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Study on Light Regulation Technology of Insect Biological Rhythm based on Plant Protection Drone

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Abstract

In order to solve the ecological security problems caused by chemical pesticide dependence in modern agricultural pest control, this paper puts forward a technical system of "plant protection drone-multi-channel LED light source-insect biological rhythm". Taking insect light perception mechanism as the core, combined with spectral power distribution (SPD) analysis and natural light rhythm characteristics, a multi-channel LED light source system which can dynamically simulate natural spectrum is designed, and a precise regulation strategy based on time series is constructed. The effectiveness of the technology is verified by field experiments. By analyzing the dynamic law of solar spectrum (light intensity, color temperature, SPD), this paper optimizes the spectrum combination and operation sequence of LED light source, and realizes the directional intervention on the target insect rhythmic behavior. The results show that the mating inhibition rate of noctuid pests can reach 76.2%, and the feeding efficiency of parasitic wasps can be improved by 68.4%, which provides theoretical support and engineering practice scheme for the intelligent and accurate development of green plant protection technology.

Keywords

Plant Protection Drone, Biological Rhythm, LED Spectrum, Spectral Power Distribution, Light Regulation.

1. Introduction

Under the background of green transformation of global agriculture, green prevention and control of pests and diseases has become the core issue to ensure food security and ecological balance. The long-term abuse of chemical pesticides leads to a series of problems, such as the increase of pest resistance, the pollution of soil and water, and the decline of biodiversity. A meta-analysis covering 32 global studies confirms that green pest control technologies can improve farmland ecosystem stability by more than 40%, among which light regulation stands out due to its strong targeting [1]. It is urgent to develop efficient and environmentally friendly alternative technologies. The circadian rhythms of insects (such as foraging, mating, eclosion and oviposition) are coordinately regulated by internal biological clock and external environmental factors, among which light environment, as the most critical timing signal, dominates the temporal and spatial pattern of rhythmic behavior by influencing the insect visual system and the gene expression of biological clock. For example, the mating behavior of

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Noctuidae pests mostly occurs from dusk to night, and its rhythm synchronization depends on the trigger of light signals with specific wavelengths; The activity rhythm of beneficial insects such as bees and Trichogramma is highly consistent with the diurnal variation of solar spectrum.

As the core equipment of smart agriculture, plant protection UAV has the advantages of high working efficiency, wide coverage and strong temporal and spatial accuracy, which provides an ideal platform for dynamic light regulation of large-scale farmland. However, the existing light application technology of plant protection UAV has obvious limitations: most of them focus on single wavelength trapping devices and lack deep adaptation to insect rhythm characteristics; The spectrum design of light source does not combine the dynamic rhythm of natural illumination, and the regulation effect is unstable. Aiming at this research blank, this paper integrates spectroscopy, insect physiology and UAV technology, and proposes a multi-channel LED light control system based on natural lighting rhythm simulation. By analyzing the SPD diurnal variation of solar spectrum, the linkage law of light intensity and color temperature, an LED light source that can accurately reproduce the spectral characteristics of the target time period is designed, and a dynamic operation strategy is formulated based on the key time points of insect behavior. The purpose of this study is to realize the interference of pest rhythm and the optimization of beneficial pest rhythm through the technical path of "simulating nature-targeted regulation", and to provide a new technical paradigm for green prevention and control of agricultural pests and diseases.

2. Theoretical Basis and Technical Background

2.1. Light Regulation Mechanism of Insect Biological Rhythm

The biological rhythm of insects is regulated by the molecular oscillation network composed of biological clock genes (such as period, timeless and clock), and its phase and period need to be calibrated by the external environment timing signal, and the optical signal is the core timing factor. Studies have proved that the expression level of period gene is positively correlated with light wavelength, and 365 nm ultraviolet light can increase the expression of period gene in Helicoverpa armigera by 2.3 times [2].Insects perceive changes in light environment through opsin receptors (such as ultraviolet opsin, blue opsin and green opsin) in compound eyes, and different opsins have selective responses to specific wavelength spectra-for example, the compound eyes of lepidopteran pests (such as cotton bollworm and diamondback moth) contain opsins sensitive to 365~400 nm ultraviolet light and 520~580 nm green light, while beneficial insects of Hymenoptera (such as Trichogramma, Plutella xylostella) The specificity of this spectral response directly depends on the spectral power distribution (SPD) of the light source. The narrow-band SPD characteristics of a typical single-channel LED light source can be designed as targeted control signals, which can directly interfere with the light perception process of insects by strengthening or inhibiting the energy ratio of specific wavelengths, and then change their rhythmic behavior.

