RESEARCH ARTICLE

Preliminary Application of Unmanned Plant Protection Machinery for Control of Cauliflower Diseases and Insect Pests in a Greenhouse

Zhibin Wang[1,*], **Zhenzhen Fan**[2], **Xifeng Chen**[2], **Xiaojun Qiao**[1] and **Jianbo Shen**[3,*]

[1] Information Technology Research Center, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China
[2] College of Plant Protection, China Agricultural University, Beijing 100193, China
[3] Department of Smart Agriculture and Engineering, Wenzhou Vocational College of Science and Technology, Wenzhou 325006, China

Abstract

Regular control of diseases and pests is crucial for maximizing cauliflower yield and quality. Spray application of chemical pesticides causes environmental pollution, pesticide residue accumulation, and is labor-intensive. To address these challenges, we developed an unmanned plant protection device integrating ozone sterilization, light traps, and Internet of Things (IoT) technologies. Installed in a greenhouse, the device included an ozone generator, high-speed fan, and insect traps. It was remotely controlled via a mobile app for real-time adjustments to ozone release, fan speed, trap lamp operation, environmental data collection, and system monitoring. Greenhouse experiments tested the device against cauliflower aphids, Pieris rapae, and black rot. Infestation/infection rates of aphids, Pieris rapae, and black rot in the greenhouse with the device were 23.18%, 19.72%, and 45.83%, respectively—22.52%, 7.21%, and 6.95% lower than the rates in the conventional greenhouse with pesticide sprays. No adverse effects on cauliflower growth were noted, and pesticide use was significantly reduced, lowering both agrochemical and labor costs. The results demonstrate that the unmanned device effectively controls pests and diseases and is safe for use. This offers a bio-friendly solution for pest control in cauliflower production.

Keywords: plant protection machinery, unmanned, pesticide reduction, smart phytoprotection, disease, insect pest, agriculture facility.

Submitted: 19 July 2025
Accepted: 22 August 2025
Published: 28 August 2025

Vol. 1, **No.** 1, 2025.
10.62762/DIA.2025.202928

***Corresponding authors:**
Zhibin Wang
wangzb@nercita.org.cn
Jianbo Shen
lyshenjianbo@163.com

1 Introduction

Brassicaceae crops are among the most widely planted crops worldwide. Cauliflower is especially popular on account of being nutrient-rich, low in fat, and low in calories. China is the leading producer of cauliflower in the word, with a planting area of 500,000 ha and an annual crop yield value exceeding 20 billion yuan [1].

Citation
Wang, Z., Fan, Z., Chen, X., Qiao, X., & Shen, J. (2025). Preliminary Application of Unmanned Plant Protection Machinery for Control of Cauliflower Diseases and Insect Pests in a Greenhouse. *Digital Intelligence in Agriculture*, 1(1), 24–34.

Diseases and insect pests impact on cauliflower yield and quality. Typical cauliflower diseases [2] include black rot, soft rot, downy mildew, Virus disease, and bacterial spot rot, and serious insect pests [3] include aphids, diamondback moths, red spider, and Pieris rapae. At present, spray application of chemical pesticides proves to be the most effective for combating diseases and insect pests on cauliflower [4]. However, under this approach, real-time and continuous control of pests and diseases is difficult, and excessive application of such chemicals may lead to accumulation of pesticide residues, pathogen resistance, and environmental pollution. With improvement in living standards and greater awareness of the importance of environmental protection, the pressure for reduction of pesticide pollution, environmental protection, and ecologically sustainable development is increasing [5–7]. Thus, reduction in the use of chemicals and development of intelligent green technologies for prevention and control of pests and diseases are pressing issues for sustainable agricultural development [8, 9].

Commonly used green prevention and control technologies mainly include biological control technology [10–13] and physical control technology [14–17]. Physical control technology usually adopts light, heat, temperature, electricity, radiation, and mechanical devices, to control diseases and insect pests. The primary methods used include light traps [18], colored sticky traps [19], insect-proof screens [20], and ozone sterilization [21, 22]. Physical control can effectively reduce the use of pesticides and has good prospects for sustainable agricultural production. Recently, the application of information technology in the plant protection field has promoted the development of plant protection informatization, especially driving technological development for modern and smart plant protection [23–27]. By combining information technology with physical control technology and plant protection agronomy, intelligent plant protection equipment has increasingly been applied in agricultural production [28–31]. These developments greatly improve the efficiency of plant protection, reduce chemical pesticide use and production costs, and enable prevention and control measures to permeate the entire process of crop growth.

To date, intelligent green prevention and control plant protection devices, for example, solar insecticidal lamps, are applied mainly in the field, however the application is relatively limited in the pest control of crop production. Notably, insecticidal lamps provide no protection against disease and therefore play no role in disease prevention or control. At present, the commonly used physical prevention and control measures in facilities comprise colored sticky traps, insect-proof screens, and high temperature. There remains a lack of efficient and intelligent green prevention and control technologies and devices, hampering precise prevention and control of insect pests and diseases, as well as intelligent management of crop protection operations.

