

Research on the Current Status of Light Supplementation Technology for Dragon Fruit

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Abstract. Dragon fruit has a good market prospect for its good taste and high nutritional value. At the same time, since its planting conditions are easy to meet, dragon fruit is widely planted in many regions of China. However, the problem of insufficient sunlight in spring and winter still leads to an insufficient supply of dragon fruit production. To improve the quality as well as the annual supply cycle of dragon fruit fresh fruit, and improve the economic benefits of dragon fruit cultivation, fruit growers generally use artificial light supplementation technology to regulate the flowering cycle of dragon fruit to prolong the production period. This paper reviews the impact of different light qualities, light intensities, and photoperiod on the production and quality of dragon fruit, and summarizes the shortcomings of the existing supplementation technology. The feasibility of the combination of photovoltaic, energy storage, and dragon fruit light supplementation technology is also comprehensively analyzed, and the outlook is put forward, aiming to provide a direction for the further development of dragon fruit light supplementation technology.

Keywords: Dragon fruit; Light Supplementation; LED; Renewable energy

1. Introduction

1.1 Characteristics and Value of Dragon Fruit

Dragon fruit belongs to the cactus family, also known as dragon pearl fruit. It has high requirements during its flowering, pollination, and fruit growth periods. It also requires high temperatures, humidity, adequate lighting, and other conditions. Therefore, dragon fruit is generally suitable for growth in tropical and subtropical regions. During the growth process of dragon fruit, there are certain temperature requirements: the temperature at night in winter should be above 0 °C, preferably above 8 °C, and the suitable temperature during the growth period is 20–35 °C. The requirements for soil are not strict, and it can adapt to a variety of soils, with neutral or slightly acidic (pH 5.5–7.5) loam being the best [1].

Dragon fruit is native to Brazil in South America and Mexico in North America, where it has been cultivated for hundreds of years. It was introduced to China in the 17th century, with Taiwan being the first province to introduce dragon fruit cultivation. At present, dragon fruit planting areas of China is mainly concentrated in Taiwan, Guangdong, Guangxi, and Hainan. Among them, the production areas of dragon fruit in Guangxi are mainly concentrated in Nanning, Qinzhou, and Fangchenggang. There are also small amounts of cultivation in areas such as Chongzuo, Guigang, and Wuzhou. As of 2019, the planting area of dragon fruit in Guangxi reached 20300 hectares (ha), ranking first in the country, accounting for 35.26% of the national planting area, which is 5000 ha more than the second place. Moreover, its production area and production rate both rank first in the country [2].

1.2 Characteristics and Value of Dragon Fruit Light Characteristics of Dragon Fruit

The stems (branches) of dragon fruit are dark green and triangular in shape, in a fleshy or semi-fleshy state. They are the main part responsible for photosynthesis. Moreover, the stems (branches) are prone to producing aerial roots, which produce a large number of absorptive hairy roots when they are close to walls or other wet objects [1].

As a tropical long sunshine plant, dragon fruit needs sufficient light hours every day to induce its flowering, so it is not suitable for cultivation in low-temperature and dark environments. It needs to be planted in places with sufficient light and water sources but not easily flooded [3]. The most suitable light for dragon fruit cultivation is 8000–12000 lx, and below 2500 lx, it will affect the differentiation of flower buds as well as the growth of dragon fruit. At the same time, the light exposure time is also an important influencing factor in inducing dragon fruit flowering. When the lighting time is less than the critical day length, the flowering period will be delayed or not flowering. Therefore, under conditions such as insufficient natural light in autumn and winter, dragon fruit flowering will be delayed to early April of the following year, which will have an impact on the dragon fruit harvest [4].

Dragon fruit seed germination also requires light, and cannot germinate under dark conditions. As the sowing depth deepens, the seedling emergence rate decreases rapidly. When the sowing depth reaches 8 cm, the seeds stop germinating. Under light conditions, mature dragon fruit seeds can germinate 100% in 8–30 °C, with the fastest germination speed under temperature changes of 25 °C or 17 °C [5].