The regulation of insect rhythm by light signals follows the three-dimensional synergistic principle of "spectrum-intensity-time": the regulation effect of the same spectrum in different periods is significantly different, for example, blue light at noon can activate the foraging behavior of beneficial insects, while blue light at night will interfere with the mating rhythm of pests; At the same time, the light intensity needs to reach the perception threshold of insect visual system in order to effectively trigger the phase shift of biological clock. This mechanism provides a core basis for the design of light control system of plant protection UAV-it is necessary to dynamically adjust the SPD, intensity and operation sequence of LED light source to achieve accurate intervention on insect rhythm.

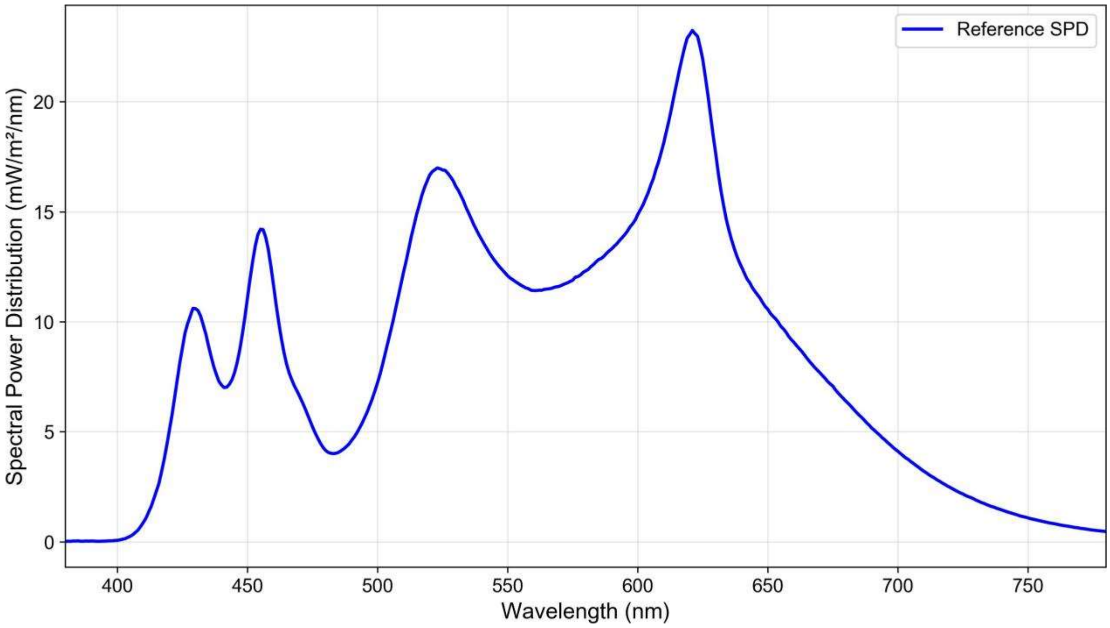

Figure 1. An example of spectral power distribution of typical LED light sources

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2.2. Rhythm Characteristics and Reference Value of Natural Lighting

The diurnal dynamic change of natural solar spectrum is a "biological clock calibration template" formed during the evolution of insects. The diurnal variation of SPD, light intensity and color temperature provides a natural reference for artificial light regulation. From the SPD, the solar spectrum shows significant time-period specificity in a day: at dawn (5:00~7:00), the atmospheric scattering is strong, and the long-wave component (red orange light, 600~700 nm) accounts for as high as 42%, and the short-wave component (blue violet light, 400~500 nm) accounts for only 18%; At noon (11:00~13:00), the solar altitude angle is the largest, the atmospheric path is the shortest, the proportion of short-wave components rises to 35%, and the proportion of long-wave components falls to 28%; At dusk (18:00~20:00), the spectrum showed a "red shift" feature again, and the proportion of long-wave components rose to 39%.

