The application of LED illumination and intelligent control in plant factory, a new direction for modern agriculture: A Review

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Abstract. Because of its cold light source and adjustable spectrum characteristics, light-emitting diode (LED) is widely used in modern agriculture, it can promote the growth and photomorphogenesis of the plant, also can improve yield and quality. Here, we introduce the advantages of LED over traditional light sources, and analyze the effects of different wavelengths of light on phototrophic plants and the ways in which different light detection systems interact in plants. We also analyze the effects of LED illumination on plants, the response of plants to LED illumination systems. In addition, we summarize the typical LED supplement light devices and intelligent control system in the world, and introduce their working methods and advantages respectively. Finally, we look forward to the future development direction and application prospects of LED with the intelligent control and machine in modern agriculture.

1. Introduction

According to statistics, the global population will exceed 9 billion by 2050. Population growth has caused global problems such as food shortages, resources deficiency, and environmental degradation. Deterioration of the natural environment includes soil compaction caused by human factors, soil salinization, heavy metal pollution, severe haze and desertification (UN, 2014) [1]. As a result of climate change, it is difficult to produce crops steadily. Simultaneously, per-person cultivated land area and per ca-pita share of grain are decreased, and with the development of technology, young people are even more reluctant to farm or take part in the agricultural sector. Therefore, it is difficult to achieve predictable and consistent yields [2, 3].

A closed production system such as plant factories and vertical farms can be in extreme harsh environmental conditions for production such as extreme droughts or hot weathers that can become challenging for farming. Such an arrangement as this will help agriculture get rid of resources and environmental constraints that cause a challenge and we are able to achieve sustainable agricultural development. The system is achieved by adapting to the indoor climate and using a high-precision environmental control system to minimizing illumination, temperature and relative humidity, it also combines intelligent control, modern industry, biotechnology, nutrient solution cultivation and...
information technology to implement high-precision control of environmental factors in the facility so that plant growth is, or rarely restricted by external natural conditions [2, 5].

Factory-style plant production system aims to produce the standardized horticultural products with high quality and cleanliness. At present, most green leafy vegetables and herbs produced by plant factory are not sold in large supermarkets or grocery stores, but are sold to food service industries, including household substitution industries.

In these industries, leafy vegetables produced using plant factory are free of pesticides, contaminants and insects without cleaning, which greatly reduces the cost of sanitary processing [3, 10].

Therefore, the plant factory is considered to be an important way to the shortage of resources and high demand of food, to solve problems such as lack of new generation labor in the future. It is also an important means of achieving food self-sufficiency in the future exploration of space engineering, the moon and other planets, and it has been widely valued by countries around the world. At present, plant factory is mainly distributed in East Asia, Europe and the United States, most representative country are Japan, the Netherlands and China. Among them, Japanese industrialization of artificial light plant factories are relatively fast, leading the way.

The goal of this article is to summarize the primary research and application, and to provide recommendations for future research on this topic.

2. The advantages of LED illumination

As an important physical environmental factor, light plays a key role in regulating plant growth and material metabolism. One of the main features of the plant factory is the complete artificial light source and the intelligent adjustment of the lighting environment [4], which now has become a common consensus in the industry.

The light source used in plant factory mainly includes: high pressure sodium lamp, fluorescent lamp, metal halide lamp, incandescent lamp, etc. A significant disadvantage of this typology is the high energy (electricity) requirements for artificial lighting, which is required for photosynthesis. In addition, high-density crop cultivation and lack of natural ventilation may result in high demand for cooling and steam removal [5]. Compared to the listed light, LED has become a very promising light source in the lighting of plant crops. LED has the advantages of high radiation efficiency, long life, small size, low temperature, narrow spectrum, strong physical robustness, etc., and have strong appeal [6-10].

