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SPATIAL LIGHT DISTRIBUTION CHARACTERIZATION AND MEASUREMENT OF LED HORTICULTURAL LIGHTS

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Abstract

The demands to light are different between plant and human, and the type and irradiation ways of the lighting products in horticultural and general lighting also vary greatly, thus the conventional characterization and measurement methods for spatial light distribution of general lighting products are no longer applicable for most horticultural lights. This paper studies the main light parameters affecting plant growth and the applicability and limitations of existing measurement instruments for spatial light distribution. A robot spectroradiometer is proposed to comprehensively measure the horticultural lights. Moreover, typical LED horticultural lights are measured, and comparisons show that the photosynthetic photon flux density (PPFD) distribution of a horticultural light should be investigated at distances close to practical applications, and not only the horizontal but also the inclined planes need be investigated. Furthermore, several quantities are proposed in this paper, e.g. using the uniformity of R/B ratio to characterize the spectral uniformity of irradiation.

Keywords: LED horticultural lights, Spatial light distribution, Characterization and measurement methods, Solutions

1 Introduction

In recent years, the LED horticultural lighting develops very quickly, and it is estimated that its global market will reach $1.424 billion by 2020, with an average annual growth rate over 30%. Along with industry development, the characterization and measurement of the performance of LED horticultural lights have attached close attention, and relevant standards have been issued in some areas. However, the spatial light distribution characterization quantities proposed in these standards can't meet the practical application requirements. The demands to light are different between plant and human, and the type and irradiation ways of the lighting products in horticultural and general lighting are also vary greatly. Started from the light demands of plants, the characterization and measurement methods of spatial light distribution of LED horticultural lights are studied by theoretical analysis and practical measurement comparison.

2 The Properties of Horticultural Lighting and Horticultural Lights

The main factors affecting plant growth include light quality (spectrum), light density and photoperiod.

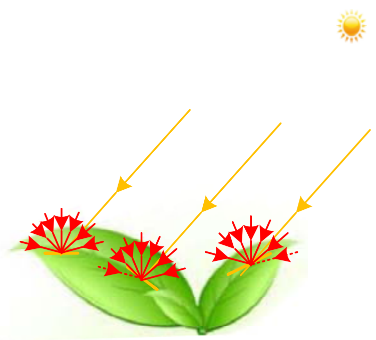
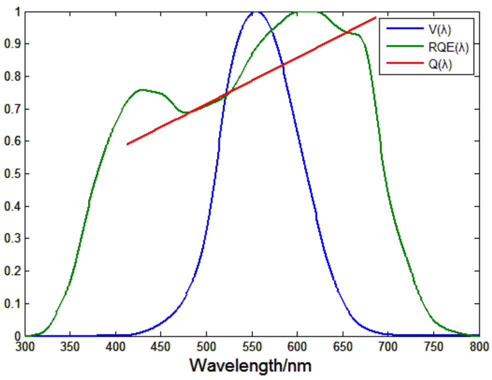
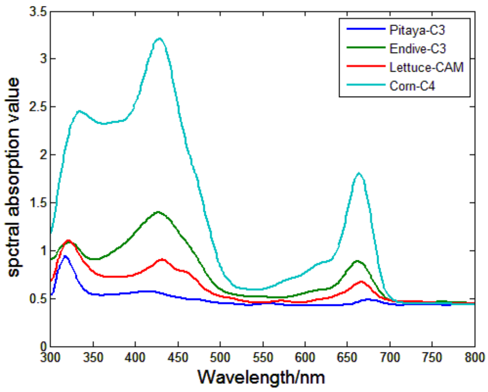


Figure 1 – irradiation diagram of leaf surface

It is generally believed that the effective wavelength range of plant photosynthesis is from 400nm-700nm, and the photon quantum system rather than photometric system is usually used to characterize plant lighting, as shown in Figure 2(a). Meanwhile, the spectral photosynthesis sensitivity curves of different plant are also different, and Figure 2 (b) shows the spectral absorption curves of several typical plants. Researches have shown that radiation from 280nm to 800nm has biological effects on plants, and at present, ultraviolet and far red components are added in more and more horticultural lights in order to meet specific biological needs.