The present study focused on the need for green prevention and control of diseases and insect pests in the production of cauliflower. We provide a sustainable and unmanned approach for control of cauliflower diseases and insect pests in a greenhouse by integrating ozone sterilization, light trap, and Internet of Things technologies to develop a plant protection machinery. The effectiveness of the novel unmanned plant protection machinery in the prevention and control of pests and diseases, and its impact on cauliflower growth, was evaluated. The results provide a reference for the development of new intelligent plant protection machinery and green control of diseases and insect pests in facilities for cauliflower production.

2 Materials and methods

2.1 Unmanned plant protection machinery

To realize the timely disinfection and sterilization of bacteria, fungi, viruses, and insect pests in crop production facilities, a new type of plant protection machinery, termed a multifunctional plant protection device (Figure 1), and an associated information management system have been developed. This device integrates multiple technologies, such as ozone sterilization, a light trap, and the Internet of Things, to achieve physical control of diseases and insect pests in production facilities. The main technical functionality of the plant protection device is as follows.

(1) Ozone sterilization. The device generates ozone through a high-voltage discharge, which can be rapidly and uniformly dispersed throughout the entire facility using high-velocity and high-capacity fan coupled with special ventilation duct. Once reaching the concentration required, the ozone can oxidize and eliminate insects' eggs and larvae, bacteria, and fungi, and suppresses virus replication, thereby achieving the diseases and pests prevention and control.

(2) Light trap. The bottom of the device is equipped

with yellow and blue light trap lamps, and a high-speed rotating fan. The device can accurately trap and kill pests according to the characteristics of their sensitivity to light. During operation of the device, the yellow and blue light trap lamps attract adult pests to fly close to the equipment, by taking advantage of their phototactic behavior, allowing the high-speed rotating fan to suck the pests into the device and kill them.

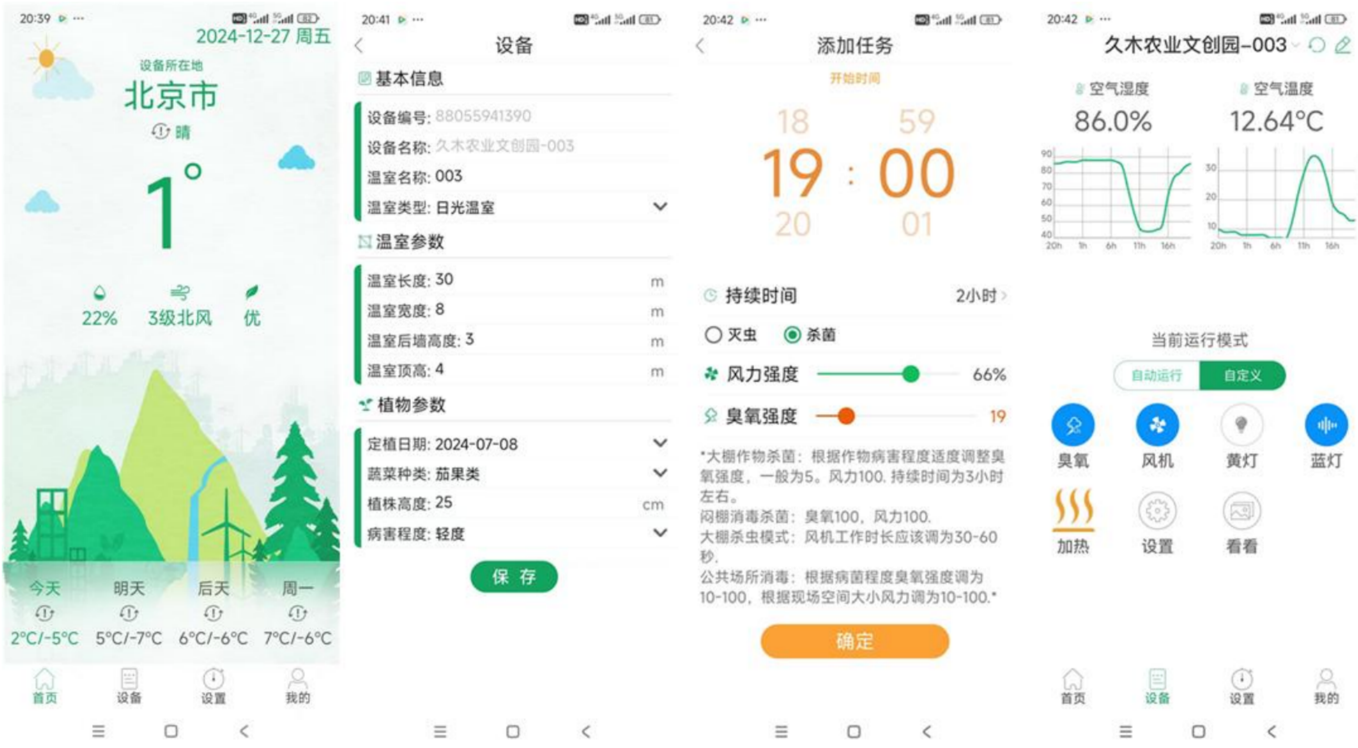
(3) Remote control. Remotely operated via a mobile phone app, the device enables integrated control over multiple functions: adjusting fan speed in real time, regulating ozone emission, collecting environmental data, switching the trap lamp on or off, and monitoring its operational status. Figure 2 shows the interface for operating the plant protection device app in the mobile phone. For example, users can operate the app to dynamically adjust the ozone concentration or the operating hours of the light trap, based on the growth period of the crop and the severity of diseases and insect pests. In addition, when multiple plant protection devices are installed and used in different areas, the user can manage all devices under an account in real time and remotely control multiple devices through the app for collaborative disease and insect pest prevention and control. This technology will contribute to reduced human involvement in plant protection operations.

