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ILLUMINATION SCREENING AND UNIFORMITY SIMULATION OF HYDROPONIC LETTUCE IN ARTIFICIAL LIGHT PLANT FACTORY

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With the development of LED plant lighting technology and its wide application in agricultural production, LED plant grow lights have become the mainstream light source used for plant lighting in plant factories with artificial light (PFALs). Artificial plant light source is different from natural light source, its biggest characteristic in light quality, light intensity, photo period and light form all can be accurately and intelligently regulated, ideally can continue to provide plants with light energy at the lowest cost, guarantee annual production and supply with high quality and efficient agricultural products, for the different living environment of people continue to supply the essential fresh plant products. Illumination and illumination uniformity have a significant impact on plant photosynthesis and growth, and are also the basis of the design of plant lighting system in PFALs. In this paper, taking the lettuce varieties planted in the field as the test materials and experimental objects, we design the illumination gradient test, simulate the illumination uniformity of LED forms with different arrangement by using the computer simulation method, and study the influence of different illumination and LED arrangement forms on the growth and biomass of hydroponic Lettuce in PFALs, so as to provide the best lighting solution for the industrialization and standardized production of lettuce in plant factories. The results of the study showed that: for hydroponic lettuce in PFAL's lighting environment, the illumination uniformity of matrix LED light source is the best. The optimal lighting distance is between about 25cm and 30 cm from the lettuce. A red-blue light mixture ratio of 7:1 is the best light quality ratio for lettuce during seedling stage, and a red-blue light mixture ratio of 6:1 is the best light quality ratio in the growth period. The optimum light intensity is 400 $\mu mol / m^2 \cdot s$*. The best daily illumination time is 16* h / d*, and the illumination time can be appropriately extended to achieve the purpose of harvesting lettuce in advance.*

Key words: *LED plant light source; light formula; illumination uniformity; hydroponics; plant factory with artificial light; urban agriculture; smart agriculture.*

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Introduction. In recent years, the artificial light plant factory (PFAL) (Yang Qichang, 2014; Liu Wenke et al., 2014; He Dongxian, 2018; Kozai, 2019; Kozai et al., 2020; Huebbers et al., 2020) will become the mainstream production mode of urban productive agriculture because the plant growth environment is highly controllable and is not limited by the natural climate, geographical location, land resource and other conditions (Lee, 2018). Moreover, the agricultural products of plant factories have the advantages of no-pollution, no-pesticide-residue, no-washing ready-to-eat, green-healthy-environmental protection, which are expected and loved by people (Ares, 2021; Huang Lichun, 2019; 2021). The PFAL is the highest form of facility agriculture development that is a new agricultural production mode to develop intensive and efficient modern agriculture, more suitable for the development of industrialized and commercial plant production in urban areas and that has very good development prospects (Orsini et al., 2020).

Light is an energy substance necessary for photosynthesis, growth and development, morphological construction, and material consumption of plants, and the light conditions required by different species of plants at different growth stages vary greatly. Therefore, focusing on the optimal light conditions for a particular plant, including light quality, light intensity, light period, and form of light production, has become a hot spot for research on artificial light plant factories. Light emitting diode (LED) has many advantages, such as low voltage, low consumption, safety, energy saving, easy control, long service life, small and light weight, a wide working environment and so on that has become a common light source used as plant lighting in greenhouses and artificial climate chambers and that has also become the mainstream light source used in PFALs with the rise and development of PFAL (Tsuruyama et al., 2018; Prikupets et al., 2019; Wei et al., 2020; Paucek et al., 2020; Jiang et al., 2020).

In China and many countries around the world, lettuce is widely cultivated in fields and greenhouses and it is very popular because of its crisp-tender-fat leaves, good fresh-eating taste and easy to digest, green health care, high nutritional value. Moreover, it does not require a higher growth environment, easy to survive and grow faster, lush leaves, compact growth, lower plant height, short growth cycle, very suitable for cultivation in PFALs. As the demand for light is different for a particular plant at a certain growth stage, Philips took the lead in proposing the concept of plant light formulation, which has played an important role in guiding the design, development and production of plant growth lights. Light formula refers to the light conditions required by a crop at a certain growth stage in a particular growth environment (Wang Mengmeng et al., 2015; Liu Wenke et al., 2017; Marondedze et al., 2018). A light formula usually consists of eight parts in three aspects: (1) the first aspect is light characteristics, which are light quality, light intensity, photoperiod, light source installation location, lamps and LED beads quantity, and light uniformity. (2) environmental factors, that is, other environmental parameters based on light formula, such as temperature, humidity, etc. (3) light effect, such as energy saving effect. All the above factors are interdependent, interactive, intertwined and coupled together. Moreover, coupled with the complex biological mechanism of the plant itself, the study of plant light formula becomes extremely complex.

