

Article

Laser and LED Hybrid Plant Lighting System Design Based on the Particle Swarm Algorithm

Yongping Huang  and Jianshe Ma *

Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China;
hyp18@mails.tsinghua.edu.cn

* Correspondence: ma.jianshe@sz.tsinghua.edu.cn

Received: 10 October 2020; Accepted: 26 October 2020; Published: 28 October 2020



Abstract: This paper developed light-emitting diode (LED) and laser models suitable for the design of uniform surface irradiation systems that use computer algorithms. During the evaluation factor for a two-dimensional particle swarm algorithm, the effects of energy utilization and uniformity were comprehensively considered and LED and laser models were given. The optimal design method was used with a laser and LED hybrid light source. According to the lighting requirements of lettuce, three types of lighting were simulated for the LED and laser models, and the best simulation results were selected for experiments. The experiment verified the feasibility of the above method and obtained a laser and LED hybrid lighting system with an energy utilization rate of about 78% and a uniformity of up to 85%.

Keywords: computer algorithm; plant lighting; uniformity design; LED; laser; irradiance model of light source

1. Introduction

The reduction of arable land and the rapid population growth pose severe challenges for the global food supply. Increasingly, scholars have paid attention to the use of artificial light sources to provide energy for plants. This is a good thing because the production mode of plant factories is not restricted by cultivated land, it can produce what people need in some places with low utilization such as basements, as shown in Figure 1. In the past, people used high-sodium lamps and fluorescent lamps as artificial light sources for plant factories, but the emission energy spectrum of the light source did not match the plant absorption, and the high energy consumption was not suitable for plant lighting [1,2]. With the development of light-emitting diode (LED) technology, public interest in the use of LED lighting in plant factories has surged because of its spectrum similar to plant absorption spectra and high photoelectric conversion efficiency [3–6]. Many scholars have conducted in-depth research on plant factory lighting technology and achieved significant progress [7–11].

However, when plant lighting technology is actually used, it is not only necessary to consider the characteristics of the light source itself but also to consider the uniformity of the illumination plane and the different needs of different plants in different periods of light intensity. The uniformity of illumination on the illuminated surface directly determines the cycle of food production in the factory. For this reason, many scientists have done a lot of work on the uniformization of LED lighting [12–15]. In order to meet the needs of plant factories for the light intensity of different plants during different periods, researchers have developed intelligent LED light source control systems that adjust a light source's light intensity at all times [16–20]. However, when designing a light system, the above scholars did not consider the relationship between illumination uniformity on the illumination plane nor the energy received by the illumination plane via the energy emitted by the light source. Thus, they have ignored the problem of the energy utilization rate. In order to comprehensively discuss the issues

of energy utilization and uniformity, this paper changed the traditional light quantum model to an irradiance model, established a particle swarm algorithm suitable for this optical model, added a comprehensive evaluation of uniformity and energy utilization to the algorithm function, and finally used the algorithm to conduct experiments and simulations to provide a way for subsequent scholars to conduct plant lighting design to improve energy efficiency.

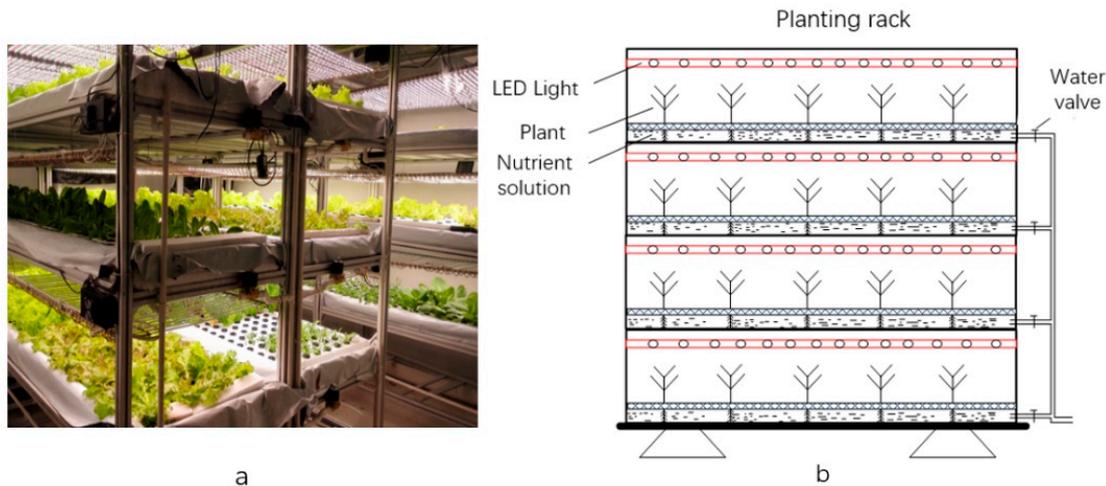


Figure 1. Plant factory. (a) shows the plant factory laboratory; (b) is the model of the plant factory laboratory.

Lasers have characteristics of narrow line width and concentrated energy. Ooi et al. used a single wavelength laser for plant lighting, which proved that lasers can be used for plant lighting such as traditional light sources [21,22]. Plants rely on plant pigments to capture light energy [23]. The absorption spectrum of each plant pigment is specific. Combining the characteristics of plant pigments to capture light and the characteristics of laser light emission, we can use a variety of wavelength lasers to combine the same plant light source with the plant absorption spectrum. This improves plants' use of light energy as well as increases plant photosynthesis and yield. However, due to the limited current semiconductor technology, the production of full-band lasers is not possible, and the photoelectric conversion efficiency of high-power LEDs is low. Some scholars have proposed the use of lasers and LEDs to approximate plants with light, i.e., low-power LEDs provide the broad spectrum required by plants. The laser accurately fills up light at the absorption peak of the plant, as shown in Figure 2, so that the use of laser and low-power LED hybrid lighting has become a new generation of plant factory lighting technology research hotspot. Due to the narrow laser beam angle and the luminous intensity following the Gaussian distribution, new requirements have been put forward for the uniformity design of plant lighting. In order to solve the above problems, this paper developed hybrid laser and LED models suitable for plant lighting. Further, we established a particle swarm algorithm that comprehensively considers energy utilization and uniformity and uses this algorithm for experiments and simulations.