(a)



(b)

Figure 2 – Comparison of spectral response curves for human eye and plant

The light radiation received by plants is mainly investigated in the horticultural lighting, i.e. light density, and the commonly used quantity is PPFD, considering the above-mentioned effective biological radiation, it is also characterized by irradiance or weighted irradiance. Meanwhile, due to the growth variety of plant, the spatial distribution, including the distance to light source and inclined angle, of the leaf surfaces which receive light differ in thousands of ways. Therefore, it is far from enough to consider only the horizontal light density at a distance, and it is suggested to investigate the light density quantities at various distances and inclined angles, so as to characterize the performance of horticultural lighting comprehensively.

There are many types of horticultural lights with different shape, size and functional application. For greenhouse supplementary lights, the light intensity (radiation intensity) distribution is applicable, because the lights are relatively far from plants, and they are not the objects discussed in this paper. However, the illumination distances of the lights for inter-plants application and those in all-artificial light plant factories are very short, which are different from general lighting applications, and this paper will also focus on the spatial light distribution characterization and measurement of these types of horticultural lights.

It is worth mentioning that, in order to improve energy efficiency, the emitting surface of the LED horticultural lights is often composed of separated LED packages and without a diffuser, and many of them are red & blue or high & low CCT arrangement, that is, the spectral radiance distribution on the emitting surface has a large non-uniformity, and this may result in large variation of spectral irradiance on the plant surface. Studies have shown that when the uniformity of spectral irradiance received by plants is poor, the yield and nutrient composition of plants will be greatly affected[1-4].

Figure 3 – Example of red and blue LED horticultural lights in a plant factory

3 Characterization of Spatial Light Distribution of Horticultural Light

Based on the above analysis, the spectral irradiance or PPFD can represent the practical application effect of the horticultural lights and effectively guide the lighting settings in plant factories. In order to more specifically characterization, a coordinate system is established as shown in Figure 4, where, (x, y, z) is a spatial position coordinate with the photometric center of the horticultural light as its origin, and (θ,φ) is used to represent the spatial direction of a surface element. The spectral irradiance and PPFD of any surface element can be expressed as E_e (λ,x,y,z,θ,φ) and PPFD (x,y,z,θ,φ) correspondingly.

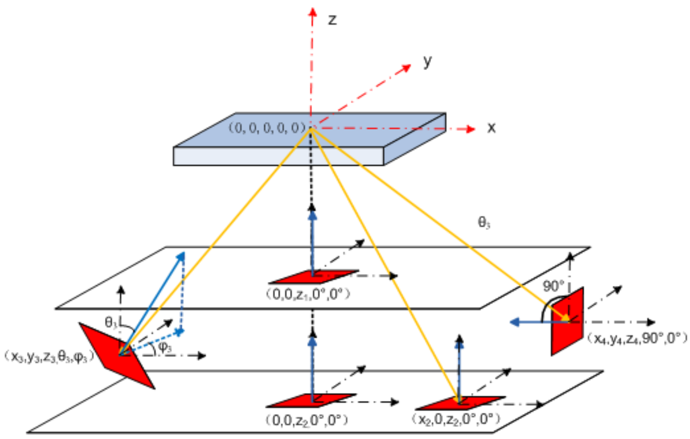


Figure 4 – Spatial light distribution characterization coordinate system of horticultural lights

4 Measurement Solutions of Spatial Light Distribution

4.1 Conventional Far-field Goniophotometer

The quantity Photosynthetic Photon Intensity Distribution (PPID) proposed in *Testing and Reporting Requirements for LED-based Horticultural Lighting* V1.1, 2019 by Design Lights Consortium (DLC) is measured under far-field conditions[5]. In general lighting, the (spectral radiant) intensity distribution can be used to analyze the spectral irradiance/illuminance distribution of an illuminated surface through the Inverse Square Law, as shown in equation (1).

$$E_e(\lambda, x, y, z, \theta, \varphi) = \frac{I(\lambda, \theta_s, \varphi_s) \cdot \cos(\theta)}{d^2} \tag{1}$$

where, $\theta_s = \arccos(z / \sqrt{x^2 + y^2 + z^2}), \varphi_s = \arctan(y / x)$.

However, the Inverse Square Law can only applied when the distance between the light source and the illuminated surface is far enough that measured light source can be regarded as a point source, as shown in Figure 5(a); but in horticultural lighting, the distance between the plants and the horticultural lights is very close so as to improve energy efficiency. The light distribution at near distance is significant different from that in far-field, as shown in Figure 5(b) ,where Φ is the beam angle of a single LED.

