Controlling average number of photons received per cell to promote the growth of *Synechocystis* sp. PPC 6803

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Abstract

To investigate the actually received light of microalgae cells in the photobioreactor, a light attenuation model of *Synechocystis* sp. PCC 6803 was established. The relationship between the average number of photons received per cell (APRPC) and the growth of microalgae was analyzed. The results demonstrated, Cornet model was accurately fitted with the light attenuation of *Synechocystis* sp. PCC 6803 and the cell growth rate was affected by APRPC. A maximum specific growth rate of 0.05 h^{-1} was achieved with APRPC from 10^{-6} to $4 \times 10^{-6} \text{ } \mu\text{mol/cell}$. After 156 h cultivation, compared to two control groups (constant light intensity: 100 and $1800 \text{ } \mu\text{mol}/(\text{m}^2 \cdot \text{s})$), the dry cell weight of the experimental group was higher by 79.1% and 20.0%, respectively. This study indicated that APRAC could be used as a light intensity regulation criterion to improve microalgae production despite different types of reactor and density of microalgae broth, which provided a theoretical basis for improving the biomass yield of *Synechocystis* sp. PCC 6803 or other microalgae.

Introduction

The rapid development of the global economy has improved the quality of human life but caused serious environmental problems (Tang et al. 2021). In response to climate change and environmental problems, carbon neutrality has become the main theme of development (He 2022). *Synechocystis* sp. PCC 6803, as a photosynthetic autotrophic organism, has the advantages of a short growth cycle and high photosynthetic efficiency. It could synthesize a variety of beneficial substances by using CO_2 and solar energy (Velmurugan et al. 2021; Neag et al. 2019; Phachayaton et al. 2021) and it was also widely used in the field of genetic engineering (Rodrigues et al. 2021; Gao et al. 2020).

Since most photosynthetic autotrophs can only get energy for their metabolism through light, light is one of the most important factors for the growth of microalgae (Muramatsu et al. 2009). However, the unsuitable light intensity has adverse effects on the growth of microalgae (Kopečná et al. 2012), thus it is significantly important to study the effect of light intensity on the growth of microalgae. Some researchers reported the optimal incident light intensity when microalgae grow fastest (or produce the highest) in the shake flask (Jie et al. 2020; Weizhe et al. 2021; Wang et al. 2000), bubble column photobioreactor (PBR) (Hou et al. 2020; Wang et al. 2010), flat-plate PBR (Lijuan et al. 2019; Brendan et al. 2019) and fermentation tank (Xiaoqian et al. 2020). However, light attenuation was not taken into account in these studies, leading to great limitations in application to different culture systems. To exactly describe the relationship between light and microalgae growth, it is necessary to consider the light attenuation in microalgae broth.

At present, most scholars use Lambert-Beer model (Quentin et al. 2013) and Cornet model (Fernandez et al. 1997) to predict the light attenuation of microalgae. Huang et al. (2014) analyzed the light-dark cycle of *Chlorella* in the flat-plate PBRs with different inner structures based on the light-attenuation model, and determined the optimal inner structure of the PBR. Sheng et al. (2018) took the influence of pigment content on light attenuation into consideration in the mathematical model of light attenuation, and

studied the influence of volumetric average light intensity and mixing characteristics on the bubble column PBR with different tube diameters. Wang et al. (2020) experimentally determined the influence of average volume light intensity on *Galdieria sulphuraria* growth in 1 L and 15 L bubble column PBRs based on the light attenuation model, and finally scaled up the reactors based on the average volume light intensity. Xi et al. (2021) proposed a method to improve β -carotene production in *Dunaliella salina* by controlling APRPC. However, there are no reports on the optimization of the light conditions of *Synechocystis*.sp 6803 by using the APRPC as an indicator.

Given this, the effect of incident light intensity on the growth of *Synechocystis* sp. PCC 6803 was firstly studied in this paper. Then, the light attenuation in the *Synechocystis* sp. PCC 6803 was measured, and the light attenuation model was established. Then, the relationship between the APRPC and the growth rate of *Synechocystis* sp. PCC 6803 was established based on the light attenuation model. The cultivation effect of *Synechocystis* sp. PCC 6803 was investigated by controlling the APRPC. Finally, the best incident light intensity of different tube diameter bubble column PBR under specific microalgae density was obtained.