2. Research on Dragon Fruit Cultivation Technologies

The research on dragon fruit cultivation technologies starts earlier outside of China. Rahmah et al. [6] measure and compare the growth and development of two dragon fruit varieties under the climatic conditions in Saudi Arabia. The experiment shows that soil treated with algae-rich Klebak fertilizer can accelerate the growth of *S. undatus* dragon fruit, while the growth of *S. costaricensis* dragon fruit requires the soil to be treated with a combination of Klebak fertilizer and volcanic rock. The experimental results provide useful suggestions for dragon fruit cultivation in arid areas. Sousa et al. [7] investigate the effect of low and high salinity irrigation on dragon fruit seedling yield under different lighting conditions. The research finds that 50% shading can increase the plant height, secondary shoot number, and root length of dragon fruit plants. Irrigation with medium saline water (5.0 dS/m) can reduce the number and length of secondary shoots of dragon fruit seedlings. While under sufficient light and high salinity water irrigation, the diameter of primary shoots, aboveground dry biomass, and total dry biomass are all larger, resulting in higher production. Cavalcante et al. [8] study the growth and early development of dragon fruit under different light intensities and organic fertilizers. According to the results, it is necessary to use coverings to prevent direct sunlight in the cultivation of dragon fruit, and the best effect is achieved when 50% or 75% shadows are artificially created. For organic fertilizer, the growth of dragon fruit is best at 20 L Cova-1 cow manure. Trindad et al. [9] conduct a survey and state that considering the impact of global climate change and natural resources, the lower water requirement and higher economic benefits of dragon fruit will attract people's attention, indicating that the promotion of dragon fruit cultivation is an unstoppable trend in the future.

The research in China mainly focuses on asexual reproduction, variety selection, introduction, pollination, cultivation techniques, post-harvest storage, and processing of dragon fruit. Due to the relatively late introduction of dragon fruit in China compared to other fruits, the research time of dragon fruit is relatively short, and there is still not much in-depth exploration in various research fields.

China's dragon fruit has developed rapidly in the past 10 years, and the planting area has expanded rapidly from 3333.33 ha in 2012 to 70000 ha in 2021. China's dragon fruit planting area has exceeded 66700 ha since 2020, with a production of about 1.54 million tons. Both the area and

production have surpassed Vietnam, ranking the first place in the world [3]. In the past two years, the planting area has remained stable at about 73300 ha, and the products are mainly sold in the domestic market as fresh fruits. Qiao et al. [10] conduct a feasibility analysis on the introduction of dragon fruit to the north. The research suggests that planting dragon fruit in the north can improve production and quality and prolong the production period by changing facility conditions and planting modes. The dragon fruit industry, combined with greenhouse cultivation, has become a characteristic sightseeing agriculture in the north. Currently, more research is being conducted on how to plant well in the north and achieve high yield and quality.

To overcome the limitations of cutting seedling cultivation, He et al. [11] establishes a rapid propagation technology system for red flesh dragon fruit tissue culture using stem segments as explants through in vitro culture technology. The research find that the optimal culture medium has a rooting rate of up to 100%, an adventitious sprouting coefficient of up to 7.33, and a plant survival rate of 98.9%.

In recent years, with the continuous expansion of the market for dragon fruit in China, research on dragon fruit planting methods has been increasing. Huang [12] proposes that intercropping is an effective way to solve the problem of low land use efficiency in column cultivation, while also achieving full utilization of sunlight. Dragon fruit orchards are recommended to achieve higher economic benefits through intercropping short-term crops and other fruit trees. For the cultivation techniques of dragon fruit in Guangxi, Li et al. [13] find that it is necessary to supplement the organic matter in the soil before flowering, during peak fruiting periods, and after harvest each year. Due to the high demand for calcium magnesium phosphate fertilizer due to the abundant rainfall in Guangxi, it is necessary to adjust the pH value in a timely manner between 5.5 and 7.5. To avoid poor fruit quality caused by excessive dispersion of nutrient supply during fruit development, nutritional regulation must be carried out, mainly through pruning and twisting branches, thinning buds and fruits, etc.