Application of narrowband LED with the best wavelength combination can optimize the light source and promote photosynthesis [11-13]. As a new solid-state semiconductor light source, LED has incomparable photoelectric advantages, including: 1. Adjustable spectrum, can be modulated spectrum according to plant growth and its development demand, use light on demand, high biological light efficiency. 2. Cold light source, can close to plant irradiation, improve space utilization. 3. Controllable, can accurately control light intensity, light quality and photoperiod, suitable for factory production. 4. Energy saving, environmental protection, long life, small size, light weight. 5. LED light source device diversity (lamp board, lamp belt, lamp tube and light bulb), suitable to protected horticulture [14-16].

At present, there are panel lights, strip lights, lamp tubes, lamp belts and other lamps for plants that have been developed, and promote the application. Physiological factors mainly determine the appearance and quality of crop grown under the environmental conditions. In the middle of the physiological factors light is the most vital one. As noted in the beginning light also plays multiple roles life plants which as: 1. To ensure the photosynthesis of plant. 2. To regulate various processes for morphogenic signaling in the plant. 3. To drive a number of light-dependent biochemical reactions. LED can provide a reasonable lighting environment for plant growth and is very suitable for the application of plants in multi-layer cultivation.

3. Regulation of the LED lighting in plant factory

Light environment in plant factory affects plant morphological formation, photosynthesis rate, substance metabolism and DNA expression [18]. The light environment is divided into three parts:
light intensity (amount of light), light quality (i.e. spectral composition) and light period (i.e. alternating period of light and shade). In plants, plant morphogenesis, photosynthesis, substance metabolism and gene expression are affected by the light environment.

3.1. Effects of Light Intensity on Plants

Light intensity mainly affects the rate of photosynthesis in plants. In low light conditions, the respiratory intensity of plants is higher than that of photosynthesis. As light intensity increases, the rate of photosynthesis in plants increases, and when the CO$_2$ absorbed by photosynthesis is equal to the CO$_2$ released by respiration, plants begin to accumulate organic matter. The light intensity at this moment is called the light compensation point. As the light intensity continues to increase, the photosynthetic rate of plants increases gradually, and the light intensity when the photosynthetic rate increases to the maximum point becomes the light saturation point of plants. Therefore, when plants are cultivated in plant factory, the light provided to plants should be close or equal to the light saturation point of plants. According to the size of the plant light saturation point, the plants are divided into positive plants, neutral plants and shade plants.

For example, in the tissue culture of medicinal plants, the content of artemisinin increases obviously with the increase of light intensity. The increase of light intensity also induced oxidative stress characterized by increased concentration of reactive oxygen species ROS which enhanced the content of artemisinin [18]. However, for different medicinal plants, the effect of light intensity on the formation and accumulation of medicinal components is different, some promote the accumulation of medicinal components, and some inhibit the accumulation of medicinal components [19].

In plant culture, photosynthesis begins to manifest itself at a certain level of light at which the plant is exposed to, in many cases it begins at the level of PPFD of 20 µmol·m$^{-2}·s^{-1}$ and increases monotonically to 1000-1500 µmol·m$^{-2}·s^{-1}$ [20].

The range of photosynthetic photon flux density where light plays its role the role of the signal is much broader. The response mediated by photoreceptors (mainly plant pigments) is categorized into three types: very weak fluence response, weak fluence response and strong fluence response [21]. It has been observed that some cultivars are better adapted to low light conditions, while others take advantage of high PPFD [22]. At present it is very difficult to be able to precisely determine the PPFD content to conduct the chloroplastic retrograde signals. This is because it is dependent on the type of plant that we are dealing with and especially the growth conditions and finally the response type. [23].

| Table 1. Some examples of different PPFD and their effect on plants. |
|---|
| Number | Plant | PPFD/(µmol·m$^{-2}·s^{-1}$) | Light source |
| 1 | Lettuce | LED: 100<br>LED: 200<br>LED: 300 | Red LEDs (660nm)<br>Blue LEDs(450nm) |
| 2 | Mustard, Spinach | Total:300 | Red LEDs(638nm)<br>and HPS lamp |
| 3 | Red leaf lettuce | LED:300 | Red LEDs (640nm)<br>Blue LEDs(440nm) |
| 4 | Baby lettuce | LED:210<br>HPS:300 | Red LEDs(638nm)<br>and HPS lamp |

1. When lettuce is maintained at 100, 200, and 300 µmol·m$^{-2}·s^{-1}$ using red LEDs (660 nm) and blue LEDs (450 nm) the results showed the total increase of dry weight of lettuce [23].