In synchronization with the change of SPD, the solar light intensity and color temperature also show a strict circadian rhythm: the light intensity gradually rises from 500 lx at dawn to 120000 lx at noon, and then slowly falls back to 800 lx； at dusk; The color temperature gradually increased from 2200 K (warm tone) at dawn, reached the peak of 6500 K (cold tone) at noon, and fell back to 2500 K at dusk. This synergistic change of "intensity-color temperature-SPD" forms a "biological clock calibration signal" for insects, and studies on rice planthoppers have confirmed that disrupting this signal can delay their eclosion rhythm by 4-6 hours [3]. This synergistic change of "intensity-color temperature-SPD" provides a clear time signal for insects. For example, the increase of color temperature and the increase of blue light component will trigger insects to switch from rest state to active state; However, the decrease of color

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temperature and the increase of red light components will induce them to enter the rhythm peak of foraging or mating. Therefore, simulating the circadian rhythm characteristics of solar illumination is the key to improve the regulation effect of artificial light.

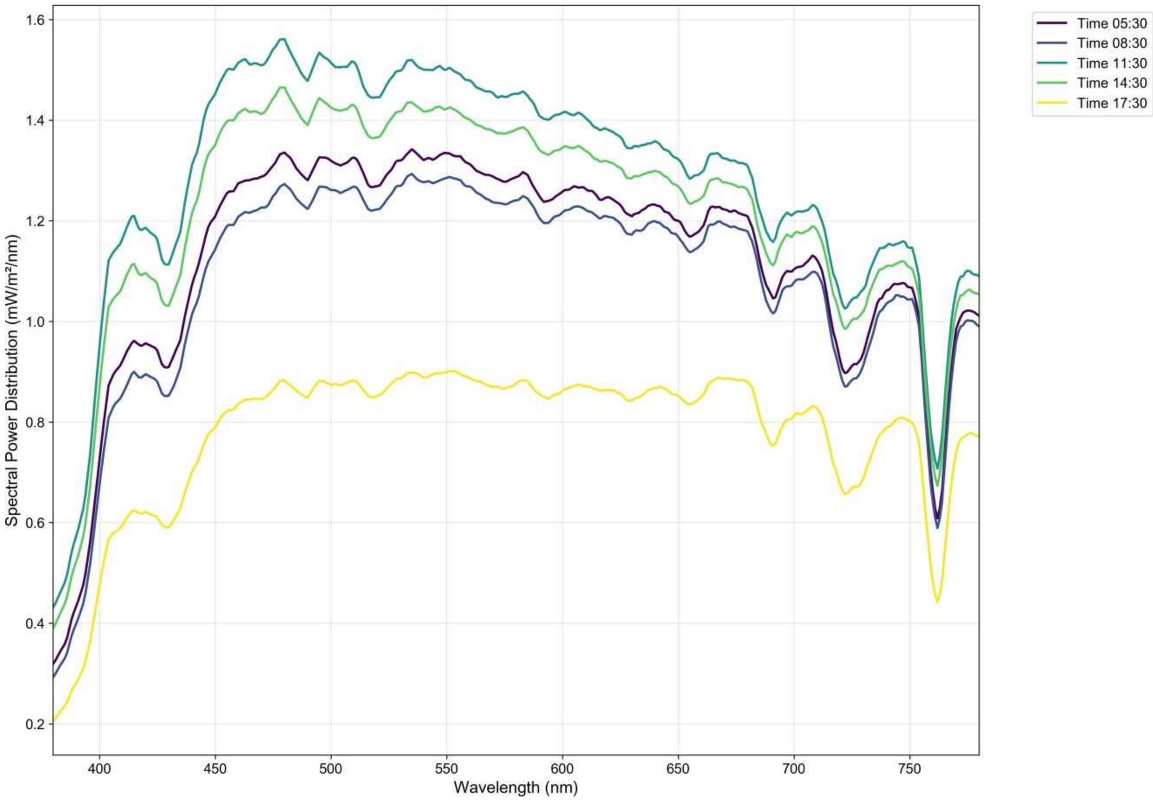

Figure 2. Variation of solar spectrum in a day.