For the storage of dragon fruit after picking, the current research focus is on packaging materials, modified atmosphere preservation, and so on. Wei et al. [14] study the effect of different preservatives on the storage quality of fresh cut dragon fruit. It is found that fresh cut dragon fruit treated with 0.5% chitosan has the best preservation effect. Li et al. [15] study the storage characteristics of Hainan red flesh fruit with different maturity levels after harvesting. The experimental results show that eight ripe fruits can effectively delay the occurrence of peak SOD and POD activities during storage, thus maintaining the appearance and internal quality of the fruits well during storage, and better meeting the storage, transportation, and sales after harvest, which is conducive to the improvement of economic benefits.

For the pulp part, it is mainly made into juice drinks, jam, preserved fruits, and fruit vinegar through specific techniques and processes. In addition to fresh fruit, there are also many ways for post-processing to maximize the utilization of dragon fruit. Based on the high nutritional value and health benefits of dragon fruit, the extraction of nutrients such as polyphenols, anthocyanins, and plant sterols from dragon fruit has become a research hotspot. The fruit peel can be fermented to produce fermented beverages such as yogurt [16].

3. Overview of Light Supplementation Technologies

Light is one of the important factors in plant development, providing necessary energy and signaling factors for plant growth and development. Plant light supplementation technologies refer to the use of artificial light sources to supplement light to vegetables, flowers, fruit trees, and other plants, in order to achieve the optimal lighting conditions for plant growth or meet specific needs in production, such as adjusting production period, flowering period, annual production, and rapid seedling cultivation. By adjusting the duration of light exposure, the light conditions for plant flowering can be met, thereby adjusting the production period. In recent years, in order to promote faster and better plant growth, the use of artificial light sources and shading nets to improve lighting

conditions in plant production has become increasingly widespread. It has achieved effects such as shortening plant growth cycle, increasing production, improving its morphology or quality, inhibiting dormancy, and increasing seedling survival rate. Meanwhile, research on artificial lighting control is also receiving increasing attention [17].

3.1 Effects of Light on Plant Flowering and Growth

Light has a significant impact on plant morphogenesis and is an important environmental signal for plant structural differentiation. Adjusting lighting conditions can affect the distribution and accumulation of nutrients within plants, achieving the goal of regulating plant growth, development, and physiological metabolism. Among them, light intensity, light quality, and light period are important influencing factors that have a significant impact.

Light intensity is the most important factor affecting plant photosynthesis. In the field of plant physiology research, photosynthetic photon flux density (PPFD) is generally used to measure light intensity. Between the light compensation point and the light saturation point of photosynthesis, the net photosynthetic rate of plants increases with light intensity [17]. However, the range of light radiation intensity that is most suitable for plant growth is not fixed. It will change with the species, variety, and growth environment of plants, but most of them are distributed between 200–1500 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ [18]. Therefore, it is necessary to determine the adjustment range of light intensity based on the actual situation of plants.

According to the different spectral components, light can be divided into different light qualities. The effective spectral range required for plant growth is between 380 nm and 760 nm. In addition, the proportion of light sources required by different plants or the same plant at different times is also different [19]. The photoreceptors in plants can perceive small changes in the spectral composition of their surrounding environment, which can lead to physiological or morphological changes in the plant itself. The photomorphogenesis of plants is mainly controlled by the long-term light regulation of photosensitizers that absorb red (R) light and far red (FR) light, as well as cryptocyanins and phototropins that absorb blue UV-A light [20]. Red light is crucial for the normal development of photosynthetic organs, as it can increase starch accumulation in leaves by inhibiting the output of photosynthetic products [21]. Blue light mainly affects the growth and development of plant roots and stems, which can improve the vitality and absorption area of seedling roots, while also having an inhibitory effect on stem elongation. Compared with white light, blue light significantly reduces plant height, but can increase stem thickness [22]. Not only does single light quality have a positive effect on plant growth, but an appropriate proportion of red green blue light mixing can promote plant growth and have a good effect.