LED is a cold light source, and the closer it is to the plant, the stronger the illuminance, and the higher the utilization efficiency of light energy (Wang Haiou et al., 2004; Massa et al., 2008; Yang Qichang et al., 2011). Illuminance $\left(E\right)$ refers to the size of the luminous flux $\left(\varphi\right)$ received by the light receiving surface of the object in the unit area $\left(S\right)$, and the illuminance calculation method is shown in formula (1). The illuminance of LED lamp changes with the change of power supply voltage, which can be measured by spectrophotometer.

$$E = \frac{\varphi}{S} \qquad (1)$$

For different plants, different numbers of red and blue LEDs need to be selected for matching and combination, and the required illumination and illumination uniformity should be considered at the same time. Different kinds of plants need different light illumination uniformity (Wu Rengmao et al., 2009; Zhu Zhou et al., 2015). The illumination uniformity $\left(U_0\right)$ refers to the ratio of the minimum illuminance $\left(E_{min}\right)$ of the light receiving surface to the average illuminance $\left(E_{ave}\right)$ within a certain irradiation area, which is calculated as shown in formula (2). The value of illumination uniformity is $\left(0,1\right)$, and the closer the value is to 1, the more uniform the light received by lettuce and the better the overall growth.

$$U_0 = E_{min} / E_{ave} \qquad (2)$$

The planting process of Hydroponic Lettuce in PFALs is divided into three stages, which are germination stage, seedling stage and growth stage, and its cultivation cycle is generally about 30-50 days. The requirement of light is not high in the budding stage, so light regulation is rarely carried out. The best compound ratio of red and blue light in seedling stage is 7:1, and the best compound ratio in growth stage is 6:1. The best illumination time is 16 hours in the seedling stage and growth stage. Generally, the LED light beads are arranged at equal intervals, and the light of different arrangement modes irradiates the lettuce, the illumination uniformity is also very different, which will affect the overall growth of the lettuce.

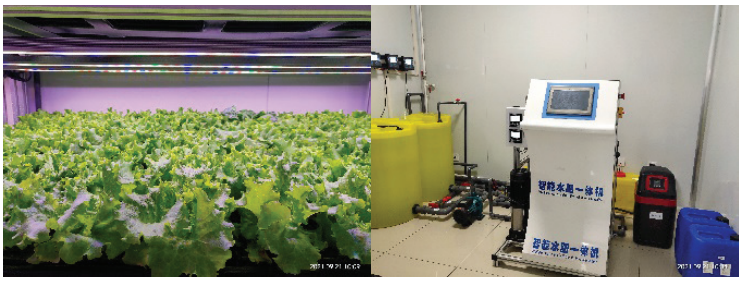
With the advancement of the industrialization process of the PFAL and the deepening of its research, improving the automation and accuracy of light environment regulation under the condition of full artificial light and maximizing the efficient growth of plants, which are effective ways to reduce energy consumption and improve the comprehensive utilization of resources (Saito et al., 2020; Yuan Fang et al., 2021). In this study, different LED illuminance and arrangement methods were used, and the illumination gradient experiment and illumination uniformity simulation experiment were designed, using the research methods of comparative experiment and computer simulation, the effects of different illuminance and led arrangement methods on the overall growth of lettuce under the condition of the PFAL were studied, in order to provide a standard illumination scheme for the industrialized production of artificial light plants.

Illumination gradient experiment.

1.1. Experiment site and test material

The laboratory is decorated with fully enclosed thermal insulation materials, the hydroponic room is designed with opaque light, the plant growth is illuminated by LED lamps with controllable red blue and white colors, the environment of the planting room is regulated by cabinet type air conditioning, fresh air system, humidifier and other equipment, which are combined and intelligently controlled by centralized control software, and the air flow of planting layer shelves are regulated by DC shaft fan. The nutrient solution circulating in the hydroponic layer shelves are intelligently regulated by the water and fertilizer integrated system controlled by the program. The experiment was conducted in staggered time periods from early June 2021 to the end of December 2021. Several lettuce varieties were used in the experiment. All lettuce seeds were purchased from formal seed industry companies and obtained market permission. All the test materials were taken from lettuce hydroponically cultured by laboratory personnel. The experimental site and some main experimental equipment are shown in Fig. 1.