Figure 1. Plant protection device used in the study.

The device integrates a hook, ozone generator, adjusting plate, air outlet, air inlet, high-velocity fan, sensors, control unit, trap lamp, and insect corpse bin. The device features a diameter of 800 mm, a height of 318 mm, and a boom length of 410 mm. It operates under the conditions of 220 V, 50 Hz with a rated power of 290 W, delivering an ozone output of 10 g/h, and an outlet ozone concentration of 4.3–10.7 mg/m^3.

The app incorporates functions for device user registration, device management, device maintenance, working mode settings, real-time data query, and visual display (Figure 2). The system has four main operation interfaces: login, device registration, device operation mode, and operating device. The main functions of each interface are as follows. (a) Login interface. After registration, users log in to the home page of the system. This module mainly consists of four buttons: home page, device, settings, and user information. By clicking on the different buttons, the system navigates to different operation interfaces. In addition, the local weather conditions can be displayed on this interface. (b) Device registration interface. This module is mainly used to collect information on the greenhouse for equipment installation. It includes three main submodules: basic equipment information, working environment, and crop growth information. This interface allows users to register and operate the plant protection equipment, while also collecting data on device working conditions and crop growth. (c) Device operation mode interface. This module is mainly used to set the operating mode of the plant protection equipment. With it users can set the fan velocity, ozone intensity, and equipment working time for sterilization or pest control according to crop growth status and working conditions. (d) Operating device interface. This interface shows the information on the equipment's working environment, such as relative humidity, temperature, light intensity, and CO2 concentration, inside the greenhouse, as well as device control buttons. Users can access this interface to remotely change and manage how the device operates, and visualize the collected environmental data.

In practical application, the plant protection device is suspended and installed from the roof the greenhouse. Through the app, users can remotely control and adjust the working mode of the device, or set a fixed working mode in advance, as shown in Figure 3. Generally, the initial emission rate of ozone and the fan wind intensity are set to 15% and 20%, respectively, and the device is operated continuously for 2 h at 2-hour intervals at night. If ozone emission from the equipment



(a) (b) (c) (d)

Figure 2. Control interfaces of the mobile phone app for the plant protection device. (a) Login interface, (b) device registration interface, (c) device operation mode interface, and (d) operating device interface.

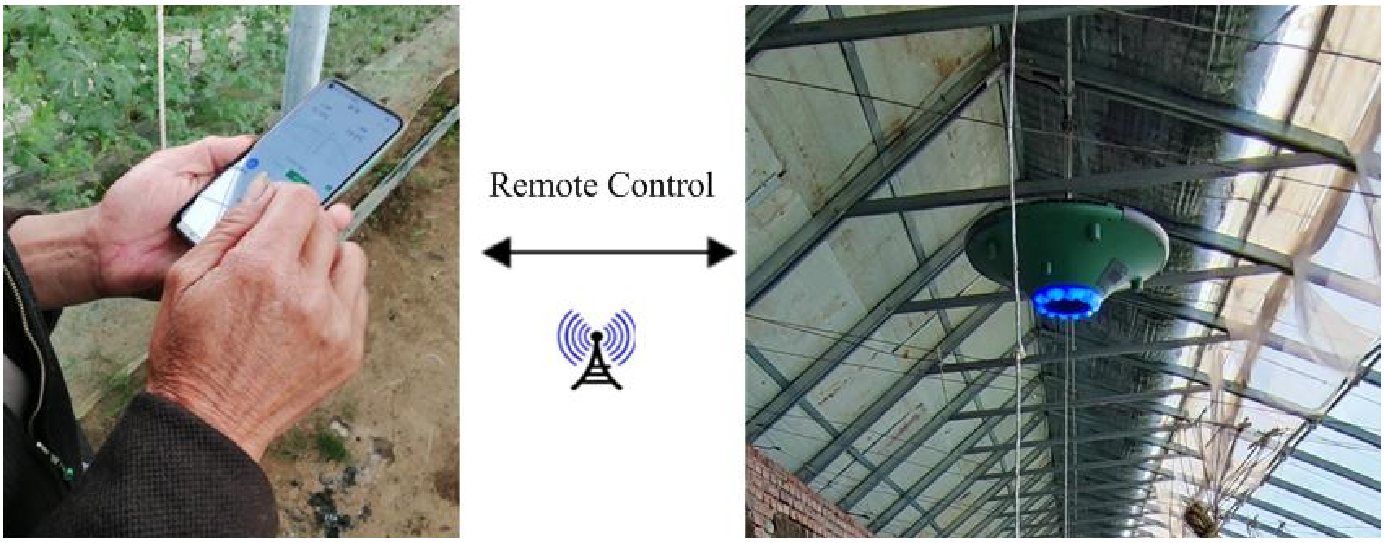


Figure 3. Illustration of user using the mobile phone app to control the plant protection device.

continuously exceeds 20%, the system will send a text message to remind the user that excessive ozone may damage crops.