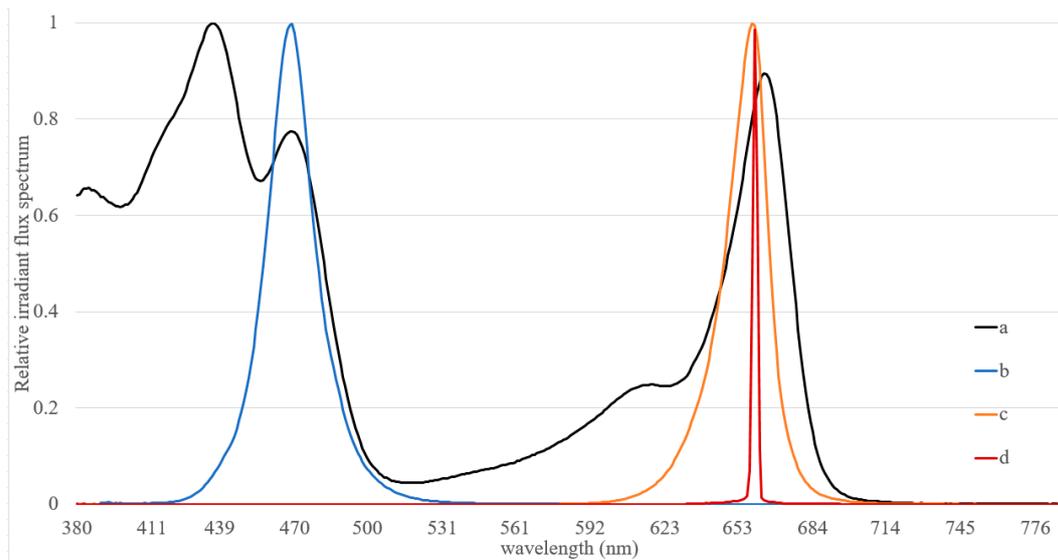


Figure 2. Relative irradiant flux spectrum. (a) is relative irradiant flux absorption spectrum of lettuce; (b–d) are emission spectra of blue light-emitting diode (LED), red LED, and red laser.

2. Materials and Methods

2.1. Light Source Mathematical Model

2.1.1. LED Mathematical Model under the Light Intensity System

Assuming that the luminescence of the LED chip conforms to Lambert’s law of radiation, and there is no energy attenuation during the propagation process, the luminous intensity curve can be roughly expressed by Formula (1) [24]:

$$I(\theta) = I_0(\cos\theta)^m \tag{1}$$

where θ is the angle between the light and the optical axis, I_0 is the light intensity on the axis and m is the light source radiation mode, which is related to the light intensity of half the emission angle ($\theta_{\frac{1}{2}}$) at different vertical heights [25,26]:

$$m = \frac{-\ln 2}{\ln \cos \theta_{\frac{1}{2}}} \tag{2}$$

As shown in Figure 3, the light intensity generated by the LED light source chip placed at the spatial point A(X,Y,Z) at the receiving plane point B(x,y,z) can be expressed as:

$$E_1(x, y, z) = \frac{(z - Z)^{m+1} I_0}{[(x - X)^2 + (y - Y)^2 + (z - Z)^2]^{(m+3)/2}} \tag{3}$$

Assuming that the number of each type of lamp is C, the total light intensity of each type of LED light source at the receiving surface point B(x,y,z) is as follows:

$$E(x, y, z) = \sum_{i=1}^C \frac{(z - Z_i)^{m+1} I_0}{[(x - X_i)^2 + (y - Y_i)^2 + (z - Z_i)^2]^{(m+3)/2}} \tag{4}$$

The plane is equally divided into N points and the uniformity can be measured by the ratio of the standard deviation σ of the light intensity on the target plane to the mean value \bar{E} :

$$\bar{E} = \frac{1}{N} \sum_{i=1}^N E_i \quad \sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (E_i - \bar{E})^2} \tag{5}$$

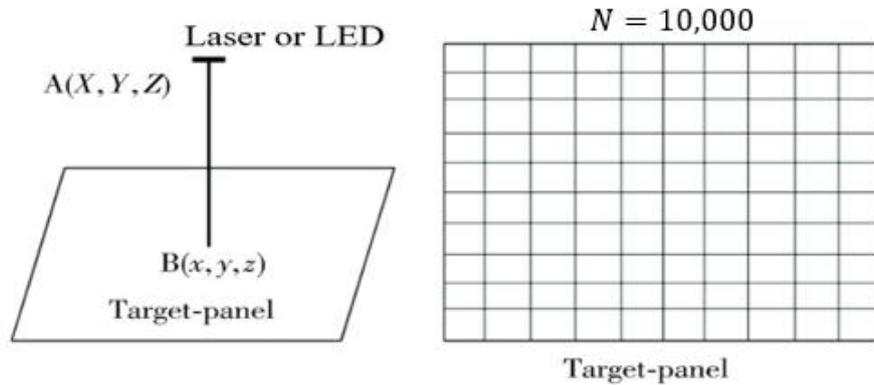


Figure 3. Laser and LED lighting model.