The PPID reflects the light signals on the receiving surface far away, but cannot derive PPFD information in near-field. Therefore, the PPID obtained in far-field measurement does not have effective guiding significance for the design and application of horticultural lights, and it is easy to create gaps between manufacturers and the users of the lights.

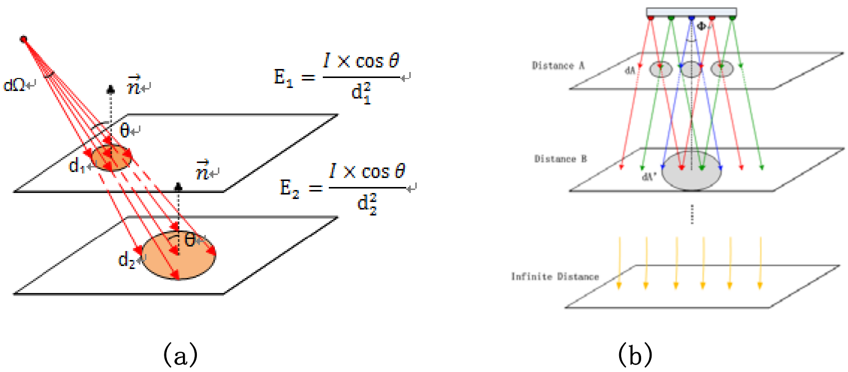


Figure 5 – The Inverse Square Law of Distance is valid (a) and not valid (b)

4.2 Near-field Goniophotometer

In general lighting, the near-field distribution of a light source can be measured and analyzed using a near-field goniophotometer as shown in Figure 6, that is, an ILMD based on photometric effective function collects the luminance distribution of a light source in all directions, and the luminous flux of each emitting element of the light source in all directions is deduced, so as to establish a detailed ray model to derive the illuminance distribution on arbitrary surface.

However, on one hand, the spectral response characteristics of plants differ greatly from the V(λ) function; on the other hand, the spectral radiance distribution of the emitting surface of horticultural lights may have large non-uniform. Therefore, the near-field goniophotometer based on ILMD is not suitable for the near-distance light distribution analysis of horticultural lights. Theoretically, a feasible solution is to use a near-field goniophotometer based on a hyper-spectral-imaging-radiance-meter to measure and analyze the horticultural lights, that is to obtain the quantity L_e (λ,x,y,z,θ,φ). But it is difficult to be widely used currently in horticultural lights analysis, due to the high cost, complicated calculation and large amount of data.

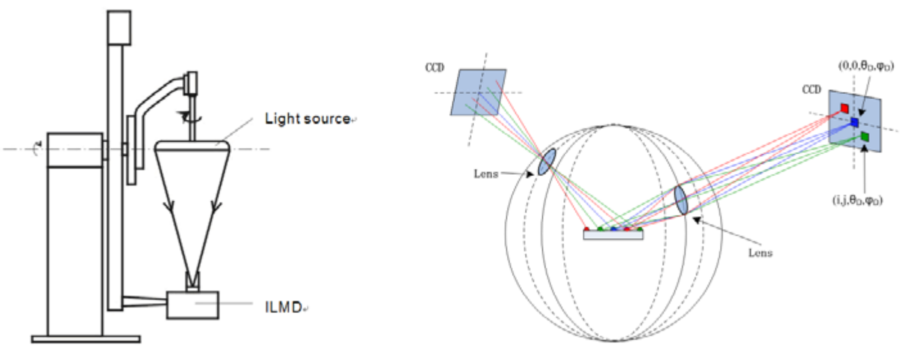


Figure 6 – Near-field goniophotometer based on ILMD and its measurement principle

4.3 Robot spectroradiometer

Based on the above analysis, it is better to directly measure the spectral irradiance distribution on specified surface to characterize the spatial light distribution of horticultural lights, but it has high the requirements on the freedom of the measuring instruments. In order to solve the above questions, this paper proposes a robot spectroradiometer for measurement, as shown in Figure 7. The robot spectroradiometer can measure and analyze E_e (λ,x,y,z,θ,φ) and PPFD (λ,x,y,z,θ,φ) on different irradiation surfaces at different distances and angles, which can provide data support for the lighting settings in plant factories and the design of plant lighting products.