2.2 Experimental Design

The trial took place in the No. 3 Greenhouse, Jiumu Cultural and Creative Park, Yangsong Town, Huairou District, Beijing. The dimensions of the experimental greenhouse were as follows: height 5.5 m, length 70 m, and width 12 m. The interior of the greenhouse was isolated into two independent experimental plots. The plant protection device was installed in experimental plot I to control cauliflower diseases and insect pests, and was operated daily from 19:00 to 07:00 (i.e., the next day). The working mode of the device could be remotely adjusted by users according to the crop growth conditions. The initial emission rate of ozone, and the fan wind intensity were set to 15% and 20%, respectively, the yellow and blue lights alternated every 1 h, and the device worked continuously for 2 h at a 2-hour interval at night. Conventional spray application of chemical pesticides, for example pymetrozine, was conducted in experimental plot II as the comparison group. Users mainly sprayed pymetrozine based on the severity of disease and insect pest incidence. The daily management of the two experimental plots, such as watering, fertilization, and ventilation, was identical.

The loose-curd cauliflower cultivar 'Jingsong No. 2' was used. Plants require approximately 90 days from transplanting to harvest in autumn when grown in open fields, and approximately 70 days in spring in open fields in North China. In the experiment, cauliflower planting began on April 20, 2024. Each experimental plot comprised 17 ridges, with two rows per ridge, and 12 cauliflower plants per row. Thus, a total of 408 cauliflower plants were planted in each experimental plot.

2.3 Experimental Investigation Method

In accordance with guidelines for pesticide field-efficacy trials, the general investigation method was used to calculate the infestation/infection rate of cauliflower diseases or pests. The infection rate was calculated using Equation 1:

$$\text{Infection rate of disease or insect } (\%) = \frac{\text{number of occurrences}}{\text{total number of investigations}} \times 100 \tag{1}$$

Assessments of pest and disease incidence in the greenhouse were conducted three times throughout the entire growth cycle of cauliflower, on May 9, May 21, and June 7, with an average interval of once every 2 weeks. The growth of cauliflower plants was observed after pest and disease prevention and control, and presence/absence of symptoms were recorded for each pest and disease that was monitored were recorded as well as any abnormal symptoms that were observed.

3 Experimental Results

3.1 Equipment Application

The application of the plant protection device, and assessment of disease and insect pest symptoms in the experiment are illustrated in Figure 4.

During the cauliflower growth period, users could remotely control the device's working mode in real time through a mobile phone and observe ambient parameters, such as relative humidity, temperature, light intensity, and CO^2 concentration, inside the greenhouse. These operational data were helpful for users to manage the cauliflower crop and predict pest and disease outbreaks. Operational results displayed by the mobile app during the experiment are shown in Figure 2.

Figure 4. Plant protection device operation and assessment of disease and insect pest symptoms.

3.2 Pest and Disease Control

After the harvest of cauliflower curds grown in the production facility at the Beijing Jiumu Agricultural Cooperative, based on the experimental results and production efficiency evaluation by the management, the effectiveness of the plant protection device for control of diseases and insect pests was judged from three perspectives: control efficacy, economic benefits, and safety. The two management methods (plant protection device vs. conventional chemical spray application) were applied in experimental plots I and II, respectively, as discussed in Section 2.2.

First, with regard to the efficacy for control of diseases and insect pests, the infection rates of cauliflower aphids, Pieris rapae, and black rot in the greenhouse with the installed plant protection device were 23.18%, 19.72%, and 45.83%, which were 22.52%, 7.21%, and 6.95% lower, respectively, than the infection rates in the control greenhouse subjected to conventional pesticide spray applications. In addition, common diseases that were liable to occur in previous years, such as viral diseases, downy mildew, and gray mold, were not recorded. The effectiveness of each method in preventing and controlling cauliflower diseases and insect pests is shown in Table 1, and Table 2 shows the results of the three experiments.

Second, considering the economic benefits, the crop management in experimental plot I reduced the frequency of pesticide application by five-fold during the entire growth period of cauliflower, achieving a reduction in costs (e.g., on pesticides and labor) of 1000 yuan/mu/season. Despite the reduction in pesticide applications in experimental plot I, the cauliflower crop yield was not impacted (approximately 2000 kg/mu/season). Moreover, the quality of the harvested cauliflower curds from experimental plot I was superior to that of experimental plot II because disease spots or insect pests were rarely detected on the former.

Third, no detrimental impacts were observed on the normal growth of cauliflower plants during the operation of the plant protection device in experimental plot I. The appearance of cauliflower plants at different growth stages is shown in Figure 5.

