus states of *D. officinale* in aeroponic cultivation under short light/dark cycles of 4 h/4 h and 2 h/2 h were better than that under 12 h/12 h. The dark net CO_2 exchange percentages of *D. officinale* were negative in short light/dark cycles of 4 h/4 h and 2 h/2 h, and the daily net CO_2 exchange amount and dry/fresh weight increases were doubled compared with those in 12 h/12 h light/dark cycle. High soluble polysaccharides content and the soluble polysaccharides yield of *D. officinale* were obtained in the shorter light/dark cycle of 2 h/2 h. Therefore, the photosynthetic pathway of *D. officinale* could be switched from CAM to C3 by short light/dark cycles of 4 h/4 h and 2 h/2 h, and its higher biomass accumulation and soluble polysaccharides yield could be obtained by the shorter light/dark cycle of 2 h/2 h in aeroponic cultivation.

Keywords: dark net CO_2 exchange percentage, photosynthetic pathway, short light/dark cycle, soluble polysaccharides
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1 Introduction

Dendrobium officinale, an Orchidaceae, has high medicinal value. However it grows very slowly in natural environment. It takes 3-5 years to harvest under artificial cultivation environment. This may be due to its special photosynthetic characteristics of CAM[1]. CAM photosynthetic pathway is an effective means to optimize water use, carbon balance, and photon quantum efficiency of higher plants under environmental stresses[2]. The physiological and biochemical processes of CAM photosynthetic pathway are usually divided into four phases according to the 24 h light/dark cycle[3]. Phase I is the storage of malic acid after CO_2 absorption at night or dark period. Phase III is the decarboxylation of stored malic acid during daytime or light period, and the process of carbon assimilation using photon quantum. At this time, high intracellular CO_2 partial pressure causes stomatal closure. Phases II and IV are transitions between phase I and III[4]. The C3 photosynthetic pathway does not require malic acid to be loaded into vacuoles by active transport in dark period. Therefore, fixing CO_2 through C3 pathway saves about 10% of the metabolic cost compared with CAM pathway[5].

CAM and C3 pathways of CAM plant *Kalanchoe blossfeldiana* can be induced by short light period and long dark period, and plant pigments are involved in these processes[6-8]. Studies on *D. ekapol* showed that short light period increases net CO_2 absorption in dark period, while long light period increases net CO_2 absorption at early and end of light period[9]. The photosynthetic pathway and CO_2 uptake of *Doritaenopsis* Queen Beer "Mantefon" can also be affected by light/dark cycle[10]. *D. officinale* as a facultative CAM plant usually has a photosynthetic pathway of coexistence of C3 and CAM under natural conditions[1,11]. Its photosynthetic pathway can be induced into an obligate C3 pathway in 4 h/4 h short light/dark cycle, and its daily net CO_2 exchange amount increases compared with in 12 h/12 h light/dark cycle[11,12]. However, it deserves further study whether short light/dark cycles can significantly promote the growth and development of *D. officinale* in a long-term cultivation.

Artificial cultivation of *D. officinale* is mainly imitating wild cultivation and substrate cultivation in shaded greenhouses. As an advanced soilless cultivation technique, aeroponic cultivation has been applied to many horticultural crops including lettuce, tomato, cucumber, chrysanthemum, and poinsettia[13-16]. Compared with substrate cultivation, aeroponic cultivation can significantly increase the growth rate and soluble polysaccharide content of *D. officinale*[17,18]. Therefore, the aim of this study was to investigate the effects of short light/dark cycles on photosynthetic pathway switching and growth as well as soluble polysaccharides accumulation of *D. officinale* in aeroponic cultivation.

2 Materials and methods

2.1 Experimental materials and cultivation conditions

The high buds of *D. officinale* were domesticated and cultivated in the plant factory laboratory of China Agricultural University in Beijing for 2 years before using as experimental materials. Two hundred *D. officinale* seedlings with uniform size

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were selected. The base of stem was clamped with sponge and planted in a cultivation tank (1200 mm×900 mm×120 mm). There were 117 holes in the cultivation panel. One seedling was planted in each hole. Nutrient solution was sprayed to the roots one time per hour and 10 seconds for each time. The formula of nutrient solution for aeroponic cultivation was followed by Cheng et al.[12] EC and pH of the nutrient solution were controlled at 0.6-0.7 ms/cm and 6.0-6.5, respectively.