2. When using red LEDs (640 nm) and blue LEDs (440 nm) and the PPFD maintained at 300µmol·m$^{-2}·s^{-1}$ the anthocyanin, antioxidant potential and leaf area of lettuce increased [24].

3. When red LEDs (638 nm) and high pressure sodium (HPS) lamp was used and maintained at 300 µmol·m$^{-2}·s^{-1}$ PPFD the results showed increase of the vitamin C in mustard and spinach [25].
4. When attached to a fixed value of 210 µmol·m$^{-2}$·s$^{-1}$ and to a fixed value of 300 µmol·m$^{-2}$·s$^{-1}$ for HPS under the same conditions increased the phenols, tocopherols and antioxidant capacity of lettuce [26].

The most used PPDF band in the field of plant cultivation is as follows: first band 200-250 µmol·m$^{-2}$·s$^{-1}$ second band 500-800 µmol·m$^{-2}$·s$^{-1}$. note that in most cases the last value strongly depends on the leaf area index of the crop [23, 27]. The distance between plant and LED influence the PPDF.

It is very difficult to be able to predict the PPDF for one for a better reduction both in terms of plant needs and economic profitability of electrical energy. The level of PPDF used in the plant factory varies from 210 to 1600 µmol·m$^{-2}$·s$^{-1}$ and depends to a large extent on plant species, density, growth conditions and selected optimality criteria. The selection of the best criteria is based on specific objectives of plant cultivation. This may include maximum growth productivity (biomass) of leafy vegetables.

3.2. Effect of photoperiod

The photoperiod is the timer and starter of life activities controlled by the length of the photo. The photoperiod responses of the plant is mainly to induce the formation of flower buds [28], while affecting its growth, which has manifested characteristics that are closely related to the number of illumination hours. Long photoperiods promoted the growth of radish including its leaf area, leaf chlorophyll content, fresh weight, and dry weight. Whereas, this effect is reduced when photoperiod extended to 24 h [29, 30]. For example, long-term photoperiod plants need more than 14 h of sunshine time to blossom, such as wheat, spinach, poplar, etc. Short-term photoperiod plants need less than 10 h of sunshine time to blossom, such as rice, corn and sorghum. For most cultures, the photoperiod, and especially the length of the night, plays an important role in plant development. For a certain number of cultures, the use of artificial lighting makes it possible to ensure maximum productivity.

Therefore, by maximizing and increasing plant biomass, increasing the photoperiod length has a strong positive effect on plant growth. By extending the photoperiod from 16 h to 24 h, the total radiation increased by 50%, doubling the weight of all pine leaf lettuce varieties (LactucaSativaL.). When the total daily radiation (moles of photons) is the same, plants under continuous radiation are 30% to 50% heavier than plants under 16h light [31, 32]. It should be noted that this result is obtained on a low level of PPDF. On the other hand, the effect of photoperiod on the plant depends on the individual species and cultivar.

Generally, the effects of PPDF and photoperiod on plant growth and development are prevalent. Plant growth increases with PPDF in the unsaturated range. Photoperiod determines plant development according to the photoperiod response of plants [33].

3.3. Importance of the spectral composition of light

The photo-spectral distribution has an important influence on plant photosynthesis and morphogenesis. The plants on the earth are constantly adapting to solar radiation during long-term evolution, and different species have different light-selective absorption characteristics (For example, chrysanthemum) goes from 400-490nm and 660-680nm bands, close to the maximum absorption bands of chlorophyll extract 420-460nm and 640-660nm, respectively [33-35]. LED can provide a variety of single light needed for plant growth, the spectral domain width ±20 nm, after a combination of various monochromatic light LED, the spectral components can match the spectrum needed for photosynthesis and morphogenesis of various plants. Therefore, using LED as a plant lighting source can improve the efficiency of light energy utilization of plants, and its energy saving effect is extremely remarkable [36].