The growth and development of plants are also influenced by the phenomenon of photoperiod, which refers to the phenomenon where the length of sunlight controls the flowering of plants. This plays an important role in the transition of plants from vegetative growth to reproductive growth. It regulates seed germination, seedling growth, flower bud differentiation, flowering, root growth, and plant dormancy by affecting plant physiological and biochemical reactions. The photoperiod not only plays an important role in inducing crop flowering, but also has a significant impact on other external growth aspects of crops [23]. At present, photosensitive plants mainly utilize the phenomenon of photoperiod to achieve their annual production.

Photoperiod not only plays an important role in inducing flowering but also has a more significant effect on other external growth aspects of crops [23]. Currently, the photoperiodic phenomenon is mainly utilized for the whole year production of photosensitive plants.

3.2 Light Supplementation Technology for Plants

Plant light supplementation technology has become an important component of modern agriculture and plant growth research. By precisely controlling the intensity, period, and quality of light, plant lighting supplementation technology can optimize the plant growth environment, improve production and quality, and maximize resource utilization efficiency. For traditional plant

lighting sources such as fluorescent lamps and metal halide lamps, they are difficult to meet the needs of large-scale and high-precision plant lighting applications in actual environments [24]. The drawbacks of these artificial light sources are also very obvious. The one-time investment is too high, and its energy consumption cost accounts for about 50% of the total operating cost.

In recent years, with the rapid development of optoelectronic technology, it has led to the birth of light emitting diodes (LEDs) [25]. LED lights have the advantages of low energy consumption, long lifespan, and adjustable spectrum, and have become the main light source used in plant lighting technology today. By regulating specific LED lights, they can provide specific wavelengths and intensities of light, effectively simulating natural spectra and meeting the photosynthetic and morphological development needs of plants at different growth stages. Gao et al. [26] show that blue light has a promoting effect on cultivating strong seedlings, which can inhibit seedling height and improve plumpness and root crown ratio. Under red light treatment, the stems and leaf sheaths of rice seedlings significantly elongate. By adjusting the lighting intensity of the LED light supplement system, setting different lighting cycles and ratios of light quality, different plants and unified plants can meet their lighting needs at different stages. It can also meet the demand for off-season and directional growth of plants in industry and daily life, which is also the main direction of research on plant light supplementation technology today.

Light intensity has a significant impact on the physiological indicators of plants. Under low light conditions, plants usually increase the content of chlorophyll and change the ratio of chlorophyll a to chlorophyll b in order to capture more light energy. There is a lot of research on light intensity in plant light supplementation technology. Yang et al. [27] show that when using the same plant growth supplement light, the various data of strawberries at light intensities of 150 and 100 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ are significantly improved compared to light intensity of 50 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$. For different light source supplementary lamps, under the same supplementary light intensity, LED light sources with a red blue ratio of 3:1 have higher net photosynthetic rate, single fruit quality, and soluble sugar content.

For the research on light quality, the focus is mainly on studying the effects of different red and blue light ratios on plant growth. Fraszczak et al. [28] study the effect of short-term red and blue light irradiation on plant growth. It is found that using red light to irradiate plants 30 minutes before the end of the day can significantly improve the parameters of fresh plant quality, area, and height, similar to the effects of using blue light at the end of the night on plants. Mansoori et al. [29] study the growth response of tomato plants under different wavelength ratios of amber red and blue light. It is found that the average fresh weight of tomatoes treated with amber red (AR) light is 22% higher than that treated with blue amber (BA) light, and 67% higher than that treated with blue red (BR) light. The fresh weight of plants treated with BA was 36% higher than that treated with BR.