The environmental conditions of the plant factory laboratory were controlled as follows. Artificial light source was LED lamp with red to blue light ration of 1.2 (WR-LED-16W, Beijing Lighting Valley Technology Co., Ltd., China). Photosynthetic photon flux density (PPFD) at the plant canopy was about 150 μmol/m^2·s. Temperatures during the light and dark periods were 26°C±1°C and 22°C±1°C, respectively. Relative humidity was 65%±5% and mean of CO_2 concentration was 670±30 μmol/mol.

2.2 Treatment design

Three light/dark cycles were set up in 12 h/12 h, 4 h/4 h, and 2 h/2 h, respectively. There were 20 seedlings of *D. officinale* in each light/dark cycle treatment. After 150 d of treatment, chlorophyll fluorescence parameters, net CO_2 exchange characteristics, plant morphological characteristics, biomass, and soluble polysaccharide content of *D. officinale* were measured under 12 h/12 h, 4 h/4 h, and 2 h/2 h light/dark cycles, respectively.

2.3 Measurement indexes and methods

2.3.1 Chlorophyll fluorescence measurement of *D. officinale* leaves

A multi-function plant efficiency analyzer (M-PEA, Hansatech Inc., UK) was used to measure the O-J-I-P transients of the third fully expanded leaves from top of healthy plants. Maximum quantum yield for primary photochemistry (Fv/Fm), performance index (PI_{ABS}) based on absorption energy, energy absorbed by active PSⅡ reaction center (ABS/RC), and the open degree of active reaction center (ψ_o) at 2 ms were obtained by OJIP-Test. The measuring light intensity was set to 5000 μmol/m^2·s, the illumination time is set to 2 s, and the light quality is 100% of the saturated pulsed red light. Following were the measurement times for the different dark/light cycle treatments: 1:00, 3:00, 5:00, 7:00, 21:00 for 12 h/12 h; 5:00, 7:00, 13:00, 15:00, 21:00, 23:00 for 4 h/4 h; and 3:00, 7:00, 11:00, 15:00, 19:00, 23:00 for 2 h/2 h. Six plants were measured at each time in each light/dark cycle treatment.

2.3.2 Continuous measurement of net CO_2 exchange rate

The photosynthetic continuous measurement system[11] used in this study consists of four cuvettes (L25 cm×W15 cm×H6 cm), a host computer, and an IRGA CO_2 analyzer (LI-7000, LICOR, Lincoln, USA). Before the measurement, pure N_2 gas and CO_2 standard gas with the concentration of 600 μmol/mol were used to calibrate the infrared ray gas analyzer (IRGA). Then the functional leaves of living plant samples were clamped into the leaf chamber, and the leaves were kept flat, then the leaf chamber was fastened.

The inlet air source of the leaf chamber was the air outside the plant factory laboratory (the average CO_2 concentration was 370 μmol/mol). The volume of buffer bottle was 20 L and the inlet air flow rate of the leaf chamber was 1 L/min. The temperature tracking mode was used to ensure that the temperature of the leaf chamber and was consistent in the plant factory laboratory. The CO_2 concentration difference of reference air and samples of each leaf chamber were recorded once every 10 min. The leaf area of each leaf chamber was measured by referring to Yang et al.[19] Then the net exchange rate of CO_2 was calculated according to the difference of CO_2 concentration between reference gas and sample gas and leaf area. The measurement method was referred to Zhang et al.[11] Dark net CO_2 exchange amount, light net CO_2 exchange amount, and daily net CO_2 exchange amount were calculated by integral method. Dark net CO_2 exchange percentage = dark net CO_2 exchange amount / daily net CO_2 exchange amount × 100%. Three replicates were conducted in this measurement for each light/dark cycle.

2.3.3 Measurement of plant morphological characteristics and biomass

The morphological indexes measured included the increases of plant height, internodes number, stem diameter, leaf area, leaf number, and leaf thickness. In order to calculate the increases of parameters above, the measurements were conducted at the beginning of the experiment and after 150 d, respectively. Plant leaf area was calculated by the ratio of leaf image obtained by scanner to the black square of 1 cm^2. The number of leaves was determined by the number of fully unfolded leaves. The blade thickness was obtained by measuring the transverse section of the blade with an optical microscope (BX51, Olympus Co., Japan). The plant height was measured from the connection of stem and root to growing point. The length of internodes longer than 0.5 cm was counted. The biomass indexes measured included total, stem, leaf, and root dry and fresh weight increases. Six plants were measured for each light/dark cycle treatment.