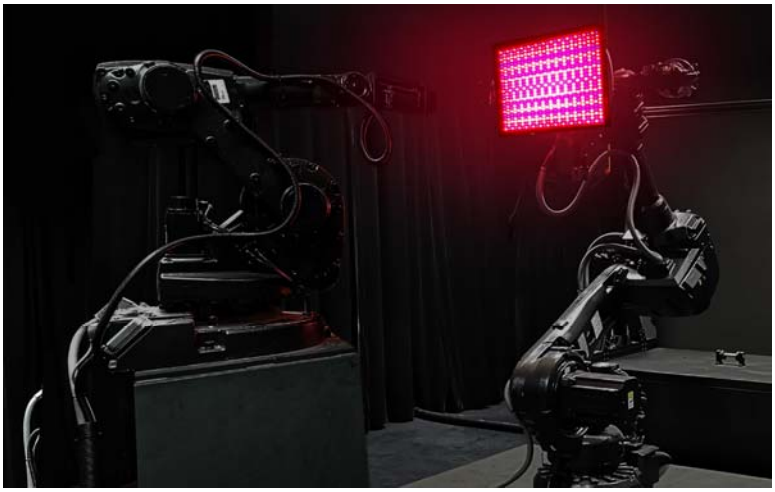


Figure 7 – Real robot spectroradiometer in practical measurement

5 Practical Measurement and Analysis of Horticultural Lights

5.1 The measured horticultural lights and measurement settings

Figure 8 shows the typical horticultural lights under measured, from left to right they are: phosphor converted LED panel (dimension: 0.6m×0.6m), red & blue LED panel (dimension: 0.6m×0.6m), red & white LED light bar (0.6m length) and phosphor converted white LED light bar (1.2 m length).

According to the actual application of the horticultural lights, the measurement distance is from 50mm to 500mm. At each distance, the spatial spectral irradiance E_e (λ, x, y, z, θ, φ) is measured when θ is 0°, 15°, 30°, 45°, 60°, 75° . The distance for the far field measurement is about 10 m.

Figure 8 – The measured horticultural lights

5.2 Comparison of horizontal PPFD distributions at different distances

Figure 9 shows the PPFD distributions of the 0.6m red & white LED light bar at the distance of 50mm, 100mm, 150mm and 200mm when angle θ is 0°, and the data are measured by the robot spectroradiometer. It is obviously the PPFD distribution varies large at different distances, and the distribution tends to be uniform with the increase of distance.

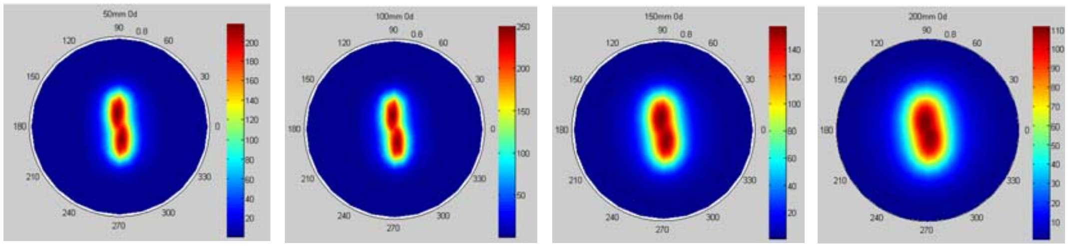


Figure 9 – PPFD distribution of 0.6m red & white LED light bar

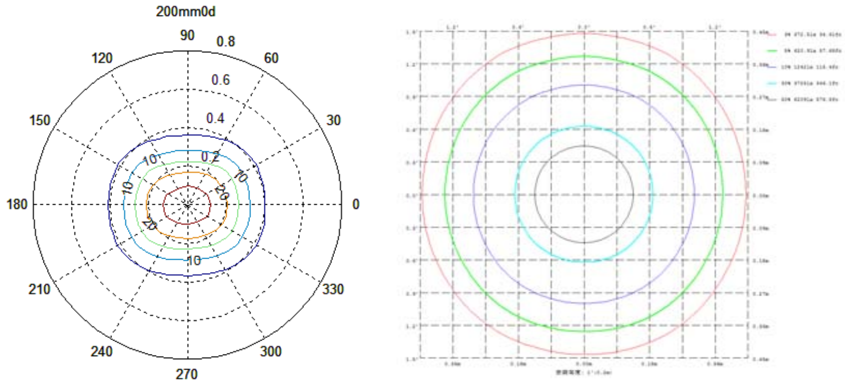


Figure 10 – Equivalent PPFD diagram of the phosphor converted LED panel

Figure 10 shows the equal PPFD curve of the phosphor converted LED panel measured at 200 mm distance, (a) is measured by the robot spectroradiometer, and (b) is calculated from the PPID measued at far-field. The shapes are different as seen from the figure, although the measured PPFD distribution at 200 mm is relatively uniform. In order to quantify the PPFD distribution, we calculated the dimension of the area where the PPFD is half of the peak value, which is called the half-peak PPFD size. As seen in Table 1, the half-peak PPFD sizes vary great between the practically measured value and the deduced value from far-field PPID, especially at close distance. And the comparison result is almost the same for the red & blue LED panel light.