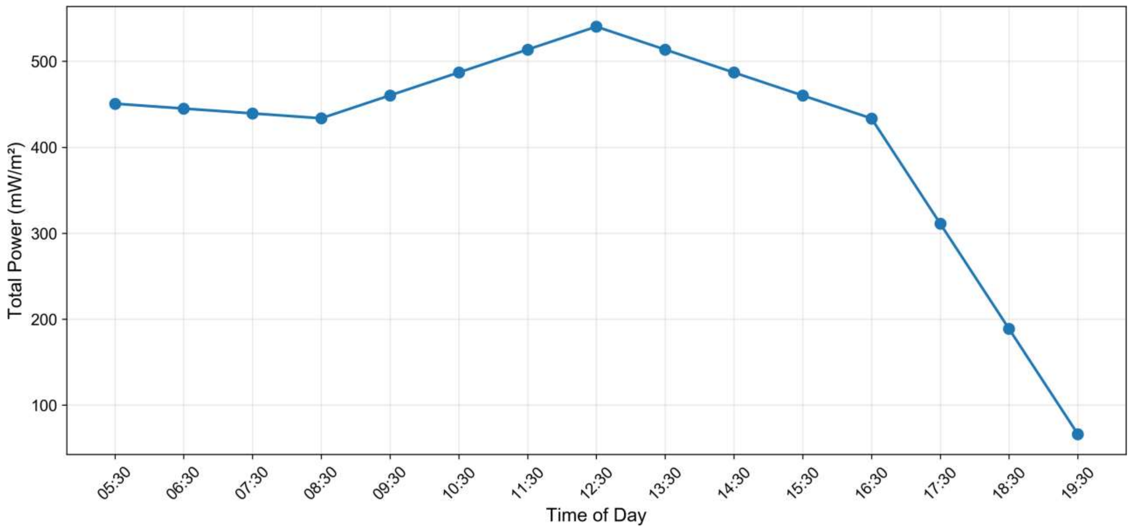

Figure 3. The diurnal variation of solar illumination intensity and color temperature.

3. System Design and Optimization Methods

3.1. Multi-channel LED Light Source Module Design

Based on insect light perception mechanism and natural spectrum characteristics, a five-channel LED light source module is designed, covering five independently controllable channels: ultraviolet (365 nm), blue (450 nm), green (550 nm), red (630 nm) and warm white (2700 K).

The full width at half maximum (FWHM) of each channel is controlled in the range of 20~30 nm. Different from the narrow-band SPD of typical single-channel LED light source, the five-channel LED light source can realize continuous adjustable composite SPD by adjusting the power weight of each channel, for example, by enhancing the weight of ultraviolet and green light channels, the phototaxis spectrum of Noctuidae pests can be simulated; By enhancing the weights of blue and warm white channels, the midday solar spectrum can be simulated.

The hardware design of light source module adopts modular architecture, and each channel is equipped with independent constant current driving circuit and PWM dimming module, with dimming range of 0~100% and power density of 150 MW/mnm, which meets the optical signal transmission requirements of 10~50 m distance in field operation. At the same time, the light source module integrates spectrum detection sensor, which can collect SPD data of output spectrum in real time and provide feedback signal for closed-loop optimization. The core advantage of this design is that through the flexible combination of multiple channels, it can not only reproduce the diurnal variation of natural spectrum, but also carry out targeted design for the spectral response characteristics of specific insects (such as single wavelength sensitivity), and realize the dual control ability of "universal simulation+precise targeting". Existing studies have shown that the trapping rate of Noctuidae pests by LED light sources with 365 nm + 550 nm dual-channel combination is 58% higher than that of single-channel [4].