(A)Laboratory of PFAL (B)Plant hydroponic shelves



(C)Hydroponic Lettuce (D) Integrated irrigation system of water and fertilizer

(E) Integrated environmental regulation system (F) dehumidifier

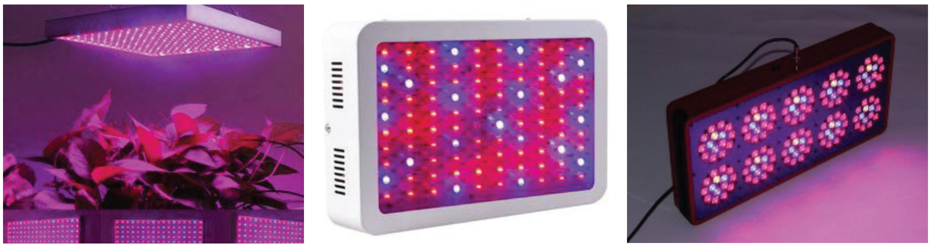
(G) Air flow regulating DC fan (H) Light sensor

Fig. 1. The PFAL laboratory of our university and some main experimental equipment

1.2. Experiment environment

The experimental LED plant growth light was custom developed by a professional manufacturer from Anhui ANCORGREEN. The light quality, light intensity and light period of LED lamp can be set according to the experimental requirements, and then intelligently controlled by the program. The light quality is composed of red, blue and white lights according to the set proportion, and the proportion of the three lights can be accurately controlled by the program, and some LED lamps used in the experiment are shown in Fig. 2. When the plants are illuminated to simulate the daytime, the indoor temperature of the laboratory is set at about 23 ℃

and the CO_2 concentration is set at about 800ppm. Moreover, when the plants are not illuminated to simulate the night, the indoor temperature of the laboratory is set at about 18 ℃ and the CO_2 concentration is set at about 400ppm. The humidity setting in the laboratory was maintained between 70% and 80%. The DC fan for airflow regulation of the growing shelves operate for 2 minutes at 10-minute intervals. The nutrient solution in the planting layer shelves is continuously supplied for 5 minutes at 30-minute intervals, in which the EC value is always maintained at 800 $\mu s / cm$, and the pH value is maintained at about 6.8. LED lamps are installed at the top of each layer of the planting shelves, 28cm away from the lettuce growing canopy, and the plant light time is set to 16 h / d .



(A) Matrix arrangement (B)Triangular arrangement (C) Circular arrangement

Fig. 2. LED plant lighting lamps for experiment

1.3. Experimental design

In order to find out the effects of different illuminations on the growth of lettuce, 60 robust lettuce seedlings were randomly selected, and each 15 seedlings were placed in 4 groups of light conditions for hydroponic culture experiment. The illuminance is set at 200, 300, 400 and 500 $\mu mol/(m^2 \cdot s)$, respectively, which are recorded as T1, T2, T3 and T4. From the first day after transplanting, five plants were randomly selected at 5 p.m. every day to measure and record the plant height, leaf length and leaf width of the outermost leaves of lettuce. When lettuce grows to 50 days, it is ripe and harvested. 8 plants in each control group with better growth are selected and the fresh weight of each plant is weighed, then the average of eight lettuce is found.

1.4. Results and analysis

After 50 days of hydroponic, the lettuce was harvested and the fresh weight of a single plant was weighed, and the results were recorded in Table 1. The lettuce growth and growth curves of different experimental groups are shown in Fig. 3 and Fig. 4, where Fig. 4(a) shows the average plant height growth curve, Fig. 4(b) shows the average leaf length growth curve, and Fig. 4(c) shows the average leaf width growth curve of lettuce.