2.1.2. LED Mathematical Model under Irradiance System

The photometric unit used to establish the above model was light intensity. Although the conversion of light measurement and radiation quantity requires the use of the human eye, the human eye’s viewing function and plant sensitivity curve are completely different, and thus the luminous flux and illuminance are not suitable for calculating and evaluating the lighting effect of plants. At this stage, there were two basic measurement methods used to evaluate the effects of the plant illumination-radiant energy method and photon number method. The radiant energy method directly indicates how much light energy is effectively used for photosynthesis, so the above light source illuminance model was modified to become an irradiance model in order to be used in plant lighting and uniformity design.

Luminous flux is integral for the radiant flux in the visible light range in the human eye, which can be expressed by the following formula [27]:

$$\phi = a\Delta\lambda K_m \sum_{380}^{780} N_i(\lambda) V_i(\lambda) \tag{6}$$

K_m is the light power equivalent and its value under photopic vision is $683lm/W$, a is the conversion coefficient between the relative value of the spectral power distribution and the actual value, $N(\lambda)$ is the relative spectral distribution of the light source, $V_i(\lambda)$ is the visual function of the human eye, and ϕ is the luminous flux of the light source.

$$P = a\Delta\lambda \sum_{400}^{700} N_i(\lambda) \tag{7}$$

$$\phi = PK_m \frac{\sum_{380}^{780} N_i(\lambda) V_i(\lambda)}{\sum_{400}^{700} N_i(\lambda)} \tag{8}$$

P is radiant power. For the LED lights of the same batch number, $K_m \frac{\sum_{380}^{780} N_i(\lambda) V_i(\lambda)}{\sum_{400}^{700} N_i(\lambda)}$ is constant. For the convenience of expression, replace it with K_λ .

It can be concluded that the luminous flux and radiant power are in direct proportion with Formula (8). I_0 on the optical axis is expressed by the luminous flux per unit solid angle on the optical axis, and the irradiance D_0 on the optical axis can be expressed by the radiant power per unit area

on the optical axis. According to Formula (8) combined with the standard uniformity Lambertian distribution, the optical axis can be obtained from the irradiance D_0 at the vertical distance z_0 from the light source. The light intensity I_0 on the optical axis should satisfy the following formula:

$$\frac{I_0}{S_0} = D_0 K_\lambda \tag{9}$$

S_0 is the area that corresponds to the unit solid angle when the vertical distance from the light source on the optical axis is $S_0 = \pi/z_0^2$.

The LED in this article is in accordance with the standard Lambertian distribution, $m = 1$. Combined with Formula (1), the light intensity distribution based on the Lambertian illuminant is converted into irradiance distribution. The standard Lambertian distribution can be obtained from the light source vertical distance z to the irradiation plane. Irradiance can be expressed by the following formula:

$$D(\theta) = D\pi/z^2 K_\lambda \cos\theta \tag{10}$$

θ is the angle between the light and the optical axis, D is the irradiance at z on the optical axis, and $D(\theta)$ is the illuminance distribution on the plane when the vertical distance from the light source is z .

The irradiance generated by the LED light source chip placed at the spatial point $A(X, Y, Z)$ at the receiving plane point $B(x, y, z)$ can be expressed as:

$$E_1(x, y, z) = \frac{(z - Z)D\pi K_\lambda}{[(x - X)^2 + (y - Y)^2 + (z - Z)^2]^{3/2}} \tag{11}$$

Suppose the number of each LED light source is C . The light source designed in this paper is installed on the same horizontal plane. Then, $(z - Z)$ is a constant, which when combined with Formula (4), the total radiation of each LED light source at the receiving surface point $B(x, y, z)$, the illuminance is:

$$E(x, y, z) = \sum_{i=1}^C \frac{(z - Z)D\pi K_\lambda}{[(x - X_i)^2 + (y - Y_i)^2 + (z - Z)^2]^{3/2}} \tag{12}$$

Refer to Formula (5) to express the uniformity.

2.1.3. Laser Mathematical Model under Irradiance System

LED and laser hybrid lighting has become a trend for light sources in plant factories, but the use of LED and laser hybrid light sources puts forward new requirements for the uniformity design of the illuminated surface. In this paper, a mathematical model of laser light sources for particle swarm optimization improves the uniformity of the irradiation surface. The light emitted by the laser light source is generally Gaussian. Assuming that the attenuation of the light in the propagation process is negligible, the light source model can be expressed by Equation (14):

$$I(x, y) = I_0 \exp\{-[x^2/2 + y^2/2]\} \tag{13}$$

I_0 is the light intensity on the optical axis, while x and y are the coordinates from the optical axis.

With reference to Formulas (6)–(12), the irradiance expression of the irradiation plane at the vertical distance z from the light source can be obtained as:

$$D(x, y, z) = D\pi/z^2 K_\lambda \exp\{-[x^2/2 + y^2/2]\} \tag{14}$$

D is the irradiance at z on the laser optical axis, while x and y are the coordinates from the optical axis.

The laser light source in this article has a small emission angle and cannot be directly used for plant lighting. It must be diffused. Therefore, a lens is introduced and the expansion factor of the lens to the light-emitting angle θ is set to τ . The light source illumination model refers to Figure 3, then in space, the irradiance generated at the receiving plane point B (x, y, z) after the laser light source placed at point A (X, Y, Z) is dispersed by the lens can be expressed as:

$$E_2(x, y, z) = \frac{D\pi}{\tau^2(z - Z)^2} K_\lambda \exp\{-[(x - X)^2/2\tau^2 + (y - Y)^2/2\tau^2]\} \tag{15}$$

Assuming that the number of each light source is C , the total irradiance of each laser light source at the receiving surface point B (x, y, z) is:

$$E(x, y, z) = \frac{D\pi}{\tau^2(z - Z)^2} K_\lambda \sum_{i=1}^N \exp\{-[(x - X_i)^2/2\tau^2 + (y - Y_i)^2/2\tau^2]\} \tag{16}$$

With reference to Formula (5), the expressions of the standard deviation of total irradiance σ and \bar{E} can be obtained. The uniformity can be measured by the ratio of the standard deviation σ to the mean \bar{E} when the computer algorithm is used to design the uniformity of plant lighting.