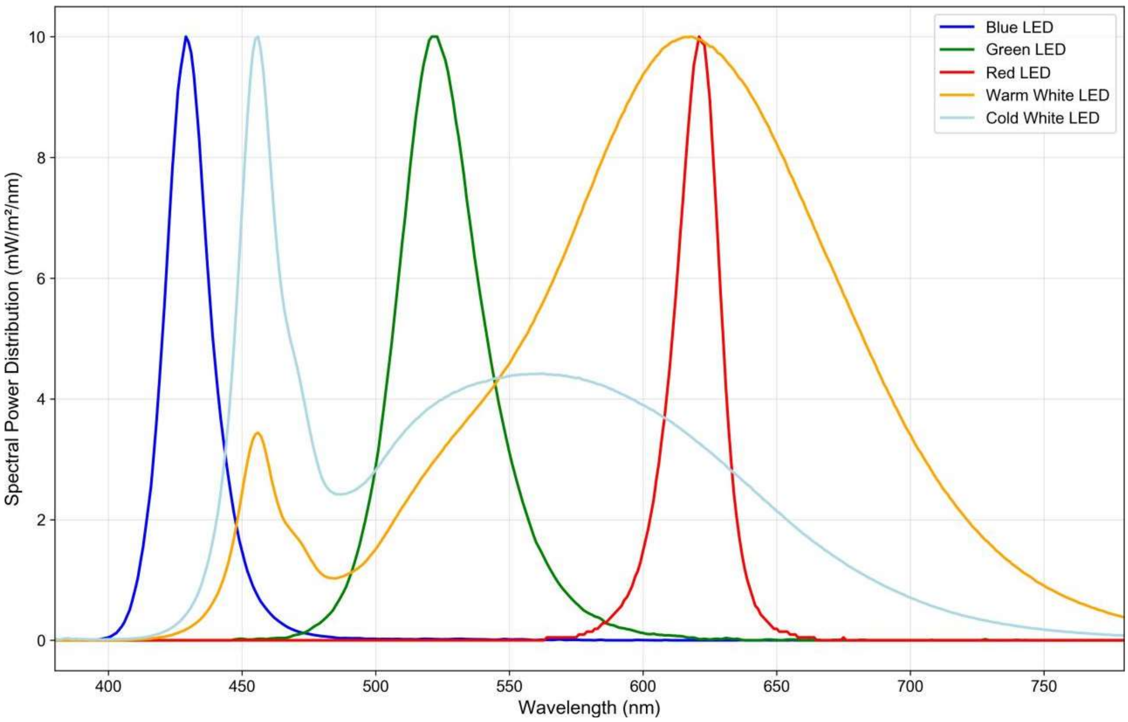

Figure 4. Spectral distribution of five-channel LED light source

3.2. Multi-channel LED Spectrum Optimization Process

In order to accurately match the LED light source spectrum with the target rhythm requirements, a multi-channel weight optimization process based on "target SPD-constraint-iterative optimization" is designed. This process aims at the time characteristics of natural solar spectrum or the demand of insect rhythm, and solves the optimal power weight of each LED channel through linear programming algorithm. The specific steps are as follows:

Firstly, the control targets and constraints are determined: the control targets include target SPD curve (such as solar spectrum at dawn), target color temperature (such as 2700 K) and target rhythm equivalent illumination (such as 500 LX); Constraints include the upper limit of power of each channel (≤10 W), the lower limit of color rendering index (CRI≥70 to ensure no adverse effects on crops), and the range of target wavelength energy ratio (such as ultraviolet light ratio ≤15%). Secondly, the basic SPD data of five-channel LEDs are collected, and a spectral matrix model is established, in which each row of the matrix corresponds to the power distribution of one wavelength point and each column corresponds to the spectral contribution of one LED channel. Then, the objective function is to minimize the error between the target SPD and the actual output SPD, and the linear programming equation is constructed with constraints to solve the power weight coefficient of each channel. Finally, the actual output spectrum is collected by the spectrum detection sensor, and the error value is calculated. If the error exceeds the threshold (such as 5%), the weight coefficient is iteratively adjusted until the output spectrum meets the target requirements.