It can be seen from table 1 and figure 3 that the growth of hydroponic Lettuce under different illumination conditions is significantly different. In terms of plant morphology, each experimental group of lettuce grew brittle green hypertrophy, but the number of lettuce leaves under 500 $\mu mol/(m^2 \cdot s)$ light was significantly less than that of the first three experimental groups. In terms of biomass accumulation, compared with the average fresh weight of single lettuce after hydroponic culture to 50 days, the biological yield of single lettuce under 400 $\mu mol/(m^2 \cdot s)$ illumination is the highest, which is about 37% higher than that under 200 $\mu mol/(m^2 \cdot s)$ illumination, 23.4% higher than that under 300 $\mu mol/(m^2 \cdot s)$ illumination and 53.8% higher than that under 500 $\mu mol/(m^2 \cdot s)$ illumination. The results showed that the illumination of 400 $\mu mol/(m^2 \cdot s)$ was more suitable for the growth of hydroponic Lettuce in PFALs.

Table 1

Single plant and average fresh weight of lettuce at harvest under different illuminance conditions (illuminance unit: ì $mol/(m^2 \cdot s)$, Fresh weight: grams)

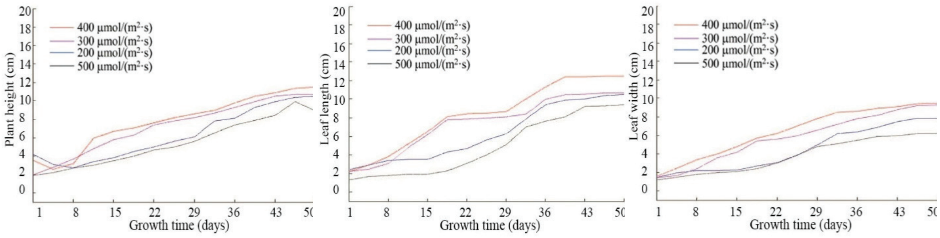
Illuminance	Fresh weight of single plant								Average fresh weight
T1	112	126	115	109	128	117	119	120	118.25
T2	136	132	128	126	131	129	138	127	130.875
T3	168	163	162	169	158	160	159	153	161.5
T4	96	112	103	97	108	102	106	116	105

As can be seen from Figure 4, with the increase of lettuce growth time, plant height, leaf length and leaf width of hydroponic lettuce show a rising trend, indicating that the illumination gradient setting is reasonable. For different growth indexes, the growth of lettuce in each experimental group was T3 > T2 > T1 > T4. The results showed that when the illuminance was set below 400 $\mu mol/(m^2 \cdot s)$, gradually increasing the illuminance

(a) T1 (b) T2 (c) T3 (d) T4

Fig. 3. Growth of lettuce in each experimental group at harvesting

could promote the growth of lettuce. When the illuminance reached 400 $\mu mol/\left(m^2 \cdot s\right)$, the growth of lettuce was inhibited by increasing the illuminance. The reason may be that the LED lamps with high illuminance have high thermal power consumption and high heat, resulting in water shortage of plants. It is also possible that high-intensity light has caused some damage to plant growth organs or some stress to physiological processes. The results also showed that the illumination of 400 $\mu mol/\left(m^2 \cdot s\right)$ was more suitable for the growth of hydroponic Lettuce in PFALs.



(A) Plant height growth curve (B) Leaf length growth curve (C) Leaf width growth curve

Fig. 4. Growth of lettuce under different illumination

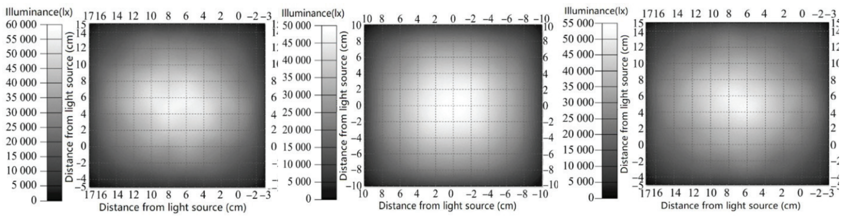
Simulation experiment of illumination uniformity.

3.1 Experimental design

Generally, led plant light sources are arranged in array, triangle and circle. In order to study the illumination uniformity characteristics of LED light sources with three arrangement modes, we use TracePro optical simulation system and three-dimensional composition method of MATLAB software to simulate the illumination uniformity, compare and analyze the advantages and disadvantages of the illumination uniformity of the three arrangement modes, and provide theoretical guidance for the design of plant light sources and plant production using artificial light sources.

(1) TracePro optical simulation experimental method

The TracePro optical simulation environment was configured systematically, 25 identical LED beads were selected and arranged into matrix, triangular and circular forms in turn, with the spacing set to 3cm and the light source 28cm away from the lettuce. After the other environmental parameters of the artificial light plant factory laboratory were set, the Tracepro software was run to export the simulation diagram, as seen Fig. 5.