2.2. Algorithm Design

2.2.1. Evaluation Function Design

In this paper, the illumination plane and the light-emitting plane were fixed, and the two-dimensional particle swarm algorithm was used to optimize the lighting system. Therefore, $(z - Z)$ was a fixed value, and only (X, Y) for each lamp bead was required. Therefore, the evaluation uniformity evaluation function $\frac{\sigma}{\bar{E}}$ can be expressed by the following formula:

$$f(X_1, Y_1; X_2, Y_2; \dots; X_n, Y_n) = \frac{\sigma}{\bar{E}} \tag{17}$$

However, in actual situations, the average value can represent the amount of energy that the light source illuminates on the target plane. The higher the average value (\bar{E}), the greater the energy utilization of the designed lighting system. Therefore, when designing the lighting system, the energy utilization rate and uniformity must be considered comprehensively, so the H function combined with Formula (20) can be introduced for comprehensive evaluation:

$$H(X_1, Y_1; X_2, Y_2; \dots; X_n, Y_n) = b_1\sigma + b_2\bar{E} \tag{18}$$

Among them, b_1 and b_2 represent the weight of the standard deviation and the mean value in the H function, respectively. A reasonable adjustment of b_1 and b_2 can obtain higher energy utilization and uniformity.

2.2.2. Algorithm Flow Design

The particle swarm algorithm is an optimization method based on iteration. The system is initialized as a set of random solutions. Through iterative optimization, the particles follow the optimal particles to search in the solution space. In each iteration, the particle updates itself by tracking the optimal solution currently found by itself (individual extreme value) and the optimal solution currently found by the entire population (global extreme value). The principle is shown in Figure 4 [28].

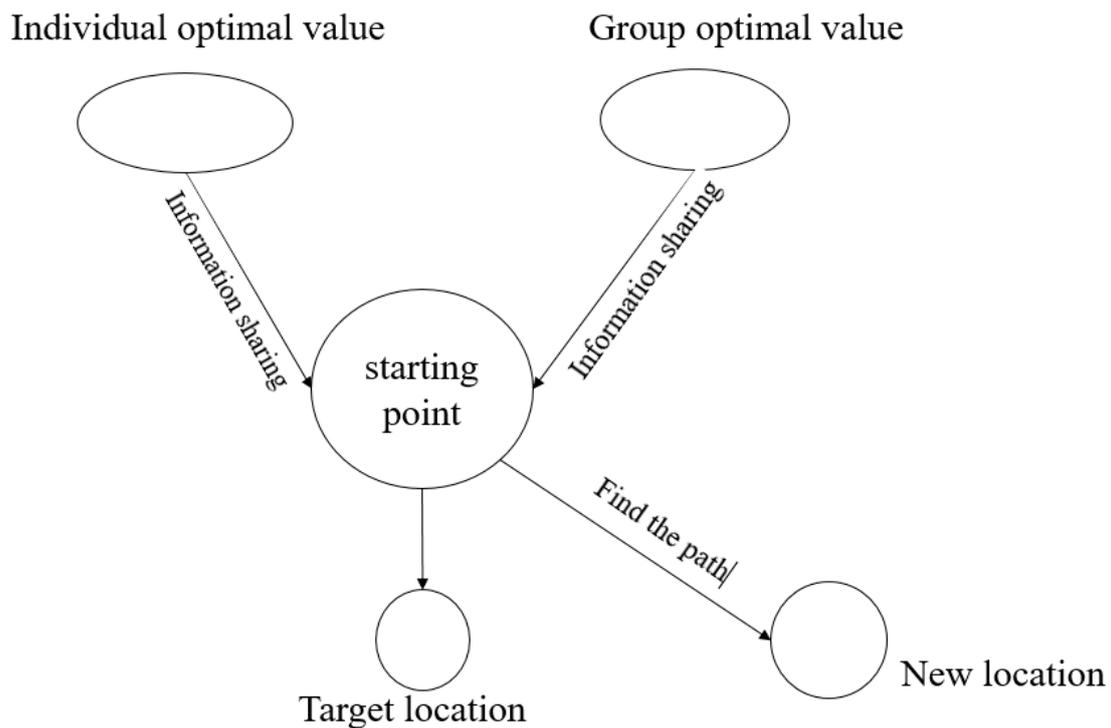


Figure 4. Schematic diagram of particle swarm algorithm.

Suppose that in a D -dimensional search space, a population composed of n particles $X = (X_1, X_2, \dots, X_n)$, where the i -th particle represents the D -dimensional vector $X_i = (X_{i1}, X_{i2}, \dots, X_{in})^T$, represents the position of the i -th particle in the D -dimensional search space, and also represents a potential value of the problem. According to the objective function, the fitness value corresponding to each particle X_i can be calculated. $V_i = (V_{i1}, V_{i2}, \dots, V_{in})^T$, its individual extreme value, is $P_i = (P_{i1}, P_{i2}, \dots, P_{in})^T$, and the global extreme value of the population is $P_g = (P_{g1}, P_{g2}, \dots, P_{gn})^T$.

In each iteration process, the particle updates its own speed and position through individual extreme values and global extreme values. The mathematical description and iteration formula are as follows:

$$V_{id}^{k+1} = \omega V_{id}^k + c_1 \text{rand}(\cdot)(P_{id}^k - X_{id}^k) + c_2 \text{rand}(\cdot)(P_g^k - X_{id}^k) \tag{19}$$

$$X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1} \tag{20}$$

where $d = 1, 2, \dots, D; i = 1, 2, \dots, n; \omega$ is the inertia weight; c_1 and c_2 are acceleration factors, and $c_1 = c_2$, ranging between 0 and 4; rand is (0, 1) and indicates random numbers.