1. Materials And Methods

1.1 Microalgae species and pre-culture

Synechocystis sp. PCC 6803 was provided by Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences. Microalgae were cultivated for 10 days in a 500 mL shake flask. Optimized cultivation conditions were liquid volume at 200 mL, temperature at 30 °C, inoculation density at 0.6~0.9 g/L, light by LED at an intensity of 70 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, and shaker rotation speed at 150 r/min. BG11 medium was used (Hwang et al. 2017).

1.2 Experimental design

1.2.1 Influence of different external incident light intensity on microalgae growth

A comparison was conducted of microalgae growth under different light intensities in column PBRs. PBR was designed with the diameter of 0.06 m, the height of 0.39 m, and the liquid loading capacity of 0.6 L. The incident light intensity of 100, 150, 300 and 450 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ was controlled by adjusting the distance between column PBRs. The light source was provided by five LEDs (22 W) placed parallel to column PBRs. Inoculation density was 0.09 ± 0.001 g/L. The temperature was at approximately 34 ± 0.5 °C, and the aeration rate was at 0.2 vvm containing 5% CO₂. All experiments were carried out in triplicate and average values with standard deviation are reported.

1.2.2 Determination of light attenuation curve

The determination of light attenuation is based on the method of Sheng et al. (2020): A transparent glass tube was wrapped with opaque black paper around and at the bottom. The incident light source was

placed on the top of the glass tube to ensure that no light leaks out. A photometer was used to measure light intensity reaching the bottom of the glass tube. The light intensity measured without microalgae was as the incident light intensity ($319.2 \mu\text{mol}/(\text{m}^2\cdot\text{s})$). Then light intensity was determined under different microalgae concentrations and different microalgae heights in the glass tube. Before determination, the microalgae was stirred evenly with a glass rod to prevent the error caused by microalgae cell settlement. The light intensity of each group was measured three times and the average value was taken.

1.2.3 Verification experiment of the effect of the average number of photons received per cell on microalgae growth

The experiment was carried out in the 1 L column PBR. The incident light intensity of the two control groups was fixed at $100 \mu\text{mol}/(\text{m}^2\cdot\text{s})$ (low light intensity control group) and $1800 \mu\text{mol}/(\text{m}^2\cdot\text{s})$ (high light intensity control group), respectively. The initial light intensity of the experimental group was $100 \mu\text{mol}/(\text{m}^2\cdot\text{s})$. Then, to keep APRPC within the range of 10^{-6} to $4\times 10^{-6} \mu\text{mol}/\text{cell}$, the incident light intensity was adjusted every 12 hours. For other experimental setups see Section 1.2.1.

2 Analysis Methods

2.1 Dry cell weight

Dry cell weight (*DCW*) was determined according to the method of Ying et al. (2019): The dry weighing disk was firstly weighed as W_1 . Then 10 mL microalgae (V) was collected to be centrifuged at 8000 r/min for 10 minutes, washed with distilled water and centrifuged again, then dried in a 105°C oven (DHG-9145A thermoelectric constant temperature air blowing drying oven) for 6 h. Then, the weighing disk was cooled and weighed as W_2 . The dry cell weight was calculated as follows:

$$DCW = \frac{W_2 - W_1}{V} \times 1000 \quad (1)$$

2.2 Optical attenuation coefficient

In this study, Lambert-Beer model (2) and Cornet model (3) were used to fit the light attenuation curves by Origin 19.0.

$$I/I_0 = e^{(-L \cdot (K_a \cdot X + b))} \quad (2)$$

Where, I is the local light intensity ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$), I_0 is the incident light intensity ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$), L is the light path (m), K_a is the light absorption coefficient (m^2/g), X is the concentration of microalgae liquid (g/m^3), and b is the fitting constant (m^{-1}).

$$I/I_0 = \frac{4\alpha_1}{(1+\alpha_1)^2 \cdot e^{\alpha_2} - (1-\alpha_1)^2 \cdot e^{-\alpha_2}}$$

$$\alpha_1 = \sqrt{\frac{E_a}{E_a + E_s}} \quad (3)$$

$$\alpha_2 = (E_a + E_s) \cdot \alpha_1 \cdot X \cdot L$$

Where, E_a is the light absorption coefficient (m^2/g), E_s is the scattering coefficient (m^2/g), X is the concentration of microalgae (g/m^3), and L is the light path (m).