In terms of photoperiod, Li et al. [30] show that supplementing light for 7 hours has the greatest impact on plant height, fruit vertical stem, and fruit set rate, while supplementing light for 9 hours has a significant effect on improving fruit quality and increasing production. Therefore, it is concluded that supplementing light for 7 hours daily before flowering and 9 hours daily after flowering and fruiting is an effective measure to increase tomato production. Dong et al. [31] investigate the effect of different photoperiods on the growth of sweet pepper seedlings. It shows that the longer the light exposure time, the larger the stem diameter and biomass of sweet pepper seedlings, and a light exposure time of 24 hours per day has the best treatment effect. The chlorophyll a content in the leaves is the highest, increasing by 20.22% compared to the control, while there was no significant difference in chlorophyll b content among different treatments. Lu et al. [32] study the effects of different light cycles on the growth and flowering of cut chrysanthemums. The research results indicate that chrysanthemums treated with 10 h/14 h day/night have the shortest time from seedling stage to bud emergence and flowering. In addition, the treatment with 11 h/13 h day/night has the shortest flowering period from the initial flower to the fully unfolded petals, and has a significant promoting effect on flowering.

4. Application of Light Supplementation Technology in Dragon Fruit

Dragon fruit is light and shade tolerant, with the characteristics of fast production, short flowering to fruit picking time, multiple annual fruit picking batches, high production, and large market demand gap. It is one of the ideal subtropical fruits for industrial adjustment and poverty alleviation in China's warm areas. In China, many agricultural towns introduce dragon fruit for large-scale cultivation. Meanwhile, due to the fact that dragon fruit belongs to a long day plant, its flower bud differentiation is mainly influenced by light exposure time and temperature. Reasonable sunshine duration and temperature control are beneficial for the growth and improvement of fruit quality of dragon fruit. High temperature and long sunshine can promote flower bud differentiation, while low temperature and short sunshine can inhibit flower bud differentiation [33]. In winter and spring, insufficient sunlight can prevent the flowering of dragon fruit, thereby affecting its harvest, which is also a major factor affecting dragon fruit production.

The main methods to solve this problem include light supplementation, thinning flowers, and applying growth regulators to promote the flowering of dragon fruit seedlings or extend the flowering period, thereby advancing or delaying harvest. Among them, light treatment shows better effects than the application of plant growth regulators [34]. The regulatory effect of plant growth regulators on flowering and fruiting periods is unstable. While light treatment can improve the uniformity of flowering and fruiting [35], without considering the early effects of growth regulators on soil and the environment. At the same time, thinning flowers consumes a lot of labor, so most of them use artificial light supplementation to regulate the flowering period.

At present, this method has been widely used in the commercial planting and production of dragon fruit. Many studies have shown that light can affect plant flowering by adjusting the light cycle, light quality, and light intensity. This section provides an overview of the effects of different photoperiods, light quality, and light intensity on the flowering and fruit quality of dragon fruit, as well as the key points of dragon fruit light supplementation techniques in different seasons, aiming to provide technical guidance for dragon fruit production.

4.1 Effects of Photoperiods on Dragon Fruit

The response of plants to the duration of day (light) and night (darkness) is called the photoperiod phenomenon. The relative length of day and night (photoperiod) is an important influencing factor for plant flowering induction and flower bud differentiation. Increasing sunshine hours is beneficial for promoting the flowering and fruiting of dragon fruit, achieving off-season production. Chen et al. [36] study the effect of light cycle on the growth of Guangxi dragon fruit by setting four different LED light supplementation conditions of different durations. It is found that the effects of these four different lighting time settings on dragon fruit are not significantly different between groups, but all show improvement compared to natural conditions. At the same time, after comparison, it is believed that a light supplementation duration of 4 hours or 5 hours is better. Although the difference in estimated output between the two methods is not significant, the 4-hour estimated output value is relatively high, and it saves electricity and significantly saves costs compared to the 5-hour supplementary lighting.

The impact of different light supplementation periods on dragon fruit plants varies. In order to determine the most suitable light supplementation period of the day, Xu et al. [37] selects the FDD light quality (red:green:blue=23:75:2) that has a significant effect in earlier light supplementation test as the light supplementation treatment. The results show that the best number of flower bud differentiation is observed in the treatment of light supplementation at midnight (22:30–2:30), followed by light supplementation in the evening (18:00–22:30), and the worst is observed in the early morning (2:30–6:30).