The specific optimization steps of the laser are shown in Figure 5, and the optimization steps of the LED are similar.

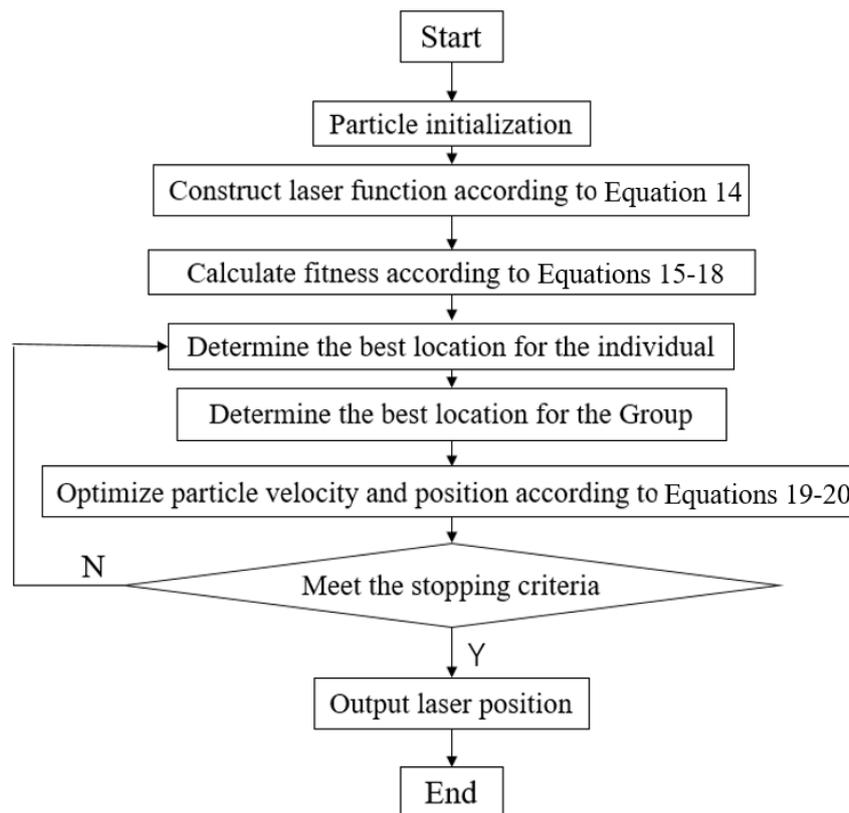


Figure 5. Flow chart particle swarm algorithm that details the process of using the particle swarm algorithm to find the position of the laser. The same process is true for the LED.

3. Simulation

3.1. Simulation Parameters

When the ratio of red to blue light intensity of lettuce is 12:1 and the total light quantum density is 200 umol/m^2 , the light energy utilization and electric energy utilization are the largest [29]. Based on the characteristics of lettuce and a light-harvesting pigment spectrum, we chose a Huaguang TO5 red laser and YL180409-045 red LED to provide red light for plants, and YL180409-046 blue LED to provide blue light for plants. The illumination plane was $50 \text{ cm} \times 50 \text{ cm}$ and the distance between the light source and the illumination plane was vertical. In total, 10 red lasers, 20 red LEDs, and 10 blue LEDs are determined from the above. When designing the uniformity design and arranging the position of the lamp beads, D and K_λ were constants obtained from Formulas (5), (12) and (16), which did not affect the uniformity and energy utilization. For the convenience of calculation, the initial parameters are shown in Table 1. Because the spectrum of each lamp was different, to meet the needs of plants for spectrum energy, when designing the uniformity, the arrangement of each lamp must be separately designed to achieve a higher uniformity. In order to comprehensively consider the issues of energy utilization and uniformity, we set $\frac{b_2}{b_1} = d$. We simulated three input modes for the laser and LED, i.e., $d = 10$, $d = 1$, and $d = 0.3$. The energy utilization rate was represented by the average irradiance received by the illumination plane \bar{E} \times the area of the illumination plane, divided by the radiant power emitted by the light source. Uniformity was obtained via Formula (17).

3.2. Simulation Procedure

Below details an explanation of the specific steps to use the two-dimensional particle swarm algorithm that can find the laser's location. LED is similar to it.

- a. Use Equation (15) to construct the irradiance generated by a single laser placed at the light source plane point at the illumination plane point.
- b. Set the number of lasers to 10 and use the algorithm to generate 10 random position points. Enter and set the constraints of f and H , as well as the number of iterations.
- c. Referring to Figure 2, divide the illumination plane into 10,000 points, use Formula (16) to calculate the total irradiance of the 10 laser light source illumination planes, and use Formula (5) to calculate the variance.
- d. Use Formulas (17) and (18) to calculate the values of the f function and the H function, and verify whether the constraint conditions are met. If they are not, then the algorithm is iteratively updated according to Formulas (18) and (19) to update the light source position.
- e. When the number of iterations is reached, the final f function value is the output, which results in uniformity.
- f. Calculate the energy utilization rate (energy utilization rate=average irradiance received by the illumination plane, area of the illumination plane S , and the radiant power emitted by the light source).

Table 1. Initial parameters of particle swarm algorithm.

