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Development of a UVC application machine for managing plant diseases in soilless greenhouse crop production

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This study aimed to develop a UVC machine designed for the treatment of common fungal, bacterial, and viral diseases in greenhouse-grown crops, serving as an alternative to chemical applications. The machine utilizes standard battery carts or trolley infrastructure for mobility along heating pipes in greenhouses. The machine is equipped with 8 UVC lamps, four on each side, each having a power of 145 W and a length of 1.5 m, complete with reflectors. The lamps can be adjusted both vertically and horizontally to optimize their positioning based on the crop conditions. Two 24 V switches control the lamp power levels according to data received from the microcontroller. Each lamp can be controlled via software, allowing them to be turned on or off as needed. The lamps on either side of the machine can be operated independently to provide the specific dosage required for treating plant diseases within a range of 5 to 100 mJ/cm^2. UVC doses were measured at various machine speeds and lamp-sensor distances. Statistical analyses confirmed a significant effect of PWM speed on UVC dose ($p < 0.05$), demonstrating the inverse relationship between machine speed and accumulated UVC exposure. The UVC machine has proven effective as an autonomous device for crop disease management. Operating the lamps at slower speeds increases the dosage but may delay treatment, which is critical for stopping the spread of diseases or pests.

Keywords UVC light, UVC machine, Greenhouse crops, Plant diseases, Soilless cultivation

The European Union's (EU) Pesticide Residue Standards establish strict criteria for food safety, with Maximum Residue Limits (MRL) reviewed annually by the European Food Safety Authority (EFSA). In 2022, 4.9% of EU-marketed products exceeded MRL thresholds[1], increasing pressure on farmers to adopt alternative disease management strategies. As a response, ultraviolet (UVC) light application has emerged as a promising non-chemical approach to plant disease control while complying with MRL regulations. UVC light, with a wavelength range of 100 to 285 nm, is widely recognized for its antimicrobial properties, effectively eliminating microorganisms, insects, and even plants, depending on dosage. Although UVC exposure can be harmful to humans without protective measures, its effectiveness in air and water purification, laboratory biosecurity, food preservation, and medical sterilization is well-documented[2,3]. Given its pathogen control capabilities, UVC technology has gained significant attention in agriculture, particularly in soilless crop production, where chemical alternatives are increasingly sought after.

Traditionally, synthetic fungicides and insecticides have been used to manage plant diseases and pests in both open fields and greenhouses. However, the emergence of pesticide-resistant pathogens and the growing consumer demand for pesticide-free fruits necessitate sustainable and ecologically viable alternatives[4,5]. While post-harvest UVC treatments have been effective in reducing decay and food-borne pathogens in harvested fruits and vegetables[6–8], pre-harvest UVC applications have been limited due to potential plant damage[9]. Nevertheless, research indicates that short-interval UVC applications at low doses, followed by a dark period, can effectively manage agricultural pests such as the two-spotted spider mite (*Tetranychus urticae*) on strawberries[10].

Most studies on UVC disinfection for plant disease and pest control focus on strawberry production. One disease-management strategy involves treating strawberry plants with low doses of UVC for a short duration, followed by a specific dark period, significantly increasing UVC lethality against powdery mildew[11]. Research

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has confirmed the efficacy of UVC in eliminating powdery mildew fungi and other pathogens in greenhouse strawberry systems, although leaf burn has been reported as a side effect[12]. Additionally, nightly 30-minute UVB irradiation treatments have been found to induce resistance in strawberry plants against fungal pathogens[13]. Further studies have demonstrated that low UVC doses (≤ 72 J/m²), when followed immediately by darkness, can control fungi responsible for gray mold, anthracnose, and powdery mildew, as well as pests like two-spotted spider mites and greenhouse whiteflies, with minimal phytotoxic effects[14,9,10].

Recent studies have expanded UVC applications to other crops. Patel et al.[15] found that a UVC dose of 7.2 J/m² applied every night, or 70 J/m² every fourth night, prevented powdery mildew in greenhouse cucumbers without affecting leaf area or yield. Similarly, Sidibe et al.[16] demonstrated that a total UVC dose of 1.6 kJ/m² reduced Xanthomonas campestris pv. vitians (Xcv) by up to 90%, improving crop quality. Additionally, in tulips, UVC irradiation doses of 100 to 500 mJ/cm² successfully eliminated Fusarium without adverse effects on crop development[17]. Advances in UVC application technology have explored various deployment methods, including fixed lamps in greenhouses, UVC-equipped wheelbarrows and trolleys, and even mobile robotic devices[18,19].