Blue light can affect the content of chlorophyll in plant cells, but the degree of influence on different kinds of plants or different tissues and organs of the same plant is different. A large number of studies have confirmed that blue light is beneficial to the development of chloroplasts and can increase the content of chlorophyll in algae cells [37, 38]. The ratio of red light to Far-Red Light can regulate the germination process of plant seeds and inhibit seed germination when the r/fr ratio is low.
Both Blue violet light and ultraviolet light can inhibit stem growth. Blue light can regulate the phototropism of plants, and blue light with higher light intensity (more than 100 µmol·m⁻²·s⁻¹) weakens the phototropism. Blue light with lower light intensity (less than 100 µmol·m⁻²·s⁻¹) enhances the phototropism of plants. It can then be conclude that phototropins promote plant growth by controlling and integrating a variety of responses that optimize photosynthetic performance under low photosynthetically active radiation in the natural environment [40]. Red light is the most effective light substance to inhibit the flowering of short-day plants and promote the flowering of long-day plants during the intermittent dark period, while far red light can counteract this red light effect [41].

The light of different spectral components can change the content, active and inactive forms of hormones in plants, and regulate the transport of hormones. It is also known that the combination of LEDs (blue, green, red) have an influence on the rate of photosynthesis, growth and morphogenesis of lettuce.

Unlike the photosynthesis of different plants, the photosynthesis rate of crops can be significantly increased by the light in the yellow-green range, because this light can reach a lower level of closed cultivation [42]. Green light is absorbed less by chlorophyll compared with red and blue light, which results in more green light reaching the lower layers of a leaf, i.e. the gradient of green light is less steep compared with those for blue and red light [43]. The coefficient of extinction of light of different wavelengths inside the leaf depends on the structure of the leaf, and the structure of the leaf depends on the anatomical structure and the light intensity of the species during leaf formation [44]. However, it should also be noted that the structure of the crop also influences it, which in turn also depends on the height of the plant, the leaf area index, the position of the leaves in relation to luminous flux, etc. After some experiment to demonstrate that when there is an increase in the PPDF towards the saturation point of the light of the chloroplasts, there are places to notice a gradual decrease in the mixed light (red and blue) which is done this time under the form heat. The action of white light in plant cultivation has been of great importance, knowing that it is almost inseparable from green light. Which has the advantage over blue-red light of penetrate deeper into the leaf and absorb the lower chloroplasts, which will lead to an increase in photosynthesis which is good for plant growth. It should be noted that this happens when plants are been grown under white light and high PPDF [43].

Scientists have determined the effect of the ratio of blue to red LEDs on the leaf shape, plant growth and accumulation of antioxidant phenolics in red and green tendril lettuce varieties. In many reports, concluded that the combination of red light and blue light can significantly reduce the accumulation of nitrate in lettuce, which is essential for the cultivation of lettuce and enhanced lettuce growth and produced more biomass [45]. The Red and blue lights have the greatest impact on plant growth because they are the major energy sources for photosynthetic CO₂ assimilation [46]. The effect of light quality is more complex, with mixed results. Additionally, there are inconstant spectral demands and photosynthetic responses for different plant species, so it is necessary to study and establish. However, the spectral distribution has not been customized and optimized. The best light quality adjustment strategy will enable people to choose the most effective spectral components to enable plants to grow in the most energy-efficient way.

4. Illumination control system

Illumination control system mainly consists of the following two aspects: machine structure and control system. This part mainly introduces typically LED supplement light and intelligent control at present.

4.1. LED supplement light device

The plant growth depends on photosynthesis [47, 48]. The growth and morphogenesis of crops are closely related to the light intensity and uniformity of illumination of light. The high density planting pattern in plant factory causes the unbalance distribution of light and temperature which affects the yield and harvest period of the crop, as shown in Figure 1. In order to improve the light distribution between plants, it is best to use LED light sources in the form of flat screens, where the LEDs are evenly distributed. The LED panel can be placed horizontally or vertically along the perimeter or inside of the crop [49]. Make use of the LED panel with a reflecting display placed on the crop surface
and above the branches. The use of photosensitive elements to automatically monitor and correct the
light in the area or harvested volume can provide more opportunities to improve the power conversion
efficiency of crops [50].