4 Discussion

Rising living standards and increasing environmental awareness are driving growing demand for reduced pesticide pollution, improved food safety, and more eco-friendly agricultural practices. Thus, the prevention and control of diseases and insect pests in vegetable production involves not only effectiveness but also environmental safety. The time and cost of prevention and control are two crucial factors in the prevention and control of diseases and insect pests. At present, spray application of chemical pesticides is typically employed for the prevention and control of diseases and insect pests in a production facility. However, three shortcomings are associated with this approach. First, the types and dosages of pesticides to be applied are mainly determined by farmers based on irregular surveys of diseases and insect pests in the crop. It is therefore difficult to achieve continuous and regular prevention and control. Second, the excessive and imprecise use of various chemical pesticides has resulted in diverse issues, such as ecosystem damage, accumulation of pesticide residues, and pathogen resistance. Third, with the overall aging of the population in China, there is an increasing shortage and aging of personnel engaged in prevention and control of diseases and insect pests, especially a shortage of young and middle-aged labor. This leads to problems such as employment shortages, high labor costs, and low workforce stability. Therefore, alternatives to pesticide use in agriculture are urgently required.

In recent years, Ozone sterilization [32–35] and light traps [36–39] have been widely applied in the control of diseases and pests. To address these issues mentioned above, we utilized information technologies, such as the Internet of Things [40], to interconnect plant protection machinery, equipment, and systems. Through remote control of these devices via the internet, real-time and continuous prevention and control of diseases and insect pests can be achieved. This approach can greatly reduce manual labor and production management costs, and benefits the overall sustainability of vegetable cultivation. Compared with traditional methods of spray application of chemical pesticides, the experimental method described herein has the following technical advantages.

1. The plant protection device uses ozone as a strong oxidizing agent to achieve disinfection and sterilization of bacteria, fungi, and viruses, and uses a light trap to attract and kill adult insects. Therefore, the equipment adopts physical prevention and control methods, which directly avoids accumulation of pesticide residues, environmental contamination, and increased pathogen resistance resulting from the overuse of chemical pesticides.

2. When the plant protection device is operating, the amount of ozone released, the switching of the insecticidal lamps, and the operational hours of the device can be remotely controlled in real time through the information management system. In contrast, spray applications of chemical pesticides require consideration of multiple factors, such as the pesticide dosage, spraying cycle, and pesticide type, which may differ at each application.

3. The plant protection equipment can be reused continuously within the production facility for a prolonged period (with a service life of more than 10 years), which can effectively reduce production input costs, such as pesticide purchase and manual application.

4. The device of plant protection can remotely acquire environmental parameters within the facility, such as relative humidity, temperature, and light intensity. This information can effectively assist farmers with crop production and the prevention and control of diseases and insect pests. In contrast, conventional methods of applying chemical pesticides require farmers to

Table 1. Comparison of the effects of the plant protection device (Plot I) and conventional chemical spray application (Plot II) on control of diseases and pests of cauliflower in a greenhouse.

Experimental plot	Infection rate of aphids	Infection rate of *Pieris rapae*	Infection rate of black rot
Plot I	23.18%	19.72%	45.83%
Plot II	45.71%	26.93%	52.78%

Note: The data are the average of the results of three independent experiments.

Table 2. Results of the three experiments.

Investigation date	Experimental plot	Number of investigated crops	Infection rate of aphids	Infection rate of Pieris rapae	Infection rate of black rot
May 9, 2024	Plot I	98	6.12%	8.16%	—
	Plot II	98	64.29%	10.20%	—
May 21, 2024	Plot I	165	50.91%	21.82%	—
	Plot II	165	67.27%	30.30%	—
June 7, 2024	Plot I	72	12.50%	29.17%	45.83%
	Plot II	72	5.56%	40.28%	52.78%

Figure 5. Different growth stages of cauliflower plants grown in experimental plot I.

observe the growth status of the crop and to judge the type and quantity of pesticides needed for pest control based on their personal experience. Such manual control struggles to achieve timely and precise pest and disease prevention and control, and is labor intensive.

5. The plant protection equipment can be widely applied in multiple facilities and managed through an information management system, achieving collaborative prevention and control of crop diseases and insect pests. The amount, duration, and frequency of application of chemical pesticides in different facilities often vary. Moreover, coordination of manual spray application of pesticides simultaneously in multiple greenhouses can be challenging.

With the fast development and application of information technology and communication technology, as well as the transformation of agricultural planting methods, plant protection technology is gradually evolving towards an era of intelligent plant protection, such as multi-scenario, large-scale, multi-machine collaboration, networked control, and unmanned intelligent operation. Previous similar research has mostly focused on a specific scenario, for example, using solar insecticidal lamps for control of insect pests in fields, whereas less research has been conducted on the control of diseases and insect pests in production facilities. This study provides a comprehensive and complete technical solution for the green prevention and control of crop diseases and pests in facilities. Our system enables efficient management of large-scale equipment deployment and coordinated multi-device operations for enhanced pests and diseases prevent and control. Furthermore, through a mobile device app, farmers can remotely operate the plant protection equipment and adjust the operational mode in real time, such as, modifying the operation duration of insecticidal lamp or regulating the emission rate of ozone. Compared with similar systems and intelligent plant protection devices, our system exhibits stability, convenience, and strong scalability in facilities. In particular, the system is user-friendly, portable, intelligent, and inexpensive.