2.3 Volume average light intensity

The volume average light intensity can be calculated by the following formula (Huang et al. 2014).

$$I_{av} = \frac{1}{V} \int_0^V I \, dV \quad (4)$$

Where, I is the local light intensity in the reactor ($\mu\text{mol}/(\text{m}^2 \cdot \text{s})$), and V is the volume of the reactor (m^3). In this paper, the volume average light intensity in column photobioreactor is calculated by MATLAB 19.0a.

2.4 Average number of photons received per cell

The average number of photons received per cell (APRPC) refers to the calculation method proposed by Xi et al. (2021), and the formula is as follows:

$$\text{APRPC} = \frac{I_{av} \cdot A \cdot T \cdot 1000}{C \cdot V} \quad (5)$$

Where, I_{av} is the volume average light intensity ($\mu\text{mol}/(\text{m}^2 \cdot \text{s})$), T is the light duration (s), V is the volume of microalgae (L), A is the light area (m^2), and C is the concentration of microalgae cell (cell/L).

3 Results And Discussion

3.1 Effect of incident light intensity on the growth of *Synechocystis* sp. PCC 6803

The effect of incident light intensity on the growth of *Synechocystis* sp. PCC 6803 was investigated in the 1 L bubble column PBR, and the results were shown in Figure 1. After 24 h cultivation, the density of microalgae cells in the experimental groups with the light intensity of 100, 150 and 300 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ were 4.48×10^7 , 5.85×10^7 and 5.37×10^7 cell/mL respectively. However, the density of microalgae cells was only 1.8×10^7 cell/mL when the incident light intensity was 450 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$. These results indicated that

microalgae could grow rapidly even at the low incident light intensity when cell density was low. However, when the incident light intensity was too high, the growth of microalgae was photoinhibited. After 144 h cultivation, in this four experimental groups, the cell density increased with the incident light intensity. The density of microalgae cells in the experimental groups with the light intensity of 100, 150, 300 and 450 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ were 3.6×10^8 , 4.9×10^8 , 5.4×10^8 and 6.08×10^8 cell/mL respectively. It was because the light intensity became a limiting factor affecting microalgae's growth when cell density was high.

Then the specific growth rate of *Synechocystis* sp. PCC 6803 at different cultivation periods was calculated (Table 1). A max specific growth rate was observed in the experimental group with the light intensity of 100 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ and 150 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ at 0-24 h, while a max specific growth rate was observed in that of 300 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ and 450 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ at 24-48 h. The concentration of microalgae broth increased with cultivation time. It was suggested that the optimal incident light intensity varied with cell densities, thus the incident light intensity could not directly predict the microalgae growth as a result of the increased light attenuation during the cultivation stage. Therefore, the light attenuation of *Synechocystis* sp. PCC 6803 was necessary to be investigated.

3.2 Light attenuation of *Synechocystis* sp. PCC 6803

In this section, the light attenuation of *Synechocystis* sp. PCC 6803 was determined under different concentrations of microalgae and light path, and the results were shown in Figure 2. The local light intensity decreased with the increase of the light path. Taking the data of dry cell weight 0.2 g/L as an example, when the light path was 0.02 m, the local light intensity was 104.9 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which was decreased by 67.11%. When the light path increased to 0.04 m, the local light intensity decreased to 52.8 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, with an attenuation of 83.43%. It indicated that the longer the light path along the illumination direction, the more severe the light attenuation. At the same time, the local light intensity also decayed with the increase of microalgae density. Taking the data of the light path is 0.01 m as an example, when the concentration was 0.2 g/L, the local light intensity was 173.5 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which decayed by 45.64% of the incident light intensity. When the concentration increased to 1.6 g/L, the local light intensity decreased to 13.2 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, decreasing by 95.86%. It indicated that the higher the density of microalgae, the more severe the light attenuation. Subsequently, the light attenuation of *Synechocystis* sp. PCC 6803 was fitted with Lambert-Beer model and Cornet model, respectively.