Table 1 – The half-peak PPFD sizes of the phosphor converted LED panel

	actual measurement		Calculation by Far-field data	
	Length(m)	width(m)	Length(m)	Width(m)
200mm	0.50	0.50	0.27	0.26
300mm	0.60	0.50	0.40	0.40
500mm	0.82	0.71	0.67	0.64
1000	1.31	1.30	1.34	1.32

5.3 Angular distribution of PPFD

The PPFD distribution of horticultural lights at different angles is also analyzed using the distribution schematic diagram shown in Figure 11. The PPFD measurement results of 0.6m red & white LED light bar at 200 mm distance are shown in Figure 12, the PPFD distribution changes significantly with the increase of the angle.

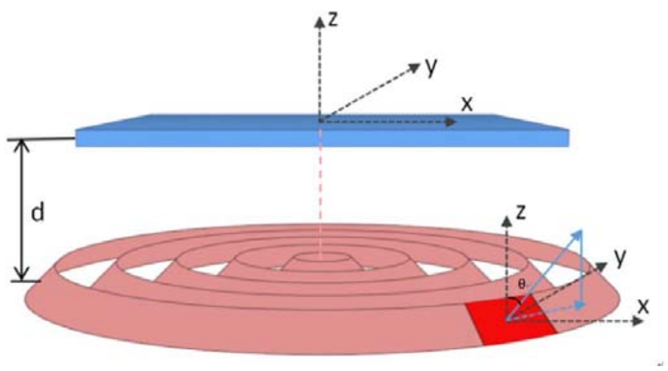


Figure 11 – Measurement schematic diagram of PPFD distribution at different angles

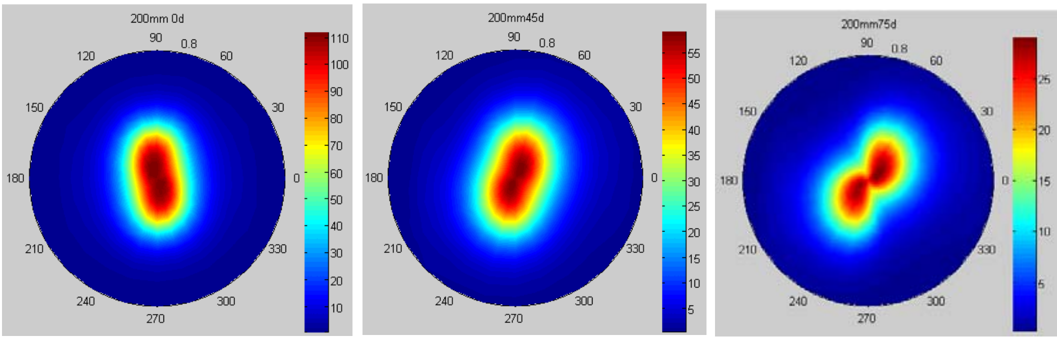


Figure 12 – PPFD distributoin of different inclined angles at the distance of 200 mm

5.4 Comparison of spatial R/B ratio

This paper proposes to use R/B ratio uniformity to characterize the spatial spectral uniformity of horticultural lights, based on the light demands of plants, and the R/B ratio is acquired as equation (2). The R/B ratio distribution at different distances and angles are analyzed. As shown in Figure 13, the 0.6m red & white LED light bar has large spatial spectral non-uniformity at near distances; For the red & blue LED panel, although the PPFD distribution is relatively uniform as described in 5.2, the spatial spectral uniformity is not good, and the distribution of the R/B ratio varies with inclined angles, as shown in Figure 14.

$$R/B\ \text{Ratio} = \frac{\int_{600}^{700} E_e(\lambda,x,y,z,\theta,\varphi)d\lambda}{\int_{400}^{500} E_e(\lambda,x,y,z,\theta,\varphi)d\lambda} \qquad (2)$$