January to June each year is the gap period for dragon fruit production. In order to extend the fruit production period of dragon fruit and improve economic benefits, it is necessary to carry out research on the spring photoperiod regulation and yield increase technology of dragon fruit. The research is mainly conducted in provinces such as Guangxi, Guangdong, Hainan, and Fujian. For

the cultivation of dragon fruit in Fujian region, Liu et al. [38] show that the best effect is to continuously supplement with yellow light for 5 hours every night during nighttime, providing a theoretical basis for adjusting the production period of greenhouse dragon fruit. For the Guilin area of Guangxi, after entering the autumn equinox, the days are short and the nights are long, and the sunshine time is reduced, which stops the differentiation of dragon fruit flower buds and switches from reproductive growth to nutritional growth, resulting in the basic end of fruit picking at the end of November each year [33]. In order to overcome the problem of difficult flower bud differentiation and inability to bear fruit, Ye et al. [39] use Guilin dragon fruit as the test material and measure the flowering number, fruiting number, and production of four batches of dragon fruit using LED yellow energy-saving lamps. From the total number of flowers in four batches, the effect of supplementing light at night for 4 hours is better, and the production is the highest. The experiment shows that the fact is not that the longer the supplementation time, the better the effect. The setting of time is also closely related to the environment and season in different regions. At the same time, Hu et al. [33] also show that artificial light supplementation can increase the number of flowering batches by 2 per year. The first batch of flower buds usually appears 15–18 days after artificial light supplementation. After 31 to 36 days of light supplementation, there is a second batch of flower buds, and the production period is extended by 43 to 77 days. The production increases by 521–748 kg per 667 m², and the total production can increase by 21%–32%. This provides technical support for increasing winter production of Guangxi dragon fruit.

4.2 Effects of Light Qualities on Dragon Fruit

Light quality refers to the spectrum of different wavelengths, which affects the photosynthetic characteristics, morphogenesis, physiological metabolism, etc. of dragon fruit by stimulating different light receptors. You et al. [40] study the effect of LED supplementary light with different light qualities on the growth of dragon fruit. The experiment find that when red:green:blue=23:75:2, the highest number of flower buds and the highest rate of flowering branches can be obtained. For the growth of dragon fruit, the best effect is achieved when red:green:blue=288:6:4.

The study of different light qualities on the growth and development of dragon fruit can also evaluate the quality of the results through different evaluation indicators and the ratio of different colored light to study the suitable light supplementation scheme for dragon fruit. Among them, soluble sugars are the main substances for carbohydrate conversion and reuse in plants, reflecting the sugar metabolism status of plants. Therefore, the content of soluble sugars in fruit stems is an important basis for evaluating plant growth. At the same time, the content of photosynthetic pigments also reflects the intensity of photosynthesis to a certain extent. Chlorophyll is the main light absorbing substance, and its content directly affects the light energy utilization efficiency of plant photosynthesis, which is also an effective indicator for evaluating plant growth. Xie et al. [41] find that supplementing red, blue, and white light can significantly promote the accumulation of soluble sugars in dragon fruit plants, and supplementing white light has the best effect. When supplementing with white light, the soluble sugar content in the stem of dragon fruit is the highest, which is 68.8% higher than the blank control group. At the same time, supplementing white light has a promoting effect on the chlorophyll content in the stem of dragon fruit, with a significant increase of 21.4% and 25.0% in chlorophyll a and chlorophyll b content, respectively. Blue light has an inhibitory effect, while red light has no significant effect on chlorophyll.