Figure 3 showed the curves fitted with Lambert-Beer model(a) and Cornet model(b), respectively. The fitting parameters of Lambert-Beer model were as follows: $K_a=0.229\pm 0.011$ $b=5.247\pm 0.294$, $R^2=0.997$. The fitting parameters of Cornet model were as follows: $E_a=0.205\pm 0.012$, $E_s=0.161\pm 0.005$, $R^2=0.999$. It can be seen from Figure 4 that the predicted values of Cornet model were closer to the determined values, which indicated Cornet model could better predict the light attenuation. This was because only the light absorption was considered but the scattering of microalgae cells was ignored in Lambert-Beer model. In the case of a high concentration of microalgae fluid, the influence of scattering increased, and the predicted value gradually deviated from the determined one. The Cornet model took both light absorption

and scattering into account, so the model predicted value was more consistent with the determined one. The determined value can be well matched even in the case of a large variation of microalgae concentration, which was similar to the study of Li et al.(2021). Therefore, the Cornet light attenuation model was used to calculate APRPC.

3.3 Effect of the average number of photons received per cell on the growth rate of *Synechocystis* sp. PCC 6803

Cornet light attenuation model was used in the formula (4) to calculate the volume average light intensity. Then according to the formula (5), APRPC at nearly 24 hours of the above four groups at different incident light intensity was calculated, and specific data was shown in Table 2. APRPC decreased continuously with the increase of cultivation time under certain incident light intensity, which was caused by the increase of the microalgae cell number and the gradually intensified light attenuation in the PBR.

The data in Table 2 were plotted with the cell specific growth rate (μ) in the corresponding time, and a good linear relationship was found between them, as shown in Figure 4. When APRPC was lower than 10^{-6} $\mu\text{mol}/\text{cell}$, the specific growth rate of *Synechocystis* sp. PCC 6803 increased with APRPC. When APRPC was in the range of 10^{-6} $\mu\text{mol}/\text{cell}$ to 4×10^{-6} $\mu\text{mol}/\text{cell}$, the specific growth rate of *Synechocystis* sp. PCC 6803 reached a peak of about 0.05 h^{-1} . When APRPC exceeded 4×10^{-6} $\mu\text{mol}/\text{cell}$, the specific growth rate of *Synechocystis* sp. PCC 6803 decreased gradually. Therefore, APRPC can be used as an indicator related to microalgae growth in the cultivation of *Synechocystis* sp. PCC 6803, and the maximum specific growth rate of microalgae can be maintained by controlling APRPC in the range of 10^{-6} to 4×10^{-6} $\mu\text{mol}/\text{cell}$ in the cultivation process. For indoor culture, appropriate APRPC can be controlled by changing the incident light intensity during the cultivation process to maintain the high specific growth rate of microalgae cells and ultimately improve the yield of *Synechocystis* sp. PCC 6803. Besides, APRPC could be kept at 10^{-6} $\mu\text{mol}/\text{cell}$ to maintain the highest specific growth rate of microalgae with minimum light energy consumption. For outdoor conditions, although the external solar radiation source can not be controlled, maintaining the optimal APRPC by shading (supplementary light) or regulating the density of microalgae cells can also promote the growth of microalgae cells.