Parameter	Parameter Value
The maximum number of iterations	500
Laser population size	10
Red LED population size	20
Blue LED population size	10
Coefficient c_1	1.4
Coefficient c_2	1.4
Laser diffuser enlargement factor τ	10
Illumination plane size	50 cm × 50 cm
Distance between laser and LED light source plane and light plane	40 cm
Irradiance D at 40 cm on the LED optical axis	1 W/m ²
Irradiance at 40 cm on the laser optical axis D	15 W/m ²
Laser and LED light intensity and irradiance conversion constant K_λ	1

3.3. Simulation Results

The experimental results are shown in Table 2. The red laser simulation results are shown in Figure 6. The red LED simulation results are shown in Figure 7. The blue LED simulation results are shown in Figure 8. The red dot is the radiation pattern of the entire illumination plane, the red dot is the position of the light source on the light source plane, and the graph is the cross-sectional view corresponding to the radiation pattern $Y = 0$.

Table 2. Simulation results.

Type of Light Source	Parameter d	Energy Utilization	Evenness
Laser	$d = 10$	100%	40%
	$d = 1$	85%	80%
	$d = 0.3$	82%	86%
Blue LED	$d = 10$	90%	70%
	$d = 1$	84%	74%
	$d = 0.3$	77%	84%
Red LED	$d = 10$	90%	70%
	$d = 1$	85%	78%
	$d = 0.3$	77%	84%

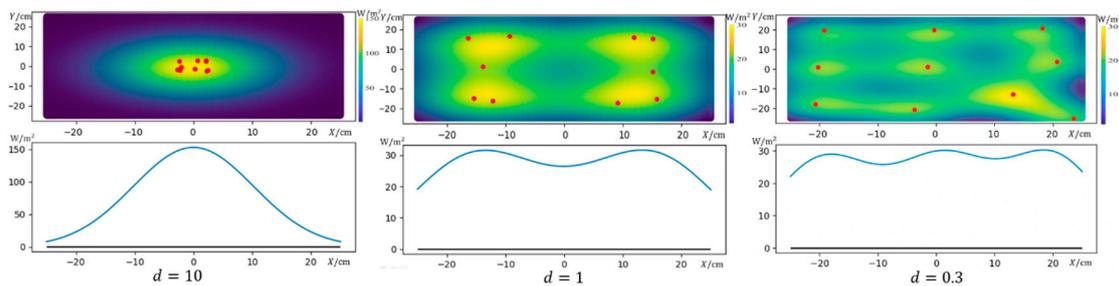


Figure 6. Laser simulation diagram.

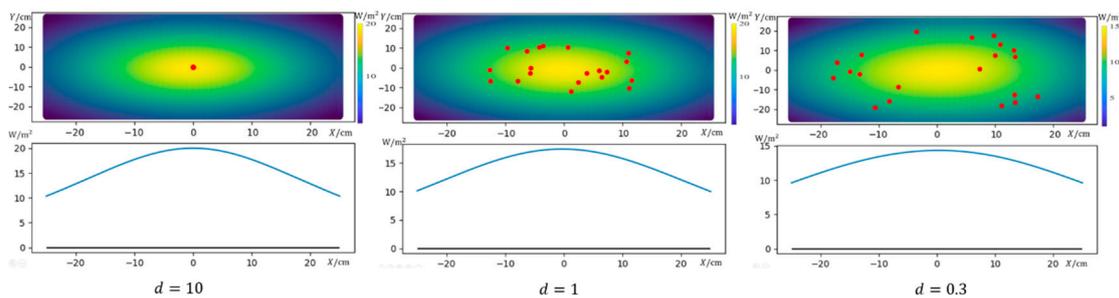


Figure 7. Red LED simulation diagram.

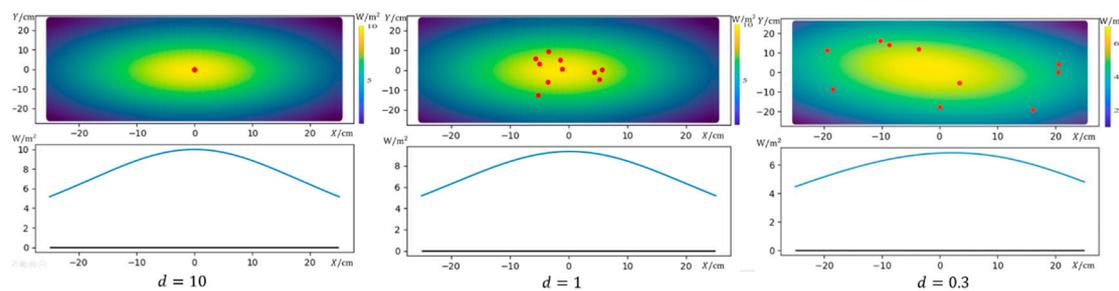


Figure 8. Blue LED simulation diagram.

It can be seen from Table 2 that, as the mean value of irradiance decreases, the lower the energy utilization rate, the higher the uniformity of the irradiation plane. The high-uniformity irradiation system can play a good contrast effect in the cultivation experiment. However, in the actual work of plant factories, energy consumption must be fully considered. However, if the energy efficiency is only high, plant growth on the entire planting plane becomes uneven. Combined with plant light saturation and light inhibition, uniformity is poor. The lighting system can lengthen the growth cycle of the entire planting plane and reduce the light energy utilization rate of the plant, which is very unfavorable for

the efficiency of the plant factory. Therefore, it is necessary to comprehensively consider the problems of high energy utilization and uniformity.

4. Experiment

Comprehensive analysis of the energy utilization and uniformity of the simulation results was conducted using the Huaguang TO5 red laser, YL180409-045 red LED, and YL180409-046 blue LED, all of which built our experimental system according to the simulation position of each light source, as shown in Figure 9 for the experiment. The position distribution map of each light source was in the system. In order to verify the reliability of the simulation results, we delineated the illumination plane at a distance of 50 cm and 50 cm at a distance of 40 cm vertically below the light source plane. The irradiation plane was equally divided into 100 points, and the radiation value of each point was measured with the LI-250A irradiance meter.