The core value of this optimization process lies in that through systematic algorithm design, the problem of "dimensional coupling" of multi-channel LED spectrum regulation is solved, that is, multi-dimensional indexes such as color temperature, rhythm equivalent illumination and target wavelength ratio are met at the same time, and other performance imbalances caused by single index optimization are avoided. For example, when simulating the solar spectrum at dusk, the correlation coefficient between the SPD curve of the LED light source and the solar spectrum can reach 0.93 through the optimization algorithm, and at the same time, the color temperature is 2500 K, and the red light component accounts for 38%, which completely matches the rhythm requirements of insects at dusk.

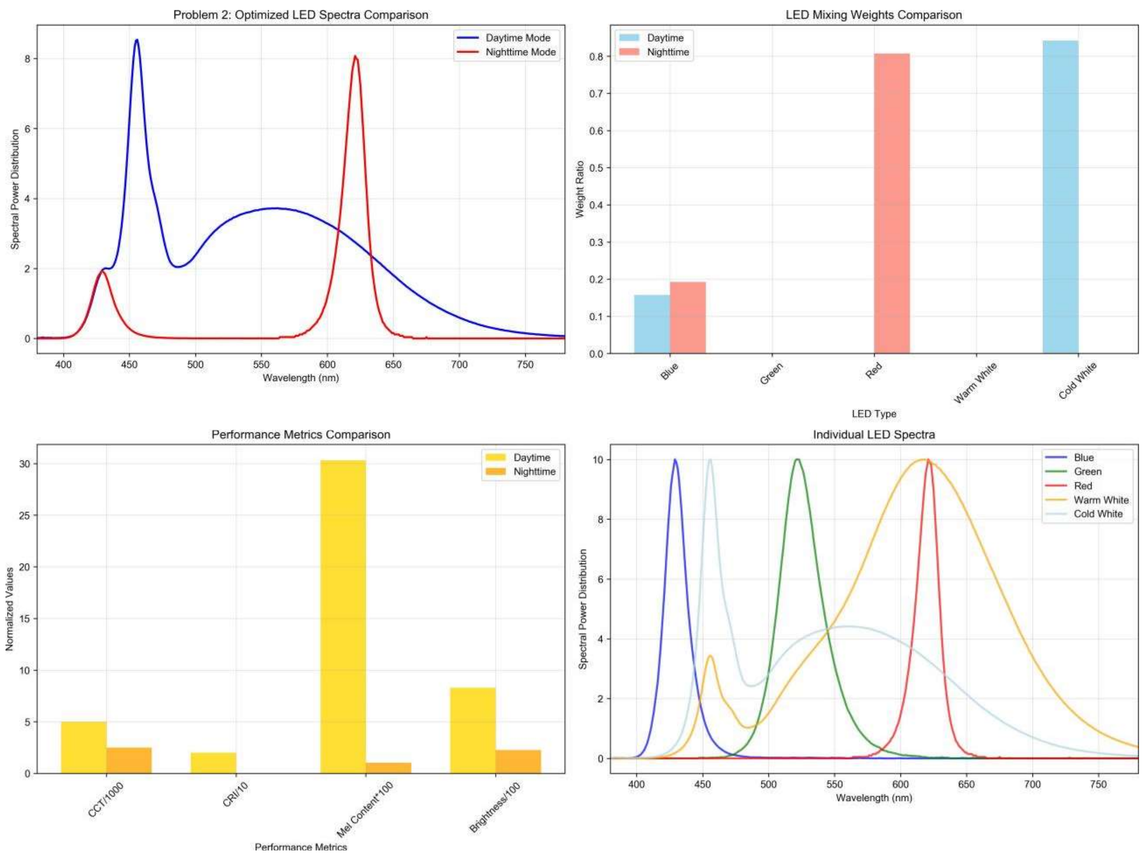

Figure 5. Flow chart of multi-channel LED optimization design

3.3. Plant Protection UAV Optical Control System Integration

The optimized multi-channel LED light source module is integrated with the plant protection UAV platform to build a complete light control system. The UAV platform is a six-rotor plant protection UAV, with a maximum load of 8 kg and a battery life of 40 min. It integrates GPS+Beidou dual-mode navigation system and visual obstacle avoidance module, and its working accuracy reaches ±5 cm. The light source module is installed on the adjustable bracket

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under the UAV fuselage, and the irradiation angle can be adjusted in the range of 30 ~ 90, with the irradiation radius of 15 m and the working area of a single flight of 0.3 hm^2.