Japanese experts have successfully designed a plant factory that can adjust the height of the light. As shown in Figure 1, the plant factory realizes the up and down movement of the LED light source through a The mechanical hinge structure is used to fix the lamp tube, and the horizontal movement of the X-shaped steel frame is converted into vertical lifting by the positive and reverse of motor, at the same time, the MCU(Microcontroller Unit) is used to control the brightness of the LED illumination, finally solving the illumination distribution on the blade of the crop and temperature uniformity. However, it should be noted that the rate or amount of light that falls on the outer leaves during the growth period is not efficient to cause the process of photosynthesis to be executed at the outer leaves without any problem. The outer leaves senescence fast and appear yellow [51], therefore harvesting or production will not be so satisfactory. Improving the light conditions of these leaves could delay senescence. Previous studies have shown that irradiation of both the ad-axial and ab-axial sides of a leaf can increase photosynthesis [52]. Newly proposed a plant factory cultivation system using a combination of downward lighting and supplement upward lighting which reduce the shading over the inner leaves and retard the senescence of the outer leaves and improved the photosynthesis leading to significant increase in lettuce yield [53]. The supplemental upward lighting increased the curvature factor of the photosynthetic light–response curve, providing the feasibility to cultivate sun-type species under relatively low downward lighting with supplemental upward lighting.

In 2017, Beijing Kingpeng International Hi-Tech Corporation of China successfully developed a new mobile light-filling device. As shown in Figure 2, the device can automatically adjust the fill-in height in real time according to crop growth requirements. The adjusting device is installed on the 3-layer light source lifting type stereo cultivation, the top layer of the device is the best lighting level, and the high-pressure sodium lamp is arranged; the middle layer and the bottom layer are arranged with the lifting and lowering adjustment system, and the LED lamp is installed, according to the detection signal of the light sensor Automatically adjust the height of the fill light to provide a suitable lighting environment for the crop. Later on a system of adjusting the light in the plant factory was carried out and this time, the proposed LED system measures environmental data, such as the distance between the plant and LED system using and infrared sensor and the ambient illuminance based on illuminance sensor. Then it converts the relationship between the data and LED PPFD, and generates an optimal pulse width (PWM) and control the data and the LED PPFD drastically [54].

The University of Southern California designed and manufactured the lighting system Figure 3. The growth panel is no longer horizontal. The panel for growing cylindrical plants is designed. The cylindrical culture panel has a water tank filled with culture liquid and passes through the gear mechanism. The cylindrical culture the plate is driven to rotate at a certain speed, so that the culture can completely absorb the nutrient solution, and the LED is a 360 degree light source, thus obtaining uniform illumination of the cultivated plants [55]. Developed an LED lighting apparatus figure 4, which would optimize light conditions for PFAL which was to use a supplemental upward lighting from underneath to obtain higher marketable Lettuce (Lactuca sativa). Lettuce (Lactuca sativa) was hydroponically grown under white, red, or blue LEDs, with light provided from above (downward), with or without supplemental upward .the proposed system used sensor. The sensor senses the growth status of the crop, and the light control system compares the data in the expert library according to the growth status of the crop, and adjusts the brightness of the upward lighting and the downward lighting in real time to meet the optimal growth conditions of the crop. The result showed the supplemental lighting retarded the senescence of outer leaves and decreased waste, leading to an improvement of the marketable leaf fresh weight.
4.2. **LED intelligent control**

Plant light environment control is achieved through a control system composed of led light sources, sensors and computers. Its objectives are two: energy saving and high quality and high yield of plants. Plant yield and quality response is the core of plant environmental control, and the light environment parameters needed for plant growth and development are the basis of plant light technology and the biological basis of light environment intelligent control. Therefore, based on LED lighting technology,
the main method of energy saving and efficiency in plant lighting is to establish targeted illumination formula (lighting recipe, lr) and light environment control strategy (light environment control strategy, lecs) based on the light environment demand characteristics of plants, and to realize automatic control through computer, which can not only maximize the productivity of plants, but also make the illumination targeted, and avoid the energy waste caused by blind ineffective illumination. Increasing plant productivity is the main way to increase plant production efficiency.