Overall, the use of an unmanned plant protection device to prevent and control crop diseases and insect pests has broad potential applications. Although unmanned plant protection equipment has been proven to effectively reduce pesticide use and improves the profitability of crop cultivation, the use of such equipment must be adjusted according to the planting environment and crop season, so as to achieve good application effect. Compared with the traditional method of spray application of chemical pesticides, our unmanned system achieved significantly improved prevention and control of aphids and Pieris rapae in the production facility (Table 1); although the system resulted in a certain level of prevention and control of black rot, the difference was not obvious between the two methods. The main reason for the aforementioned phenomenon is that the insect pest and disease control experiment was conducted in spring and summer. The temperature and humidity inside the facility will gradually increase as the weather warms up. To ensure the normal growth of cauliflower in the facility, it is necessary to ventilate the greenhouse. With regard to insect pest prevention and control, the adults of cauliflower aphids and Pieris rapae show strong phototaxis, especially towards yellow light. The plant protection device can use trapping lights to lure and kill adult pests in real time and continuously within the facility, significantly reducing pest reproduction and achieving effective insect pest control. With respect to disease prevention and control, owing to the high temperature and humidity inside a greenhouse, on the one hand, it is necessary to increase ventilation in the greenhouse to reduce the temperature and humidity. This will decrease the concentration of ozone released by the crop protection device, thereby weakening the disease prevention and control effect. On the other hand, a high-temperature and high-humidity facility environment is conducive to the development of black rot disease in cauliflower. As a result, the prevention and control of black rot by the crop protection device was less marked than that of insect pests. Therefore, in a greenhouse that requires ventilation, it is necessary to increase the amount and duration of ozone release from the equipment according to the health and vigor of the cauliflower plants, so as to achieve more effective disease prevention and control. In future research, technologies such as intelligent detection, Internet of Things, and artificial intelligence will be adopted to develop more smart plant protection equipment, for example, to enable the equipment to adaptively adjust the plant protection model based on the growth environment and crop season. In addition, multispectral insect traps and ozone sensors will be installed on the plant protection device to achieve precise pest trapping and ozone concentration control.

5 Conclusions

In this study, we explored the efficacy of a new type of unmanned plant protection machinery for controlling diseases and insect pests of cauliflower in a greenhouse. Comparative experiments with conventional spray application of pesticides were conducted in a greenhouse using cauliflower aphids, Pieris rapae, and black rot as test subjects. We conclude from the production of cauliflower in a greenhouse that use of the plant protection device can realize continuous and regular prevention and control of diseases and insect pests, reduces the use of chemical pesticides, and lowers production input costs. This technology has good prospects for sustainable agricultural production.

The next step will be to conduct in-depth research on the precise control of the plant protection device. In particular, we will integrate the agricultural characteristics of different crops to develop disease and insect pest control models, thereby improving the precision of the plant protection equipment for control of crop diseases and insect pests in a greenhouse.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported by the National Key R&D Program of China under Grant 2022YFD1401200.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Dias, J. S., & Ortiz, R. (2021). New strategies and approaches for improving vegetable cultivars. In *The Basics of Human Civilization* (pp. 349-381). CRC Press. [CrossRef]

[2] Sara, U., Rajbongshi, A., Shakil, R., Akter, B., & Uddin, M. S. (2022). VegNet: An organized dataset of cauliflower disease for a sustainable agro-based automation system. *Data in Brief, 43*, 108422. [CrossRef]

[3] Mayanglambam, S., Singh, K. D., & Rajashekar, Y. (2021). Current biological approaches for management of crucifer pests. *Scientific Reports, 11*(1), 11831. [CrossRef]

[4] Khatun, P., Islam, A., Sachi, S., Islam, M. Z., & Islam, P. (2023). Pesticides in vegetable production in Bangladesh: A systemic review of contamination levels and associated health risks in the last decade. *Toxicology Reports, 11*, 199-211. [CrossRef]

[5] Abbas, M., Saleem, M., Hussain, D., Ramzan, M., Jawad Saleem, M., Abbas, S., ... & Parveen, Z. (2022). Review on integrated disease and pest management of field crops. *International Journal of Tropical Insect Science, 42*(5), 3235-3243. [CrossRef]

[6] Chikte, T., Kopta, T., Psota, V., Arizmendi, J., & Chwil, M. (2024). A comprehensive review of low-and zero-residue pesticide methods in vegetable production. *Agronomy, 14*(11), 2745. [CrossRef]

[7] Cheng, Z., Zhu, M., & Cai, J. (2025). Reducing fertilizer and pesticide application through mandatory agri-environmental regulation: Insights from "Two Zero" policy in China. *Environmental Impact Assessment Review, 110*, 107716. [CrossRef]

[8] Huang, K., & Shu, L. (2021). Grand challenges in sustainable and intelligent phytoprotection. *Frontiers in Plant Science, 12*, 755510. [CrossRef]