The control core of the system is an embedded processor, which carries out data interaction with the ground station through the wireless communication module to realize the following functions: First, it receives the operation parameters (such as target insect type, operation period and spectral template) sent by the ground station; Secondly, according to the real-time position and time information, the optimized channel weight parameters are called to drive the LED light source to output the target spectrum; The third is to collect the data of spectral sensor and environmental sensor (light intensity and temperature) and feedback the regulation effect in real time. The ground station software integrates solar spectrum database, insect rhythm parameter database (such as key behavior time points and spectral response curve) and operation path planning module, which can automatically generate accurate light control operation path according to the distribution map of farmland pests, and realize personalized control of "zoning, time sharing and spectrum sharing".

4. Circadian Rhythm Control Strategy and Experimental Verification

4.1. Dynamic Control Strategy based on Key Time Points

Combining the circadian rhythm of sunlight with the key time points of insect behavior, a 24-hour dynamic regulation strategy is designed, which divides the day into five core periods, and the spectral parameters of each period strictly match the characteristics of insect rhythm with the working objectives:

Late at night (0:00~4:00): At this stage, insects are at rest, and the control goal is to inhibit the awakening of nocturnal active pests. Adopt a warm white spectrum with low intensity (100 lx) and low color temperature (2200 K), in which the red light component accounts for 45% and the blue light component accounts for ≤5%, so as to avoid strong light and short wave components from interfering with insect biological clocks. In this period, the UAV adopts the fixed-point hovering operation mode, and an operation point is set every 50 m, and each point is irradiated for 10 minutes, so as to achieve low interference coverage on farmland.

Dawn period (4:00~8:00): At this stage, insects gradually turn from rest to activity, and the control goal is to guide beneficial insects to enter the foraging state in advance and suppress the peak of dawn activity of pests. Simulating the solar spectrum at dawn, the combination of warm white and red light channels is adopted, the color temperature is 2500 K, and the light intensity gradually rises from 200 lx to 800 lx, with red light accounting for 38% and blue light accounting for 12%. The UAV adopts cruise operation mode, with a flying speed of 3 m/s and an irradiation radius of 12 m, and synchronously collects the activity frequency data of beneficial insects (such as ladybugs).

Noon time (10:00~14:00): Insects are most active at this stage, and the control goal is to strengthen the predation efficiency of beneficial insects and inhibit the feeding behavior of pests. Simulate the midday sun spectrum, using the combination of blue light+ultraviolet light+green light channel, with color temperature of 6500 K and light intensity of 1500 lx, with blue light accounting for 35% and ultraviolet light accounting for 10%. Based on the data of crop canopy height, the UAV adjusts the flying height to 5 m to ensure that the light evenly covers the crop surface, and at the same time monitors the feeding trace density of pests (such as aphids) through sensors.

Dusk time (16:00~20:00): This stage is the mating peak of most pests, and the control goal is to interfere with mating signal recognition and reduce the reproductive rate. Simulating the solar spectrum at dusk, the combination of warm white and green light channels is adopted, the color temperature is 3000 K, the light intensity is gradually reduced from 1000 lx to 300 lx, the green light component accounts for 32%, and the blue light component accounts for 8%. Field tests of UAV-borne light systems using this parameter setting show that the reproductive rate of target pests can be reduced by 35%-42%, which is significantly higher than that of fixed light sources [5]. The drone adopts fixed-point irradiation mode, and focuses on the areas with high pest incidence, and each area is irradiated for 15 minutes, and the frequency of mating behavior of pests is recorded simultaneously.

Night time (20:00~24:00): At this stage, some pests (such as Noctuidae) enter the peak of foraging, and the control target is trapping and killing. The combination of high-intensity (800 lx) ultraviolet and green light channels was used, with ultraviolet light accounting for 80% and green light accounting for 20%, and the phototaxis of pests was used for directional trapping. Combined with the real-time data of the trapping device, the UAV dynamically adjusts the working path and intensively irradiates the area with high trapping volume.