At present, intelligent factory light control still works with a simple control mode, based on traditional light sources, the LED light source is only used by a small number of systems and the source LED light is of fixed wavelength and light intensity. The recent development of intelligent machine vision is precision artificial lighting system enables us to control the light condition depending on the needs of the plant. Successfully developed an intelligent machine vision for the precision irrigation system and the precision LED lighting system it shows effective control of the moisture content and light intensity of the plant precisely [56]. In a large-scale factory, these systems can optimize plant growth and reduce water consumption and energy cost. Presented the method of combining machine vision and scanning laser diode lighting system to control the state of light [57]. An intelligent irrigation system using an artificial neural network can accurately predict the water deficit of the foam and respond accurately to the moisture demand of the foam pad. The line plotter transmission robot has been tested to describe the relationship between load changes and speed and transmission energy which presented acceptable result. The precision artificial lighting system identifies areas where the foam pad lacks light and provides precise light in each area of the foam pad according to its needs. A system was developed to monitor the ambient temperature and light intensity of a specific spectrum, and accurately calculate the amount of auxiliary light. Based on the two PWM signal, the intensity of red and blue light can be adjusted to meet the different needs of quantitative supplementary light at different stages and conditions [58].

Setting up wireless intelligent control system fora plant factory which help on controlling light. The system is self-organized, easy to install and expand, and can meet the requirements of large factories. Which is based on a three-layer network structure and has a monitoring center, a zigbee protocol-based data transmission network and a RS485 network-based data acquisition and control. A monitoring center consists of an industrial control computer (IPC) that runs a server/client application that can send and receive predefined packets periodically [59]. A client application is a web application that users with mobile devices can access locally or remotely to monitor the system. A data transmission network based on zigbee protocol consists of three logical devices, namely coordinator, router and terminal device. The coordinator is responsible for configuring the zigbee network and allowing others to join automatically, providing broadcast, multicast, packet unicast and packet forwarding as gateway nodes between IPC and wireless networks. The router extends wireless signal coverage and forwards packets from the terminal device to the coordinator. Terminal devices play an important role in zigbee networks and data acquisition subsystems. Which is the host device of the RS485 network, the control light quality control subsystem. The camera modules are used to monitor the growth of the plant by sampling the image with a fixed period and transmitting.

5. Conclusion

The LED combined with artificial intelligence in plant cultivation allows us to be able to change the light spot according to the evolutionary state of the plant with the advantage of reduction of energy. In addition the change of angle of the additional light gives us the advantage of giving the plant enough light for its growth and development. While following the development of the plant, the LED light source can move to suit growth of the plant and can change the wavelength to give to the plant the best light in the suitable position.

The development of science and technology and new technologies has had an impact on the development of traditional agriculture. In the future, the direction of development of the factory should be reworked with great precision, saving energy, sensors and artificial intelligence remotely controllable and an expert control system. At the same time, the future factory will continue to develop at a lower cost, with intelligence and adaptability. Using the LED light source combined with artificial intelligence can enable high-precision environmental control for factories, which can be as follows:
1. Combining intelligent control and mechanical structure, a light control mechanism capable of adjusting the size of the light spot, then achieve the goal of saving energy. 2. Combining intelligent control and mechanical structure, a light control mechanism capable of adjusting the size of the light spot, then achieve the goal of saving energy. 3. It can change the wavelength to give the plant the best light. Regulation of the LED light environment is a complex process involving the quality of light, light intensity, photoperiod and other comprehensive controls. It is believed that with new research into lighting and the promotion of LEDs, plant factories will play an important role in our society.

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