2.3.4 Measurement of soluble polysaccharide content

After 150 d, the stems of *D. officinale* were dried in an oven at 50°C, then crushed and screened by 40 meshes. The soluble polysaccharides content of *D. officinale* was measured by phenol-sulfuric acid method referenced by Li and Hirata[20]. Six plants were measured for each light/dark cycle.

2.4 Statistical analysis

SPSS 21 (IBM, Inc., Armonk, NY, USA) was used for statistical analysis. The variance analysis of the data was performed by Duncan method at the 0.05 significance level. Univariate analysis of variance (ANOVA) was used to test the difference of data mean.

3 Results and discussion

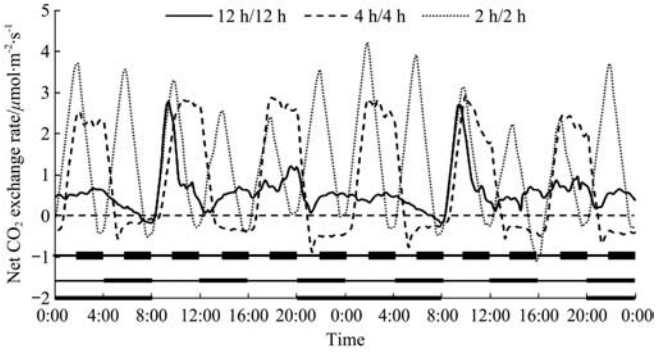
3.1 Effects of short light/dark cycles on photosynthetic electron transfer characteristics and photosynthetic pathway switching of *D. officinale* leaves

The F_v/F_m of all leaves grown in different light/dark cycles could recover to above 0.8 in dark period (Table 1), indicating that the photosynthetic organs of leaves were not damaged significantly[21]. The PI_{ABS} of *D. officinale* leaves under 2 h/2 h cycle was higher than that under 4 h/4 h light/dark cycle and much higher than that under 12 h/12 h. PI_{ABS} is a more sensitive indicator than F_v/F_m. PI_{ABS} synthesized a single multi-parameter expression through three main functional steps of photosynthetic activity (light energy absorption, excitation energy capture and excitation energy conversion to electron transfer) through the PSII reaction center complex[22,23]. With the shortening of light/dark cycle, PI_{ABS} increased gradually, which might be related to the increase of open degree of active reaction center (ψ_o) at 2 ms. There was no significant difference in the light energy absorbed by each active PSⅡ reaction center (ABS/RC) in *D. officinale* leaves under different light/dark cycles.

Table 1 Leaf chlorophyll fluorescence parameters of *D. officinale* under different short light/dark cycles

Light/dark cycle	Fv/Fm	PI_{ABS}	ABS/RC	ψ_o
12 h/12 h	0.82±0.01 NS	4.38±0.68 c	1.30±0.07 NS	0.57±0.05 b
4 h/4 h	0.82±0.01 NS	5.41±0.57 b	1.21±0.10 NS	0.58±0.05 b
2 h/2 h	0.82±0.01 NS	7.51±0.57 a	1.22±0.05 NS	0.66±0.02 a

Net CO_2 exchange rate of *D. officinale* showed a multi-phase change of CAM pathway when the light/dark cycle was 12 h/12 h. When the light/dark cycle was shortened to 4 h/4 h or 2 h/2 h, net CO_2 exchange rate of *D. officinale* showed a C3 pathway pattern, i.e. net absorption of CO_2 in light period and net release of CO_2 in dark period (Figure 1). The result is consistent with that of Zhang et al.[11]



Note: The thin black line on the horizontal axis indicates light period, and the thick black line indicates dark period.