3.4 Verification of the effect of APRPC on the growth of *Synechocystis* sp. PCC 6803

According to the conclusion in Section 3.3, the optimal APRPC of microalgae was ranged from 10^{-6} to 4×10^{-6} $\mu\text{mol}/\text{cell}$. Light intensity regulation experiments were carried out in the laboratory to verify the reliability of this method. In the experimental group, the incident light intensity was constantly adjusted within the range of 10^{-6} to 4×10^{-6} $\mu\text{mol}/\text{cell}$ every 12 h in the first 72 h, and remained unchanged after the incident light intensity was adjusted to $1800 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ (the regulation process is shown in Figure 5). The two control groups were fixed with 100 and $1800 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ light intensity, respectively. Figure 6 showed the dry cell weight and APRPC of three experimental groups. As can be seen from the figure, APRPC of the low light intensity control group and the experimental group were in the range of 10^{-6} to

4×10^{-6} $\mu\text{mol}/\text{cell}$ from 0 to 24 h, so roughly the same dry cell weight was observed in the beginning 24 h; while APRPC of the high light intensity control group was more than 4×10^{-6} $\mu\text{mol}/\text{cell}$, a growth inhibition was observed. Therefore, the dry cell weight in the high light intensity control group was lower than the other two groups. According to this phenomenon, the external incident light intensity could be adjusted to avoid the growth retardation of microalgae caused by light inhibition when the concentration of microalgae was low. From 24 to 60 h, APRPC of the experimental group was maintained at about 10^{-6} $\mu\text{mol}/\text{cell}$, while ACRPC of the low light intensity control group was gradually lower than 10^{-6} $\mu\text{mol}/\text{cell}$, so the dry cell weight of the experimental group gradually exceeded that of the low light intensity control group. From 60 to 84 h, APRPC of the high light intensity control group also reached within the range of 10^{-6} to 4×10^{-6} $\mu\text{mol}/\text{cell}$, leading an increase in specific growth rate, and the dry cell weight gradually exceeded the low light intensity control group.

In terms of microalgae production, after 156 h cultivation, the dry cell weight of the experimental group reached 1.55 g/L, 79.1 % higher than the low light intensity control group under the same culture time, and 20.0 % higher than the high light intensity control group. Before this, Zhang et al. (2010) also cultivated *Synechocystis* sp. PCC 6803 in a column PBR with a tube diameter of 70 mm and fixed external light intensity at 108 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$. After 144 h, the biomass reached 1.35 g/L and the microalgae yield was 8.96 mg/(L·h). In this study, the yield of the experimental group reached 10.35mg/(L·h) within 144 h, which was 15.5 % higher than Zhang's research. Hence, adjusting light intensity by controlling appropriate APRPC was an effective method to improve the yield of *Synechocystis* sp. PCC 6803.

3.5 Optimization of incident light intensity of column PBR with different tube diameters based on APRPC

According to the above analysis, the specific growth rate of microalgae reached the peak when the APRPC was within the range of 10^{-6} to 4×10^{-6} $\mu\text{mol}/\text{cell}$. When microalgae were cultivated, the yield of microalgae could be increased by adjusting the external light intensity according to APRPC. Considering the different types and sizes of the PBRs used for microalgae cultivation, the external incident light intensity of the column PBRs with tube diameters of 40, 60, 80, 100 and 120 mm was optimized in this section under specific microalgae concentration, and the final results were shown in Table 3. Under the same tube diameter, the optimal incident light intensity increased gradually with the increase of microalgae concentration to achieve the maximum specific growth rate. For example, when the tube diameter was 40 mm, the optimal incident light intensity was from 32.1 to 108.3 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ when the dry cell weight was 0.1 g/L. When the density of microalgae liquid reached 1.0 g/L, the optimal light intensity increased to the range from 454.4 to 1817.7 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$. Under the same dry cell weight, the larger the tube diameter, the higher the optimal incident light intensity, which was especially obvious at a high dry cell weight. Taking the dry cell weight of 1.0 g/L as an example, when the tube diameter was 40 mm, the optimal incident light intensity was from 454.4 to 1817.7 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$. When the tube diameter was 120 mm, the optimum light intensity was rapidly increased to the range from 12,426.4 to 49705.8 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$. Therefore, the PBR with a smaller tube diameter can be selected to obtain a high specific growth rate in indoor cultivation. In outdoor conditions where light intensity was up to 2000 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$,

the solar radiation intensity will be much higher than the optimal incident light even if the large PBR diameter at low dry cell weight, so a higher cell density and necessary shading should be adopted. Unfortunately, light limitation occurred with the increasing dry cell weight, thus adequate dilution was necessary to be adopted according to dry cell weight and PBR diameters.