The effect of supplementing light on dragon fruit varies slightly in different months and at different times every day. Gu et al. [42] find that using a single red light to supplement light at night from September to December in the experiment can promote the number of flowers and prolong the flowering period of dragon fruit until December. For plants that do not undergo supplementary light treatment, they will not bloom in December. Meanwhile, it is found that there are differences in the selection of optimal light quality among different regions. For example, a 1:4 ratio of blue and red light in the planting base of dragon fruit in Huzhou, Zhejiang can greatly promote the differentiation of the first batch of flower buds of dragon fruit in spring. The use of red and yellow lights to

supplement light and promote flowering in the Guangxi dragon fruit planting base has the best effect, which is likely related to local environmental factors such as temperature and light. In addition to studying the effects of different monochromatic light and different ratios of light quality on dragon fruit, the influence of LED lights with different wavelengths and powers on the light supplementation effect is also studied, providing new ideas for the selection of supplementary light quality. Chen et al. [43] conduct an analysis of variance on the sugar content of the second batch of dragon fruit under different treatments and find that LED lights of different wavelengths had no significant effect on fruit sugar content. However, in terms of flower inducing effect, LED lights with a main wavelength of 596.1 nm, a peak wavelength of 603.3 nm, a luminous flux of 1485.671 lm, and a power of 15 W have the most significant photocatalytic effect on dragon fruit.

4.3 Effects of Light Sources on Dragon Fruit

Light intensity mainly affects plant photosynthesis by affecting the structure, composition, and function of light and organs, thereby affecting plant production and quality. According to the theory of botany, only when the light intensity reaches a certain value and there is a certain intensity of light stimulation, can plants produce effective photosynthesis, which is the light compensation point [44]. Properly increasing light intensity can significantly increase the soluble sugar, carbohydrate content, and production of plants, which is beneficial for the accumulation of flavonoids in plants, while reducing nitrate content and improving plant quality.

Therefore, in plant light supplementation technology, plant growth and flowering rate can also be regulated by adjusting the intensity of light. Yue et al. [45] quantitatively analyze the differences in temperature and light intensity responses during the growth and development of dragon fruit and established relevant predictive models. They quantified the impact of light intensity on dragon fruit growth and development using the daily relative light intensity effect, and calculated the physiological development time of dragon fruit based on this. Liao [46] finds that with the increase of light intensity, the flowering rate of dragon fruit also increases. When the illumination is 644.6 lx, the flowering rate is 40.00%; When the illumination is 119.7 lx, the flowering rate of dragon fruit is 8.33%; When the illumination is 80.3 lx, the flowering rate is 0%, and light supplementation induction is unsuccessful.

There have been numerous studies exploring the effects of different supplementary light sources on plant growth. Common supplementary light sources include incandescent lamps, LED lamps, fluorescent lamps, high-pressure sodium lamps, fluorescent lamps, metal halide lamps, etc. Among them, incandescent bulbs, fluorescent tubes, sodium lamps, etc. consume a lot of electricity and generate a lot of thermal radiation, which cannot provide close illumination to plants and has low efficiency in stimulating light for plant growth, greatly increasing the cost of artificial lighting [47]. Therefore, they are not suitable for agricultural production. The radiation spectrum of fluorescent lamps is mainly concentrated in the red orange and blue purple light regions, and has a significant impact on plant growth. However, due to the presence of mercury in fluorescent lamps, which is not environmentally friendly, they are less commonly used. LED lighting has the advantages of adjustable spectrum, controllable volume size, controllable light intensity, energy conservation and environmental protection, and long service life [48]. At the same time, the power consumption of LED bubble shaped fill lights is only half of that of energy-saving lights. The power consumption cost of using LED fill lights is 42 kW·h/ha, and the brightness is superior to energy-saving lights [49]. Therefore, LED lights have a wider application value in production and have become the first choice for light supplementation or illumination in plant factories. Gan [50] studies the effects of LED light supplementation on the flowering, fruiting, production, and brix of dragon fruit plants. The results show that LED light supplementation could significantly promote the differentiation of dragon fruit flower buds, increase the number of flower buds, and increase production, but did not increase the accumulation of soluble substances. Moreover, using LDE lamps that are close to orange light, have high light efficiency values, and high light flux for light supplementation will have better results. Meanwhile, in some parts of India, plants will also increase dragon fruit

production by installing LED lights. After supplementing with LED lights, the non-harvest season yield can reach 1.6 t/ha.