Figure 1 Net CO_2 exchange rate of *D. officinale* under different light/dark cycles

Contrary to 12 h/12 h light/dark cycle, dark net CO_2 exchange amount and dark net CO_2 exchange percentage of *D. officinale* in short light/dark cycles of 4 h/4 h and 2 h/2 h were negative, and light net CO_2 exchange amount and daily net CO_2 exchange amount were higher (Table 2). This indicated that photosynthetic pathway of *D. officinale* could be switched to C3 by the short light/dark cycles. The higher daily net CO_2 exchange amounts during short light/dark cycles were mainly due to the higher light net CO_2 exchange amounts. The higher light net CO_2 exchange amounts during short light/dark cycles might be related to stomatal movement, leaf thickness, and leaf anatomical structure. This was due to the fact that the short light/dark cycles could induce the higher stomatal conductances of *D. officinale* in light period[12]. Structure features of leaf might affect CO_2 concentration in chloroplast stroma[24], thus affecting the photosynthetic capacity of *D. officinale*. Whatever it was, the photosynthetic pathway of *D. officinale* could be switched to C3 pathway, and the daily net CO_2 exchange amount could be increased by the short light/dark cycles.

Table 2 Net CO_2 exchange characteristics of *D. offficinale* under different light/dark cycles

Light/ dark cycle	Light net CO_2 exchange amount /mmol·m^{-2}·d^{-1}	Dark net CO_2 exchange amount /mmol·m^{-2}·d^{-1}	Daily net CO_2 exchange amount /mmol·m^{-2}·d^{-1}	Dark net CO_2 exchange percentage /%
12 h/12 h	50.5±2.1 b	9.2 ±1.6a	59.7±0.4b	15.4±2.8a
4 h/4 h	87.9±5.4 a	-11.8±1.0b	76.1±6.4a	–15.6±2.6b
2 h/2 h	96.6±5.5a	-13.5±3.9b	83.1±1.6a	–16.1±4.3b

3.2 Effects of short light/dark cycles on morphogenesis of *D. officinale*

After 150 d, the plant heights of *D. officinale* treated with 4 h/4 h and 2 h/2 h short light/dark cycles were significantly higher than that treated with 12 h/12 h light/dark cycle. The colors of stem and leaf were obviously red under 2 h/2 h shorter light/dark cycle (Figure 2). Compared with 12 h/12 h light/dark cycle, *D. officinale* plants treated with 4 h/4 h and 2 h/2 h short light/dark cycles had thinner and more leaves, larger leaf area, more internodes, larger plant height, and thicker stems (Table 3).

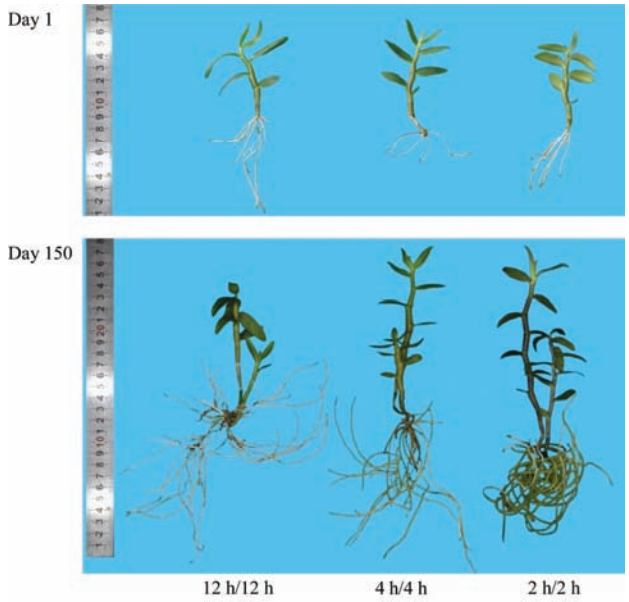


Figure 2 Morphological pictures of *D. officinale* under different light/dark cycles

Table 3 Morphological characteristics of *D. officinale* under different light/dark cycles

Light/dark cycle	Plant height increase /cm	Increase of internodes number	Stem diameter /mm	Leaf area increase /cm²	Leaf number increase	Leaf thickness /mm
12 h/12 h	10.2±0.5 b	8.0±1.4 b	5.3±0.8 b	4.7±2.1 b	3.3±0.6 b	0.43±0.01 a
4 h/4 h	19.4±4.4 a	16.0±3.6 a	6.2±0.3 a	15.2±4.4 a	6.3±0.6 a	0.41±0.01 b
2 h/2 h	15.7±1.4 a	10.5±1.3 b	5.7±0.3 ab	16.5±3.4 a	6.5±0.6 a	0.41±0.01 b

Anthocyanins were accumulated on the back of the leaves of *D. officinale* under 2 h/2 h shorter light/dark cycle, but not with plants under 12 h/12 h and 4 h/4 h light/dark cycles (Figure 3). The biosynthesis of anthocyanins was related to cryptochrome as a blue light receptor[25]. The light-activated cryptochrome could remain in the dark for a period of time[26], which might be the reason for the high accumulation of anthocyanins in *D. officinale* treated with 2 h/2 h shorter light/dark cycle.