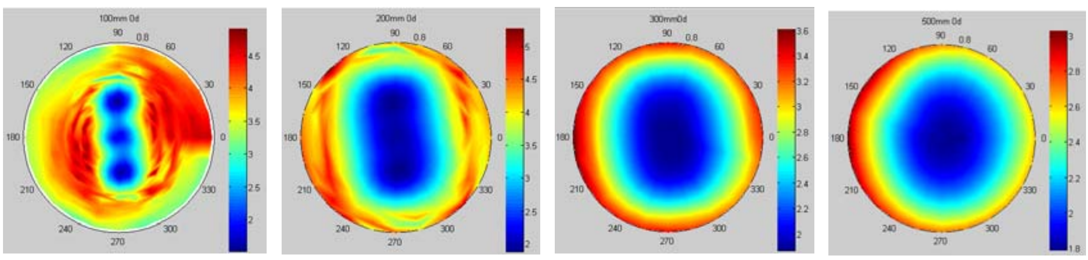


Figure 13 – Spatial R/B ratio results at 0° and different distances (0.6m red & white LED light bar)

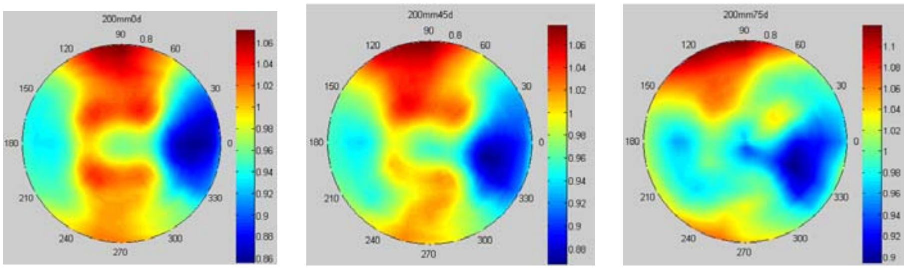


Figure 14 – Spatial R/B ratio results at 0° and the distances of 200mm (0.6m×0.6m red & blue LED panel)

To quantitatively characterize the spatial spectral distribution, the equations (3) and (4) are used to calculate the coefficient of variation and uniformity of the R/B ratio in the area where the PPFD is above the 10% peak value. The data of typical horticultural lights are listed in Tables 2 and 3.

$$S_{R/B} = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i-\overline{X})^2}}{\overline{X}} \tag{3}$$

$$U_{R/B} = \frac{X_{min}}{\overline{X}} \tag{4}$$

Where, X_i, X_{min} and $\overline{X}$ r respectively represent R/B ratio numbered i , minimum R/B ratio, and average R/B ratio in the region to be evaluated.

Table 2 – $S_{R/B}$ and $U_{R/B}$ of the 0.6m red & white LED light bar

Distance	50mm	100mm	200mm				300mm	500mm
θ	0°	0°	0°	15°	45°	75°	0°	0°
$S_{R/B}$	0.197	0.199	0.135	0.151	0.163	0.178	0.134	0.147
$U_{R/B}$	0.674	0.650	0.848	0.861	0.840	0.801	0.869	0.837

Table 3 – $S_{R/B}$ and $U_{R/B}$ of the red & blue LED panel

Distance	200mm	300mm	500mm	1000mm
$S_{R/B}$	0.033	0.027	0.025	0.021
$U_{R/B}$	0.877	0.891	0.896	0.932

It can be seen from the tables that the spatial spectral distribution uniformity tends to be better when the distance increases. In addition, we found that the spectral uniformity is also related to the LED's point interval of the horticultural lights in the measurement, and we will have more in-depth research in the future.

6 Conclusions

The development of SSL technology has promoted the application of LED horticultural lights, and further promotes the vigorous development of plant factories. Accordingly, the spatial light distribution characterization and measurement methods of horticultural lights have gradually attached close attentions. However, there is still no complete characterization and measurement solution for horticultural lights, which has become a big challenge for the development of the industry. Starts from the properties of plants and the actual lighting requirements in plant factories, this paper recommends series quantities which can effectively evaluate the spatial light distribution performance of horticultural lights, and proposes a professional measurement solution based on the analyzing the current measurement instruments for spatial light distributions. Also, the spatial light distribution of several typical LED horticultural lights are measured and analyzed by different measurement solutions. Furthermore, the spatial distribution uniformity of horticultural lights is also preliminarily proposed in this paper, and more research on the calculation method and evaluation area of uniformity will be engaged in the future.

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