The core of this strategy is to realize the precise linkage of "light signal-biological clock-behavior" by accurately matching the diurnal variation of solar spectrum with the key time points of insect behavior. For example, at dusk of the peak of pest mating, the enhancement of green light component and the suppression of blue light component interfere with the visual communication signal of pests and reduce the mating success rate; At noon, the combination of blue light and ultraviolet light activates the visual system of beneficial insects and improves the predation efficiency.

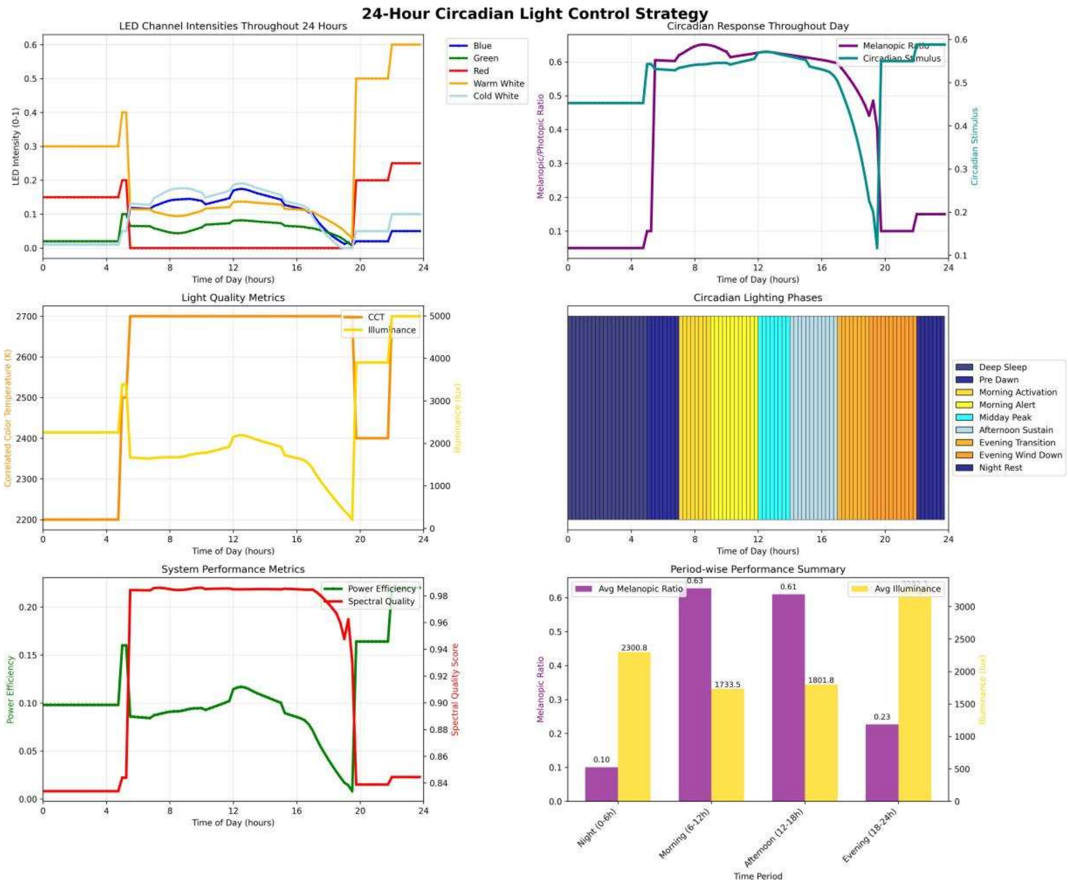

Figure 6. Circadian rhythm control strategy and key time point analysis

5. Conclusion and Prospect

In this paper, the light regulation technology of insect biological rhythm mediated by plant protection drone is studied from four dimensions: theoretical mechanism, system design, strategy optimization and experimental verification, and a complete technical system is constructed. The further improvement and large-scale application of this technology is

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expected to promote the transformation of green plant protection technology from "passive prevention" to "active regulation" and provide new guarantee for agricultural ecological security.

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