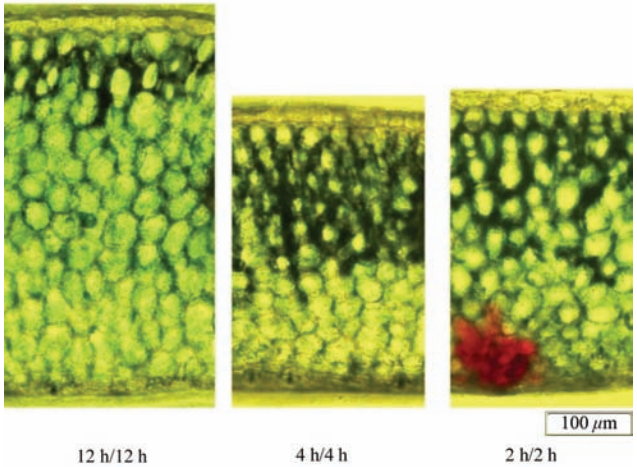
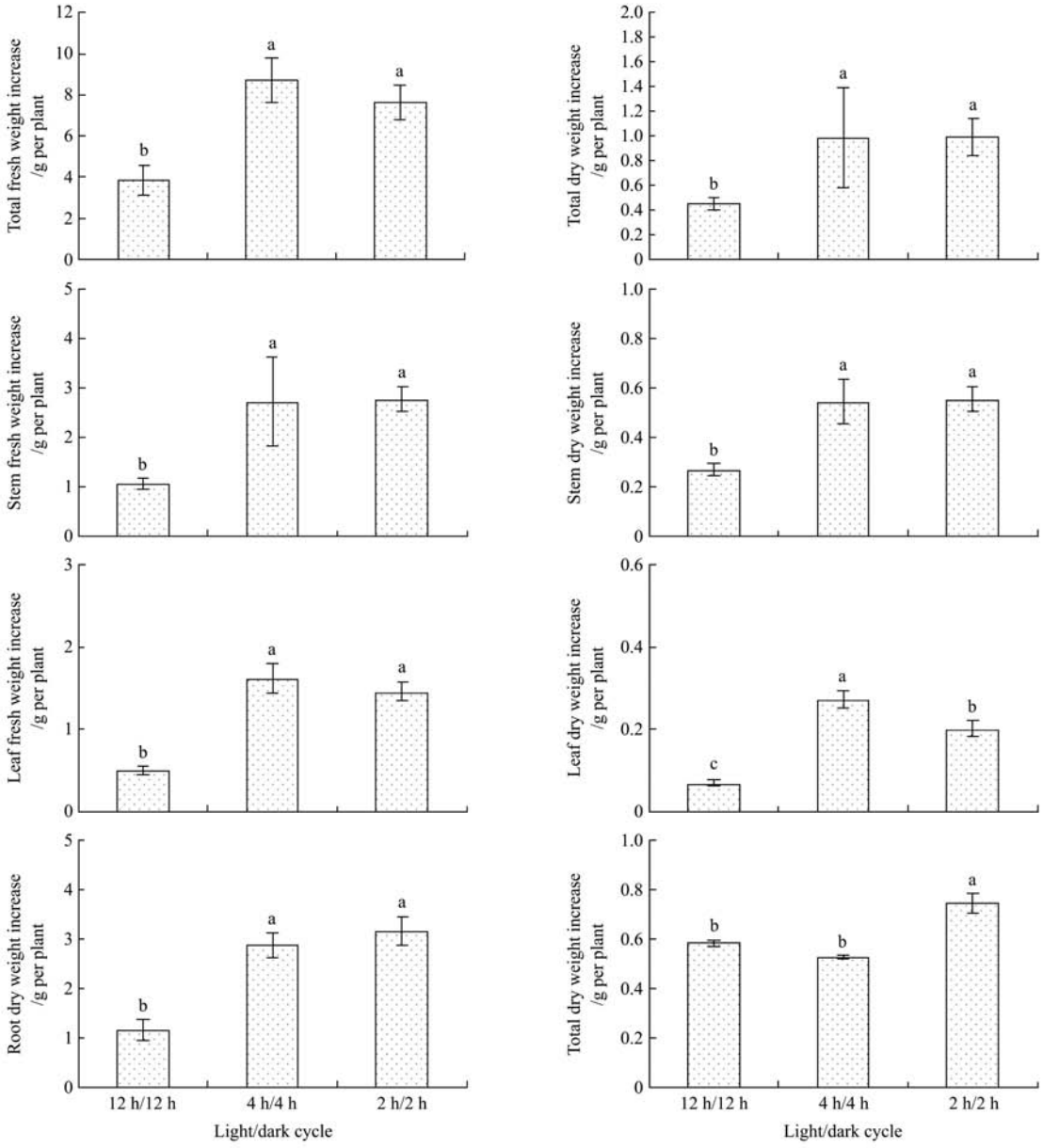