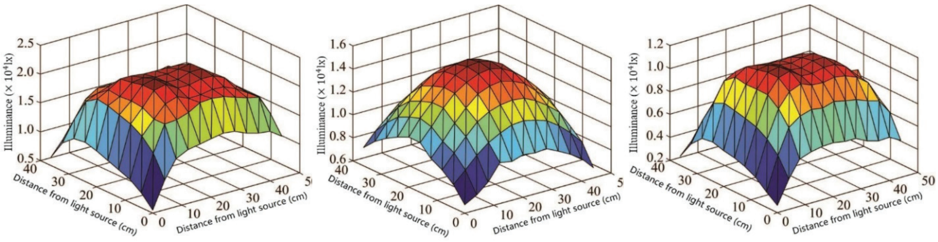


(A) Simulation results of matrix illuminance distribution (B) Simulation results of triangle illuminance distribution (C) Simulation results of circular illuminance distribution

Fig. 5. Simulation results of illuminance distribution in different arrangement modes

(2) Matlab software simulation experimental method

Through the Matlab software system, a three-dimensional diagram is constructed according to the collected illumination data to visually display the distribution of illumination uniformity. The test step is to fix the LED light beads on the top of the planting layer shelf into the form of matrix, triangle and circle with a spacing of 3cm, and the light source is 28cm away from the coordinate paper. The specification of coordinate paper is 100cm × 100cm, composed of small squares of 1cm × 1cm. After preparation, the illuminance at each small square is measured successively with the illuminance sensor, and the final summary data is constructed into a three-dimensional diagram through Matlab software, as shown in Figure 6.



(A) Matlab simulation of matrix arrangement illumination distribution

(B) Matlab simulation of triangle arrangement illumination distribution

(C) Matlab simulation of circular arrangement illumination distribution

Fig. 6. Matlab simulation of illuminance distribution in different arrangement forms

2.2. Results and analysis

(1) Optical simulation results and analysis of TracePro software

As can be seen from Fig.5, the three arrangement modes all show the light distribution characteristics that the middle area of the light receiving surface is brighter and the surrounding area gradually darkens. Among them, the overall illuminance of LED light sources arranged in matrix is significantly better than that of triangular and circular arrangement modes. Lighting uniformity index refers to the uniformity of illumination distribution. According to the simulation results, the illumination uniformity of the matrix is 80%, as shown in Fig.5(a). The illumination uniformity of triangular form is 71%, as shown in Fig.5(b). The illumination uniformity of the circular type is 79%, as shown in Fig.5(c). Through TracePro computer simulation, it can be shown that the matrix LED light source arrangement form has the best illumination uniformity.

(2) Matlab 3D simulation results and analysis

In the three-dimensional stereogram constructed by MATLAB, the areas with different colors represent different illuminance of the light receiving surface. If the color of the adjacent area is closer or the plane area of the wave crest position is larger, it indicates that the difference of the received illuminance is small and the uniformity is more. From Fig.6(a), Fig.6(b) and Fig.6(c), it can be shown that the middle regions of the three figures show similar colors such as red, dark red and orange, and the middle regions of Fig.6(a) and Fig.6(c) have more similar colors than Fig.6(b). Comparing Fig.6(a) and Fig.6(c), all of them have a certain plane area at the wave peak position, and the plane area in Fig.6(a) is significantly more than that in Fig.6(c), which indicates that the matrix arrangement represented in Fig.6(a) has the best uniformity of illumination. Therefore, the simulation method by Matlab software also proves that the matrix arrangement of LED light source has the best light uniformity.

Discussion and conclusion.