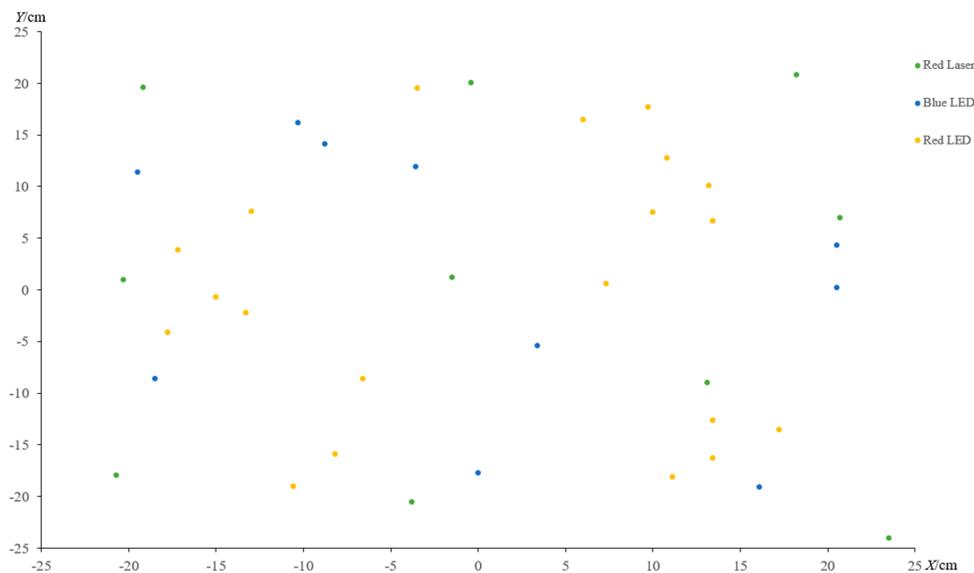


Figure 9. Location of each light source.

Figure 10 shows the irradiance distribution of the irradiation plane. Using the irradiance value of each point, the uniformity was 85.3% and the radiant power reaching the illuminated plane accounted for 78.4% of the light power of the light source. The energy utilization rate was 78.4%. We verified the authenticity of the simulation results through specific experiments. The laser and LED irradiance models established in this paper were suitable for computer algorithms and had real operability. Each plant factory laboratory had the potential to design plant lighting systems with reference to the methods in this paper. The irradiation system of energy utilization and uniformity was comprehensively selected.

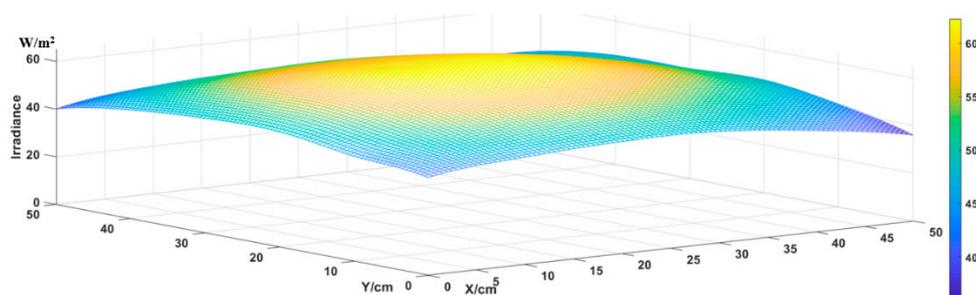


Figure 10. Radiation illuminance distribution diagram of the irradiation plane.

This paper made three simulations for the above problems and selected the arrangement of $d = 0.3$ for the experiments. The experimental results proved the feasibility of this method.

Comparing the experimental results with Tang [15], it can be seen that not only the uniformity level was comparable but also the key issue of energy utilization was considered comprehensively. Tang et al. did not consider the uniformity of the radiometer irradiation surface.

5. Conclusions and Outlook

In order to solve the problem that the traditional light distribution method does not consider the contact of uniformity and the energy utilization rate, in order to meet the needs of a new generation of laser and LED hybrid lighting plant factories, this article changed the traditional LED model to an irradiance model suitable for plant lighting and established a laser model for an irradiance system. For example, the plant factory grew lettuce, designed its lighting, comprehensively considered the impact of energy utilization and uniformity in the evaluation factors of the two-dimensional particle swarm algorithm, conducted three forms of simulation, and comprehensively considered the energy utilization and simulation results of the final selection of uniformity. From these specific experiments, we obtained a laser and LED hybrid lighting system with an energy utilization rate of about 78% and a uniformity of up to 85%. The light transmittance of the lens in this article was assumed to be 100%, but in the actual situation, the light transmittance of 100% was ideal. However, the light transmittance of the lens did not affect the method, procedure, and uniform color design of the experiment. In this case, only the transmittance rate and energy utilization rate of the lens were used to obtain the true energy utilization rate. The experimental methods and procedures in this article will not be outdated even in the future. When the laser technology is mature enough to achieve cheap multi-wave lasers and large-angle lasers, 100% accurate control of plant lighting can be achieved. Therefore, this article can be used to carry out new uniformity/energy utilization, comprehensive analysis, and plant light design.

Author Contributions: All the content of this article is completed by Y.H. J.M. provided equipment support, writing guidance and funding assistance for the experiment. Both authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Basic Research Program of Shenzhen (JCYJ20170412171744267).