Figure 3 Leaf cross sectional anatomies of *D. officinale* under different light/dark cycles

3.3 Effects of short light/dark cycles on biomass and soluble polysaccharide accumulations of *D. officinale*

The increases of total fresh weight, total dry weight, stem fresh weight, stem dry weight, leaf fresh weight, leaf dry weight, and root fresh weight of *D. officinale* treated with short light/dark cycles of 4 h/4 h and 2 h/2 h were significantly higher than those treated with 12 h/12 h light/dark cycle. The increase of root dry weight in 2 h/2 h shorter light/dark cycle was significantly higher than that in 12 h/12 h and 4 h/4 h light/dark cycles (Figure 4). The effects of short light/dark cycles of 4 h/4 h and 2 h/2 h on the long-term biomass accumulation of *D. officinale* were consistent with their effects on the short-term daily net CO_2 exchange amount of *D. officinale*.

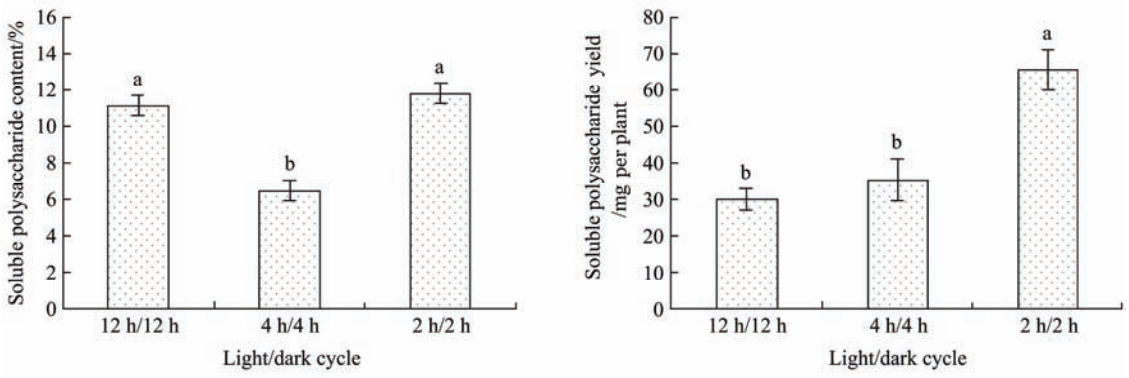


Note: Different growth parameters were recorded at day 1 and day 150, respectively. Different letters indicate statistically significant differences by Duncan's multiple range test (p<0.05).

Figure 4 Biomass accumulation of *D. officinale* under different short light/dark cycles

Compared with 12 h/12 h light/dark cycle, the soluble polysaccharides content of *D. officinale* treated with 4 h/4 h short light/dark cycle decreased significantly. When the light/dark cycle was shortened to 2 h/2 h, the soluble polysaccharides content increased to the level of 12 h/12 h light/dark cycle (Figure 5). The soluble polysaccharides yield of *D. officinale* treated with 2 h/2 h shorter light/dark cycle was significantly higher than that treated with 12 h/12 h and 4 h/4 h light/dark cycles. Studies had shown that light intensity and light quality affected the accumulation of soluble polysaccharides in *D. officinale*, while the accumulation of soluble polysaccharides was positively correlated with environmental stresses[27,28]. The soluble polysaccharides content of *D. officinale* treated with 2 h/2 h shorter light/dark cycle was significantly higher than that treated with 4 h/4 h and 12 h/12 h short light/dark cycles, which might be related to the responses of plants to a sudden induction of light environment stress. Soluble polysaccharides play a role by plants in protecting plants from abiotic stresses[29]. The accumulation of anthocyanins also proved that the shorter light/dark cycle of 2 h/2 h might cause some photopreoction of *D. officinale* against a sudden change of light. The results of Lin and Lai[28] also showed that the soluble sugar polysaccharide content in *D. officinale* was positively correlated