The light environment parameters of plant cultivation are mainly composed of light source, light quality, illumination, photoperiod, light uniformity and so on. There are many scholars who have conducted relevant studies on some of these factors and found some patterns of the effects of certain factors on plant growth. Yan Zhengnan (2020) systematically studied the effects of white-red and red-blue LED lighting environment on the growth, quality and energy utilization efficiency of two kinds of lettuce, and found that white-red LED light quality can replace red-blue LED light quality and be used in lettuce hydroponic culture to improve resource utilization. Li Dongxing et al. (2012) found that the growth trend of lettuce under 16h continuous light is generally better than that under 16h intermittent light. Kim et al.(2017) and Mu suntao et al. (2020) studied the effects of different pulsed light on the growth, quality and photosynthesis of lettuce. They found that under the same conditions as the net photosynthetic rate of continuous light, the light mode of pulsed light not only did not affect the growth of lettuce, but also improved the quality. They also found that the quality of lettuce treated with pulsed light combined with low frequency and high duty cycle was better. Therefore, they proposed that an appropriate light source should be selected in combination with pulse light energy consumption in actual application. Ding Juanjuan (2014) and Wang Xiaoxu (2017) studied the effects of different duty ratios of LED on the growth, yield, quality and Photosynthesis of lettuce. They found that the duty ratio affected the growth of lettuce from two aspects: light period and dark period, and affected the photosynthesis, growth and development, morphogenesis and yield formation of lettuce by the interaction of light period and dark period.

In this study, the illuminance gradient test found that 400 $\mu mol/\left(m^{2}\cdot s\right)$ illuminance is the best illumination under artificial lighting conditions, and the simulation of TracePro and Matlab software found that matrix LED light source arrangement has the best illumination uniformity compared with triangle and circle arrangement. Through experimental research, we obtained the best light formula of hydroponic Lettuce in PFALs: the plant growth environment temperature is kept at about 22 □ and the humidity is kept between 70%~80%. The LED light source using matrix arrangement in matrix is 28cm away from the lettuce. The compound light with the ratio of red and blue light of 7:1 is used in the seedling stage, and the compound light with the ratio of red and blue light of 6:1 is used in the growth stage. The illuminance is set at 400 Mol, and the photoperiod is set at 16h/d. The light formula can be used as a general scheme for large-scale Hydroponic Lettuce in plant factories, and can also be used as a reference light formula for other varieties of leafy vegetables. This research has certain practical significance for promoting the industrialization and commercial production of artificial light vegetables.

Data availability statement The Micro-Tom tomato datasets constructed for this study are available to the researchers in need according to relevant requirements.

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Моделювання екранування рівня освітленості та рівномірності гідропонного салату-латуку на фабриках з вирощування рослин зі штучним освітленням

З розвитком технології світлодіодного освітлення рослин та її широким застосуванням у сільськогосподарському виробництві світлодіодні світильники для вирощування рослин стали основним джерелом світла, яке використовується для освітлення рослин штучним освітленням (PFAL). Штучне джерело світла для рослин відрізняється від природного джерела світла; його найбільшою характеристикою є якість світла, інтенсивність світла, період фотозйомки та форма світла, все можна точно та розумно регулювати, в ідеалі може продовжуватись забезпечення рослини світловою енергією за найнижчої вартості, гарантувати щорічно виробництво та постачання високоякісної та ефективної сільськогосподарської продукції для різних сфер життя людей, які продовжують постачати необхідні свіжі рослинні продукти. Освітлення та рівномірність освітлення мають значний вплив на фотосинтез і ріст рослин, а також є основою проектування системи освітлення рослин у PFAL. У цій статті, досліджувались сорти салату, висаджені в полі, як дослідні матеріали та експериментальні об'єкти. В статті розроблено тест градієнта освітленості, моделюємо рівномірність освітлення світлодіодних форм із різним розташуванням за допомогою методу комп'ютерного моделювання та вивчаємо вплив різного освітлення та різні світлодіодні форми розміщення на зростання біомаси гідропонічного салату в PFAL, щоб забезпечити найкраще освітлювальне рішення для індустріалізації та стандартизованого виробництва салату на заводах. Результати дослідження показали, що: для гідропонного салату в середовищі освітлення PFAL рівномірність освітлення матричного світлодіодного джерела світла є найкращою. Оптимальна відстань освітлення становить від 25 до 30 см від салату. Співвідношення червоно-синього світла в суміші 7:1 є найкращим співвідношенням якості освітлення для салату на стадії розсади, а співвідношення червоно-синього світла в суміші 6:1 є найкращим співвідношенням якості світла в період росту. Оптимальна інтенсивність світла становить 400 мкмоль/м^2·с. Найкращий щоденний час освітлення становить 16 годин/день, і час освітлення можна відповідно збільшити, щоб досягти мети завчасного збору врожаю салату.

Ключові слова: *LED светоисточник растений; рецептура света; равномерность освещения; гидропоника; завод искусственного света; городское сельское хозяйство; интеллектуальное сельское хозяйство.*