4 Conclusion

In this study, the light attenuation curve of *Synechocystis* sp. PCC 6803 was obtained based on Cornet model. APRPC of *Synechocystis* sp. PCC 6803 was calculated accordingly, and the relationship between APRPC and specific growth rate of *Synechocystis* sp. PCC 6803 was obtained. The results showed that when APRPC was in the range of 10^{-6} to 4×10^{-6} $\mu\text{mol}/\text{cell}$, the specific growth rate of *Synechocystis* sp. PCC 6803 reached a peak. Subsequently, it was verified by indoor culture experiments that keeping the optimal APRPC in the culture process was an effective way to improve microalgae production. The light intensity regulation method based on APRPC has universal applicability to different reactors, different inoculation densities and different external light intensities, which can effectively improve the yield of *Synechocystis* sp. PCC 6803, and also provides a theoretical basis for improving the yield of other microalgae.

Declarations

Conflict of interest

The authors have not disclosed any competing interests.

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Tables

Table 1 Growth rates of *Synechocystis* sp. PCC 6803 at different cultivation periods

Cultivation periods (h)	Specific growth rate (h^{-1})			
	100 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$	150 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$	300 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$	450 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$
0-24	0.049	0.052	0.050	0.010
24-48	0.036	0.035	0.052	0.040
48-144	0.012	0.014	0.012	0.027

Table 2 Average number of photons received per cell in different cultivation periods

APRPC ($\mu\text{mol}/\text{cell}$)				
Time $\times$ h	100 ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$)	150 ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$)	300 ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$)	450 ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$)
0-24	1.78E-06	2.02E-06	3.57E-06	1.17E-05
24-48	5.20E-07	5.26E-07	6.33E-07	6.71E-06
48-72	1.86E-07	1.70E-07	1.93E-07	1.38E-06
72-96	9.20E-08	7.55E-08	8.77E-08	2.77E-07
96-120	6.13E-08	4.40E-08	5.91E-08	1.06E-07
120-144	4.39E-08	3.07E-08	4.33E-08	5.94E-08
144-168	3.40E-08	2.51E-08	3.61E-08	4.89E-08

APRPC: average number of photons received per cell.

Table 3. Optimal incident light intensity range of column reactors with different diameters under different microalgae cell densities

DCW (g/L)	Optimal incident light intensity range ($\mu\text{mol}/(\text{m}^2\cdot\text{s})$)				
	Diameter (mm)				
	40	60	80	100	120
0.1	32.1-108.3	52.2-208.9	83.3-333.4	106.4-425.5	129.1-516.5
0.2	70.6-282.3	151.7-614.9	308.4-1233.8	418.1-1672.3	518.2-2072.7
0.5	204.8-819.2	796.2-3184.9	2081.1-8324.5	2641.8-10567.2	3146.8-12599.0
0.8	352.6-1410.2	1987.7-7950.7	5341.4-21365.7	6554.5-26617.8	7962.0-31847.9
1.0	454.4-1817.7	2473.8-9895.5	8312.2-33248.9	10363.0-41451.9	12426.4-49705.8

Figures

Figure 1

Growth of *Synechocystis* sp. PCC 6803 under different incident light intensities in the column PBR. Data shown as mean $\pm$ standard deviation, n = 3.

Figure 2

Light attenuation curve of *Synechocystis* sp. PCC 6803. Data shown as mean $\pm$ standard deviation, n = 3.

Figure 3

Fitting of light attenuation curve by Lambert-Beer model (a) and Cornet model (b). Lines are simulation results and points are experimental measurements.

Figure 5

Regulation process of incident light in the experimental group

Figure 6

Changes of dry cell weight (a) and APRPC (b) in the validation experiment. Data shown as mean $\pm$ standard deviation, $n = 3$.