5. Future Research Prospects

5.1 Disadvantages of Existing Technology

Plants can achieve crop production regulation through light supplementation technology, achieving a continuous supply of vegetables, fruits and vegetables throughout the four seasons, which plays an important role in agricultural development [51]. However, there are still many shortcomings in current light supplementation practices.

First, the light supplementation method is unreasonable. This mainly shows up in three aspects: unreasonable installation position of supplementary light, low light efficiency, uneven supplementary lighting caused by unreasonable distance arrangement of light supplementation, and some users not arranging light supplementation cycles according to crop characteristics, resulting in plant damage and inability to sprout normally.

Second, the cost of light supplementation is too high. Traditional light source lamps have lower investment, but due to their high-power consumption, their later costs are higher. Although mainstream LED energy-saving light sources have low energy consumption costs, the cost of purchasing lights is relatively high. Due to the limited illumination area of a single LED light source, the same planting area requires more LED lights. This leads to electricity costs reaching around 85% of the total planting cost, and the disproportionate production ratio has become a core issue that plant factories need to face in the promotion process. At the same time, due to the small irradiation area and inconvenient deployment, the widespread application and promotion of LED light sources in greenhouses have encountered obstacles [52].

Third, there is a low willingness to supplement light and inadequate infrastructure. Research finds that less than 10% of dragon fruit greenhouses in Sichuan Province receive light supplementation. Light supplementation plays an important role in improving the quality and production of dragon fruit, such as early flowering and extending the harvest period. However, the low willingness of growers to supplement light and the poor investment capacity of lighting equipment in the park are the main factors affecting industrial development. At the same time, there are also some cases where vegetable production greenhouses are directly converted into dragon fruit production greenhouses, and the infrastructure and demand are extremely mismatched. These constraints have hindered the improvement of dragon fruit production and quality [53].

5.2 Outlook of Renewable Energy for Light Supplementation of Dragon Fruit

To solve the problems of the above-mentioned light supplementation technology, while catering to the strategic goals of carbon neutrality and modernization of agriculture and rural areas, promoting the low-carbon transformation of green energy in rural areas, improving the level of energy development and sharing, and helping fruit farmers increase their income, combining photovoltaic energy storage with dragon fruit supplementary lighting will be a new development direction of supplementary lighting technology in the field of dragon fruit in the future.

The research on the application of photovoltaics in agriculture in China starts with irrigation. As early as 2002, it is proposed that solar photovoltaic water lifting systems can be combined with water-saving irrigation for irrigation of farmland and artificial grasslands [54]. In the past decade, the integration of photovoltaic technology with agricultural production has been continuously promoted, applied to disease and pest control, photovoltaic light supplementation, etc., playing an important role in saving electricity costs and reducing agricultural costs through clean and green power generation methods. For agricultural greenhouse planting production, the biggest cost comes from the energy consumed to control environmental temperature, and photovoltaics can provide green and sustainable energy for agricultural greenhouse planting [55].

From an ecological perspective, photovoltaic light supplementation is a feasible green and low-carbon development approach that can enhance solar energy resources, reduce greenhouse gas emissions, and actively address the impact of climate change on agricultural production. From an economic perspective, as energy storage costs continue to decrease and the capacity to consume clean and renewable energy continues to increase, photovoltaic energy storage can reduce the electricity cost of light supplementation, resulting in higher benefits.

Photovoltaic light supplementation has good development prospects, but further research is still needed. On the one hand, suitable light intensity and light cycle are formulated based on different varieties of dragon fruit or different growth stages of the same dragon fruit. On the other hand, it is necessary to experiment with reasonable planting modes, improve the installation of light supplementation and other supporting technologies, arrange the height and distance between supplementary lights and plants according to the needs of different plants, and strengthen the research on the differentiation mechanism of dragon fruit flower buds to solve the technical difficulties in the dragon fruit light supplementation industry.

Acknowledgements

This work has been supported by Guangxi Power Grid Science and Technology Project (G XKJXM20220069).

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