[9] Zhang, J., Xie, S., Li, X., & Xia, X. (2024). Adoption of green production technologies by farmers through traditional and digital agro-technology promotion–An example of physical versus biological control technologies. *Journal of Environmental Management, 370*, 122813. [CrossRef]

[10] Mrnka, L., Frantík, T., Schmidt, C. S., Švecová, E. B., & Vosátka, M. (2023). Intercropping of Tagetes patula with cauliflower and carrot increases yield of cauliflower and tentatively reduces vegetable pests. *International Journal of Pest Management, 69*(1), 35–45. [CrossRef]

[11] Pandit, M. A., Kumar, J., Gulati, S., Bhandari, N., Mehta, P., Katyal, R., Rawat, C. D., Mishra, V., & Kaur, J. (2022). Major Biological Control Strategies for Plant Pathogens. *Pathogens, 11*(2), 273. [CrossRef]

[12] Maurya, R. P., Koranga, R., Samal, I., Chaudhary, D., Paschapur, A. U., Sreedhar, M., & Manimala, R. N. (2022). Biological control: A global perspective. *International Journal of Tropical Insect Science, 42*(4), 3203–3220. [CrossRef]

[13] Collinge, D. B., Jensen, D. F., Rabiey, M., Sarrocco, S., Shaw, M. W., & Shaw, R. H. (2022). Biological control of plant diseases–What has been achieved and what is the direction?. *Plant Pathology, 71*(5), 1024-1047. [CrossRef]

[14] Ahmad, F., Fouad, H., Liang, S. Y., Hu, Y., & Mo, J. C. (2021). Termites and Chinese agricultural system: applications and advances in integrated termite management and chemical control. *Insect science, 28*(1), 2-20. [CrossRef]

[15] Jobe, N. B., Chourasia, A., Smith, B. H., Molins, E., Rose, A., Pavlic, T. P., & Paaijmans, K. P. (2024). Using electric fields to control insects: current applications and future directions. *Journal of Insect Science, 24*(1), 8. [CrossRef]

[16] Al Mamun, M. R., Keya, A. C., Alim, M. S., Hossen, M. A., Mondal, M. F., & Soeb, M. J. A. (2023). Potentiality assessment of solar based LED light trap as pest management tool in tea (Camellia sinensis L.). *Smart Agricultural Technology, 5*, 100304. [CrossRef]

[17] Wang, Y., Qiao, X., & Wang, Z. (2022). Application of ozone treatment in agriculture and food industry. A review. *INMATEH - Agricultural Engineering, 68*(3), 861–872. [CrossRef]

[18] Yao, H., Shu, L., Yang, F., Jin, Y., & Yang, Y. (2023). The phototactic rhythm of pests for the Solar Insecticidal Lamp: A review. *Frontiers in Plant Science, 13*, 1018711. [CrossRef]

[19] Gao, Y., Yin, F., Hong, C., Chen, C., Deng, H., Liu, Y., Li, Z., & Yao, Q. (2025). Intelligent field monitoring system for cruciferous vegetable pests using yellow sticky trap images and an improved Cascade R-CNN. *Journal of Integrative Agriculture, 24*(1), 220–234. [CrossRef]

[20] Faliagka, S., & Katsoulas, N. (2022). Silica coated insect proof screens for effective insect control in greenhouses. *Biosystems Engineering, 215*, 21–31. [CrossRef]

[21] Li, X., Liu, Y., Zhang, C., Che, H., He, Q., Wang, L., & Yao, B. (2024). Effect of ozone sterilization on controlling leaf mildew and gray mold tomato disease in a glasshouse and its influence on other growth parameters. *Journal of the Science of Food and Agriculture, 104*(7), 4097–4108. [CrossRef]

[22] Jiang, L., Liu, B., Zhang, S., Zhang, R., Wu, C., & Qiao, K. (2024). Increasing spray volume and ozone spray of tetraconazole improve control against strawberry powdery mildew. *Crop Protection, 179*, 106602. [CrossRef]

[23] Wang, H. (2022). Smart phytoprotection and suggestions for its development. *Journal of China Agricultural University, 27*(10), 1–21.

[24] Zheng, X. (2024). Editorial: AI-empowered services for interconnected smart plant protection systems. *Frontiers in Plant Science, 15*, 1359627. [CrossRef]

[25] Zhong, Y., Teng, Z., & Tong, M. (2024). LiteMixer: Cauliflower disease diagnosis based on a novel lightweight neural network. *The Computer Journal, 67*(6), 2346–2356. [CrossRef]

[26] Kanna, G. P., Kumar, S. J., Kumar, Y., Changela, A., Woźniak, M., Shafi, J., & Ijaz, M. F. (2023). Advanced deep learning techniques for early disease prediction in cauliflower plants. *Scientific Reports, 13*(1), 18475. [CrossRef]

[27] Uddin, M. S., Mazumder, M. K. A., Prity, A. J., Mridha, M. F., Alfarhood, S., Safran, M., & Che, D. (2024). Cauli-Det: Enhancing cauliflower disease detection with modified YOLOv8. *Frontiers in Plant Science, 15*, 1373590. [CrossRef]