Acknowledgments: This work was supported by the Basic Research Program of Shenzhen (JCYJ20170412171744267).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kitsinelis, S. *Light Sources: Technologies and Applications*; CRC Press: Boca Raton, FL, USA, 2016.
2. Olle, M.; Viršile, A. The effects of light-emitting diode lighting on greenhouse plant growth and quality. *Agric. Food Sci.* **2013**, *22*, 223–234. [[CrossRef](#)]
3. Darko, E.; Heydarizadeh, P.; Schoefs, B.; Sabzalian, M.R. Photosynthesis under artificial light: The shift in primary and secondary metabolism. *Philos. Trans. R. Soc. B Biol. Sci.* **2014**, *369*, 7. [[CrossRef](#)]
4. Morrow, R.C. LED Lighting in Horticulture. *Hortscience* **2008**, *43*, 1947–1950. [[CrossRef](#)]
5. Massa, G.D.; Kim, H.H.; Wheeler, R.M.; Mitchell, C.A. Plant Productivity in Response to LED Lighting. *Hortscience* **2008**, *43*, 1951–1956. [[CrossRef](#)]
6. Singh, D.; Basu, C.; Meinhardt-Wollweber, M.; Roth, B. LEDs for energy efficient greenhouse lighting. *Renew. Sust. Energy Rev.* **2015**, *49*, 139–147. [[CrossRef](#)]
7. Chen, J. *The Effect of Different Light on the Quality and Yield of Coptis Chinensis*; Northwest A&F University: Xianyang, China, 2011.
8. Liu, S. *Application of Artificial Light Source in Closed Plant Factory*; Chinese Academy of Agricultural Sciences: Beijing, China, 2007.
9. Xu, K.; Guo, Y.; Zhang, S.; Dai, W.; Fu, Q. The effect of different light qualities on the growth and development of Fengxiang strawberry. *J. Fruit Sci.* **2006**, *23*, 818–824.
10. Xu, Y.; Anpo, M.; Fukuda, H.; Wada, T. Nature and Source of Light for Plant Factory. In *Plant Factory Using Artificial Light*; Elsevier: Amsterdam, The Netherlands, 2009; pp. 47–69.

11. Williams, L. A light salad LED lighting applications in horticulture. *Eng. Technol.* **2018**, *13*, 50–53. [[CrossRef](#)]
12. Huang, Q. Simulation Research and Design of LED Array Based on Uniform Illumination. Master's Thesis, Huaqiao University, Xiamen, China, 2011.
13. Hua, H.; Mao, X.; Tan, J.; Yu, X. Dynamic lighting design method based on LED array. *Progress Laser Optoelectron.* **2017**, *54*, 416–425.
14. Su, Z.P.; Xue, D.L.; Ji, Z.C. Designing LED array for uniform illumination distribution by simulated annealing algorithm. *Opt. Exp.* **2012**, *20*, 843–855. [[CrossRef](#)]
15. Tang, H.; Wen, S.; Fu, M.; He, G.; Zhang, H.; Liao, S.; Kang, L. LED plant lighting source design based on particle swarm algorithm under light quantum system. *Acta Luminica* **2019**, *40*, 340–348.
16. Wei, X. Design and research of LED lighting control system for plant factories. *J. Anhui Agric. Univ.* **2010**, *37*, 806–810.
17. Zhang, H.; Yang, Q.; Hu, J.; Fan, H.; Dai, J. Plant adaptive precision lighting system with controllable LED brightness. *Trans. Chin. Soc. Agric. Eng.* **2011**, *27*, 153–158.
18. Zhao, Q. Research on LED Lighting System Used for Plant Growth Supplement Light. Master's Thesis, Fudan University, Shanghai, China, 2012.
19. Zhang, J.; Yang, J.; Hu, L.; Zhao, S.; Zhao, T.; Li, L. Design of LED light source for plant tissue culture based on single chip microcomputer. *J. Hebei Agric. Univ.* **2012**, *35*, 99–104.
20. Durmus, D. Real-Time Sensing and Control of Integrative Horticultural Lighting Systems. *Multidiscip. Sci. J.* **2020**, *3*, 266–274. [[CrossRef](#)]
21. Ooi, A.; Wong, A.; Ng, T.K.; Maronedze, C.; Gehring, C. Growth and development of *Arabidopsis thaliana* under single-wavelength. *Nature* **2016**, *6*, 2045–2322.
22. Kühlbrandt, W.; Wang, D.N.; Fujiyoshi, Y. Atomic model of plant light-harvesting complex by electron crystallography. *Nature* **1994**, *367*, 614–621. [[CrossRef](#)] [[PubMed](#)]
23. Yang, H.; Bergmans, J.W.; Schenk, T.C.; Linnartz, J.P.; Rietman, R. Uniform illumination rendering using an array of LEDs: A signal processing perspective. *IEEE Trans. Signal Process.* **2009**, *57*, 1044–1057. [[CrossRef](#)]
24. Whang, A.J.-W.; Chen, Y.-Y.; Teng, Y.-T. Designing uniform illuminance systems by surface-tailored lens and configurations of LED arrays. *J. Disp. Technol.* **2009**, *5*, 94–103. [[CrossRef](#)]
25. Moreno, I.; Avendaño-Alejo, M.; Tzonchev, R.I. Designing light-emitting diode arrays for uniform near-field irradiance. *Appl. Opt.* **2006**, *45*, 2265–2272. [[CrossRef](#)] [[PubMed](#)]
26. Zhenrong, Z.; Xiang, H.; Xu, L. Freeform surface lens for LED uniform illumination. *Appl. Opt.* **2009**, *48*, 6627–6634. [[CrossRef](#)] [[PubMed](#)]
27. Gao, H.; Zhu, D. Unit conversion between human eye photometry and plant photometry. *Lamp Lighting* **2007**, *31*, 34–36.
28. Zhao, Z.; Ji, L.; Shen, Y.; Su, Z. Study on illumination uniformity of LED lighting system based on PSO particle swarm algorithm. *Acta Luminica* **2013**, *34*, 1677–1682.
29. Wang, J. *The Influence Mechanism of Different Light Intensity and Light Quality Ratios on the Photosynthetic Capacity of Lettuce under Red and Blue Light*; Chinese Academy of Agricultural Sciences: Beijing, China, 2016.

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).