with the activity of PEPC, while the expression of CAM photosynthetic pathway was closely correlated with the activity of PEPC[30]. It explained why the soluble polysaccharides content in *D. officinale* treated with 4 h/4 h short light/dark cycle was significantly lower than that treated with 12 h/12 h light/dark cycle. While it could not explain why the *D. officinale* treated with a 2 h/2 h light/dark cycle had higher soluble polysaccharides content than that treated with 12 h/12 h light/dark cycle.



Note: % represents g per 100 g. Different letters indicate statistically significant differences by Duncan's multiple range test (p<0.05).

Figure 5 Soluble polysaccharides content and yield of *D. officinale* under different short light/dark cycles

4 Conclusions

Based on photosynthetic electron transfer characteristics, photosynthetic pathways, biomass and soluble polysaccharides accumulation of *D. officinale* plants grown aeroponically under three light/dark cycles for 150 d, we concluded that photosynthetic efficiency of *D. officinale* under 4 h/4 h and 2 h/2 h short light/dark cycles was better than that under 12 h/12 h light/dark cycle because of the photosynthetic pathway switching from CAM to C3. The results also demonstrated that under 4 h/4 h and 2 h/2 h short light/dark cycles, *D. officinale* plants had great increases in daily net CO_2 exchange amount, and fresh/dry weights compared with those in 12 h/12 h light/dark cycle. The soluble polysaccharides yield of *D. officinale* in the 2 h/2 h light/dark cycle was higher than that in 12 h/12 h light/dark cycle. Therefore, shorter light/dark cycles of 2 h/2 h is recommended for light environment adjustment of *D. officinale* for achieving the growth and quality control by keep the higher soluble polysaccharides content and yield.

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[References]

[1] Su W, Zhang G. The photosynthesis pathway in leaves of *Dendrobium officinale*. Acta Phytoecologica Sinica, 2003; 27(5): 631–637.

[2] Borland A M, Griffiths H, Broadmeadow M S J, Fordham M C, Maxwell C. Short-term changes in carbon-isotope discrimination in the C3-CAM intermediate *Clusia minor* L. growing in Trinidad. Oecologia, 1993; 95(3): 444–453.

[3] Osmond C B. Crassulacean acid metabolism - curiosity in context. Annual Review of Plant Physiology and Plant Molecular Biology, 1978; 29: 379–414.

[4] Cockburn W, Ting I P. Relationships between stomatal behavior and internal carbon dioxide concentration in crassulacean acid metabolism plants. Plant Physiology, 1979; 63(6): 1029–1032.

[5] Winter K, Smith J A C. Crassulacean acid metabolism: biochemistry, ecophysiology, and evolution. Berlin: Springer-Verlag, 1996; pp.406–416.

[6] Gregory F G, Thimann K V. The interrelation between CO_2 metabolism and photoperiodism in *Kalanchoë*. Plant Physiology, 1954; 29: 414.

[7] Queiroz O, Morel C. Photoperiodism and enzyme activity. Plant Physiolology, 1974; 4: 596–602.

[8] Wilkins M B. An endogenous rhythm in the rate of carbon dioxide output of Bryophyllum. IV. Effect of intensity of illumination on entrainment of the rhythm by cycles of light & darkness. Plant Physiology, 1962; 37: 735–741.

[9] Sekizuka F, Nose A, Kavamitsu Y, Murayama S, Arisumi K I. Effects of day length on gas exchange characteristics in the crassulacean acid metabolism plant *Dendrobium ekapol* cv. Panda. Japanese Journal of Crop Science, 1995; 64: 201–208.

[10] Kim H J, Ju H L, Lee H B, An S K, Kim K S. CO_2 uptake behavior and vegetative growth of *Doritaenopsis* Queen Beer 'Mantefon' orchids as influenced by light/dark cycle manipulation. Flower Research Journal, 2017; 25: 253–261.

[11] Zhang Z, He D, Niu G, Gao R. Concomitant CAM and C3 photosynthetic pathways in *Dendrobium officinale* plants. Journal of the American Society for Horticultural Science, 2014; 139(3): 290–298.