[28] Wang, S., Xu, T., & Li, X. (2022). Development status and perspectives of crop protection machinery and techniques for vegetables. *Horticulturae, 8*(2), 166. [CrossRef]

[29] Zheng, L. I. U., Chengqian, J. I. N., Yugang, F. E. N. G., & Tengxiang, Y. A. N. G. (2024). Research status and trends of intelligent technology in plant protection machinery. *Journal of Intelligent Agricultural Mechanization, 5*(1), 40-50. [CrossRef]

[30] He, X., Yang, F., & Qiu, B. (2024). Agricultural environment and intelligent plant protection equipment. *Agronomy, 14*(5), 937. [CrossRef]

[31] Sun, X., Zhang, Y., Tang, C. L., Zhao, H. H., & Ai, C. S. (2016). Development of the field of wheat plant protection precision spraying robot control system. *Applied mechanics and materials, 851*, 427-432. [CrossRef]

[32] Li, X., Li, Y., Wang, L., Zhang, C., Tao, L., & Zhang, Y. (2024). Design and experiment of closed-loop control system for ozone sterilization in facility agriculture. *Journal of Chinese Agricultural Mechanization, 45*(9), 62–68.

[33] Barthwal, R., Negi, A., Kathuria, D., & Singh, N. (2025). Ozonation: Post-harvest processing of different fruits and vegetables enhancing and preserving the quality. *Food Chemistry, 463*, 141489. [CrossRef]

[34] Simplício, I. B. O., Sousa, S. C., Thomaz, T. S., Lima, F. S., Bezerra, J. S., Carvalho, M. C. O., Ferreira, M. S., & Miranda, M. K. V. (2023). Ozone use in surface disinfection: an integrative review. *Acta Paulista De Enfermagem, 36*, eAPE00542. [CrossRef]

[35] Cruz, L. K., Schroer, I. A., Hansen, E., Bender, B. N., da Silva, P. R. S., Brochier, B., da Silva, J., & da Silva, S. B. (2025). Ozone application for inactivation of Escherichia coli in air-conditioned environments for food production. *Ozone Science & Engineering*, 1–10. [CrossRef]

[36] Wang, Y., Chang, Y., Zhang, S., Jiang, X., Yang, B., & Wang, G. (2022). Comparison of phototactic behavior between two migratory pests, Helicoverpa armigera and Spodoptera frugiperda. *Insects, 13*(10), 917. [CrossRef]

[37] Han, D., Chen, X., Zhou, F., Wu, X., Zhao, M., & Chen, X. (2021). Control effects of blue and yellow light on Bemisia tabaci on greenhouse cucumbers. *Chinese Journal of Eco-Agriculture, 29*(5), 802–808. [CrossRef]

[38] Athanasiadou, M., Seger, R., & Meyhöfer, R. (2025). Potential of blue light-emitting diodes (LEDs) to disturb whiteflies on the crop: a new push-pull strategy? *Journal of Pest Science, 98*(3), 1117–1133. [CrossRef]

[39] Grupe, B., & Meyhöfer, R. (2024). Whitefly Detected: LED Traps Enhance Monitoring of Trialeurodes vaporariorum in Greenhouse-Grown Tomato. *Horticulturae, 10*(9). [CrossRef]

[40] Mansoor, S., Iqbal, S., Popescu, S. M., Kim, S. L., Chung, Y. S., & Baek, J. H. (2025). Integration of smart sensors and IOT in precision agriculture: trends, challenges and future prospectives. *Frontiers in Plant Science, 16*, 1587869. [CrossRef]

Zhibin Wang received the Ph.D. degree in Computer Application Technology from University of Science and Technology Beijing, China, in 2013. He is currently a professor in the Information Technology Research Center, Beijing Academy of Agriculture and Forestry Sciences. His research interests include machine learning, image processing, and smart phytoprotection. He has published more than 40 research papers. (Email: wangzb@nercita.org.cn)

Zhenzhen Fan is a master student at the Department of Plant Pathology, China Agricultural University. Her research interest covers green plant protection. (Email: fanzhenzhen059@163.com)

Xifeng Chen is a master student at the Department of Plant Pathology, China Agricultural University. Her research interest covers green plant protection. (Email: cxfyuzuru1110@163.com)

Xiaojun Qiao received the Ph.D. degree in College of Plant Protection from China Agricultural University, in 2000. He is a professor in the Information Technology Research Center, Beijing Academy of Agriculture and Forestry Sciences. His research interests include intelligent decision-making system and intelligent agricultural equipment. (Email: qiaoxj@nercita.org.cn)

Jianbo Shen received the Ph.D. degree in Forest Management at Chinese Academy of Forestry in 2018. He is currently as associate professor in the Department of Smart Agriculture and Engineering, Wenzhou Vocational College of Science and Technology, China. His research interests include statistic model, machine learning, deep learning, and their applications. He currently serves as a Guest Editor for Sustainability. He was selected as the "2024 China National Knowledge Infrastructure Highly Cited Scholars Top 5%" in 2025. (Email: lyshenjianbo@163.com)