[12] Cheng Y, He D, He J, Niu G, Gao R. Effect of light/dark cycle on photosynthetic pathway switching and CO_2 absorption in two *Dendrobium* species. Frontiers in Plant Science, 2019; 10: 659. doi: 10.3389/fpls.2019.00659

[13] He J, Lee S K. Growth and photosynthetic responses of three aeroponically grown lettuce cultivars (*Lactuca sativa* L.) to different rootzone temperatures and growth irradiances under tropical aerial conditions. Journal of Pomology & Horticultural Science, 2015; 73(2): 173–180.

[14] Biddinger E J, Liu C, Joly R J, Raghothama K G. Physiological and molecular responses of aeroponically grown tomato plants to phosphorus deficiency. Journal of the American Society for Horticultural Science, 1998; 123(2): 330–333.

[15] Molitor H D, Fischer M, Popadopoulos A P. Effect of several parameters on the growth of chrysanthemum stock plants in aeroponics. Acta Horticulturae, 1999; 481: 179–186.

[16] Scoggins H L, Mills H A. Poinsettia growth, tissue nutrient concentration, and nutrient uptake as influenced by nitrogen form and stage of growth. Journal of Plant Nutrition, 1998; 21(1): 191–198.

[17] Dai G. Aeroponic cultivation method of *Dendrobium officinale*. Chinese patent, CN102972269A, 2013-03-20. (in Chinese)

[18] Huang Q. A method of aeroponic cultivation of *Dendrobium officinale*. Chinese Patent, CN106376445A, 2017-02-08. (in Chinese)

[19] Yang J, Chen C, Han X, Li X, Liebig H P. Measurement of vegetable leaf area using digital image processing techniques. Transactions of the CSAE, 2002; 18(4): 155–158

[20] Li M, Xu G, Hirata Y, Niwa M. Quantitative analysis of polysaccharides in Chinese Grug "Shihu" (*Dendrobium*). Chinese Herbal Medicines, 1990; 10: 10–12.

[21] Bjorkman D, Demmnig B. Comparison of the effect of excessive light on

chlorophyll florescence (77K) and photon yield of O_2 evolution in leaves of higher-plants. Planta, 1987; 171(2): 171–184.

[22] Appenroth K J, Stöckel J, Srivastava A, Strasser R J. Multiple effects of chromate on the photosynthetic apparatus of *Spirodela polyrhiza* as probed by OJIP chlorophyll a fluorescence measurements. Environmental Pollution, 2001; 115(1): 49–64.

[23] Van Heerden P D R, Strasser R J, Krüger G H J. Reduction of dark chilling stress in N_2-fixing soybean by nitrate as indicated by chlorophyll a fluorescence kinetics. Physiologia Plantarum, 2004; 121: 239–249.

[24] Terashima I, Hanba Y T, Tholen D, Niinemets U. Leaf functional anatomy in relation to photosynthesis. Plant Physiology, 2001; 155: 108–116.

[25] Mancinelli A L, Rossi F, Moroni A. Chryptochrome, phytochrome, and anthocyanin production. Plant Physiology, 1991; 96: 1079–1085.

[26] Kurata H, Mochizuki A, Okuda N, Seki M, Furusaki S. Intermittent light irradiation with second- or hour-scale periods controls anthocyanin production by strawberry cells. Enzyme and Microbial Technology, 2000; 26: 621–629.

[27] Xu B, Cui Y, Guo C, Xia G. Dynamic variation of biomass and content of polysaccharide and alkaloid in protocorm like bodies from *Dendrobium officinale* at different light intensities and incubation time. Chinese Traditional and Herbal Drugs, 2012; 43(2): 355–359. (in Chinese)

[28] Lin X, Lai Z. Effects of light quality on expression of PEPC and polysaccharide accumulation in *Dendrobium officinale*. Chinese Journal of Tropical Crops, 2017; 5: 61–65. (in Chinese)

[29] Rolland F, Baena-Gonzalez E, Sheen J. Sugar sensing and signaling in plants: conserved and novel mechanisms. Annual Review of Plant Biology, 2006; 57: 675–709.

[30] Nimmo H G. The regulation of phosphoenolpyruvate carboxylase in CAM plants. Trends in Plant Science, 2000; 5(2): 75–80.