Innovations in UVC technology have led to the development of robotic and automated application systems for nighttime field treatments. For instance, a prototype robot equipped with eight 160 W UVC lamps was designed to combat powdery mildew in strawberries, offering flexible application doses ranging from 30 to 200 J/m² [20]. Other studies have proposed dynamic scheduling solutions for UVC application in horticulture, such as the "Clean Light" machine, which delivers UVC doses between 5 and 60 mJ/cm² for powdery mildew control[21]. The use of short-wavelength 222 nm UVC light has also shown promise in eliminating fungal pathogens and enhancing resistance against Colletotrichum and Botrytis infections in strawberry plants[5,22,23]. Furthermore, an intelligent UVC scheduling system was proposed to optimize pathogen control in greenhouse crops[24].

In a recent study,[25] reported that UVC applications twice a week at night, using doses of 55–110 J/m², effectively controlled mildew in spring-cultivated greenhouse strawberries without spray treatments. This method presents a competitive alternative to intensive conventional integrated pest management (IPM) strategies. However, it is important to note that while UVC effectively suppresses Tetranychus urticae, it can also harm beneficial predatory mites (Amblydromalus limonicus), necessitating careful dosage adjustments.

This study aims to develop a UVC application machine designed for managing plant diseases in soilless greenhouse crop production. The machine is intended to control the most common fungal, bacterial, and viral diseases. By ensuring that UVC light effectively reaches all parts of the plants, especially in high-density production areas, this machine aims to reduce disease pressure.

Materials and methods

Design and general structure of the UVC machine

In this study, priority was given to developing and arranging the speed control of a machine, along with managing lamps during UVC applications. The machine is designed to move along heating pipes (rails) in greenhouses. The developed UVC machine autonomously navigates along predefined rail paths within the greenhouse. While the current system requires the user to determine which rail to use, all other functions—including speed adjustments and UVC dosage control—are fully automated. Its bottom structure is similar to that of a harvest cart or trolley, but it utilizes more powerful batteries for the lamps.

In total, eight lamps with a wavelength of 254 nm were planned to be assembled on the machine, with four lamps on each side. The selected lamps are 145 W each, 1.5 m long, and equipped with reflectors, as illustrated in Fig. 2(a). In addition, 1.5-meter-long UVC lamps were selected to ensure homogeneous irradiation across different plant heights. Uniform UVC exposure on leaf surfaces is critical for effective disease control in greenhouse crops. Shorter lamps may result in insufficient light penetration for taller plants; therefore, 1.5-meter lamps were preferred. Moreover, the choice of 145 W lamp power, although recommended by the manufacturer, is also scientifically justified. Flores Gallegos[26] demonstrated that higher-power UVC lamps enhance operational efficiency by reducing application time. Compared to lower-power alternatives, 145 W lamps optimize microbial inactivation by delivering the required UVC dose in a shorter duration without the potential to damage crop leaves.

The ballasts operate between 120 V and 277 V; at 120 V, the amperage is 1.30 A, and at 277 V, it is 0.56 A. The machine is powered by both electric motors and lamps, utilizing four 12 V/95Ah batteries. The charging unit operates at 8 A and includes current and heat control features. A green light indicates that the batteries are charging, while a red light signals that the batteries have not been connected to the charging unit for 36 h. The charging process for all four batteries takes 24 h, and once fully charged, the batteries enter protection mode. The power for the lamps is managed by two 24 V relays, which respond to data from a microprocessor. An 1800 W modified sine wave inverter converts DC power from the batteries to AC power for the electric motors and lamps.

The front view of the UVC machine, including its main frames and components, is illustrated in Fig. 1. The machine is designed to move along heating pipes, allowing for adjustable distances between the lamps and crops, as well as varying lamp heights for different crop applications. This adjustment can be easily achieved through the use of a telescopic steel profile that operates on both sides of the machine. From a technical perspective, the machine frame and lamp positions are symmetrical.

Motor and motion control system

The machine is equipped with three 24 V, 350 W electric motors along with three drive brushless DC motor (BLDC) 350 W motor driver cards, as illustrated in Fig. 2(b). Pulse Width Modulation (PWM) signals from the microprocessor control the speed and direction of the motors. Additionally, limit switches are installed at both the front and back of the machine to facilitate automatic forward and backward movement. A Broadcom Wi-Fi chipset (BCM43362) and an STM32F205 120 MHz ARM Cortex M3 microcontroller were chosen for the

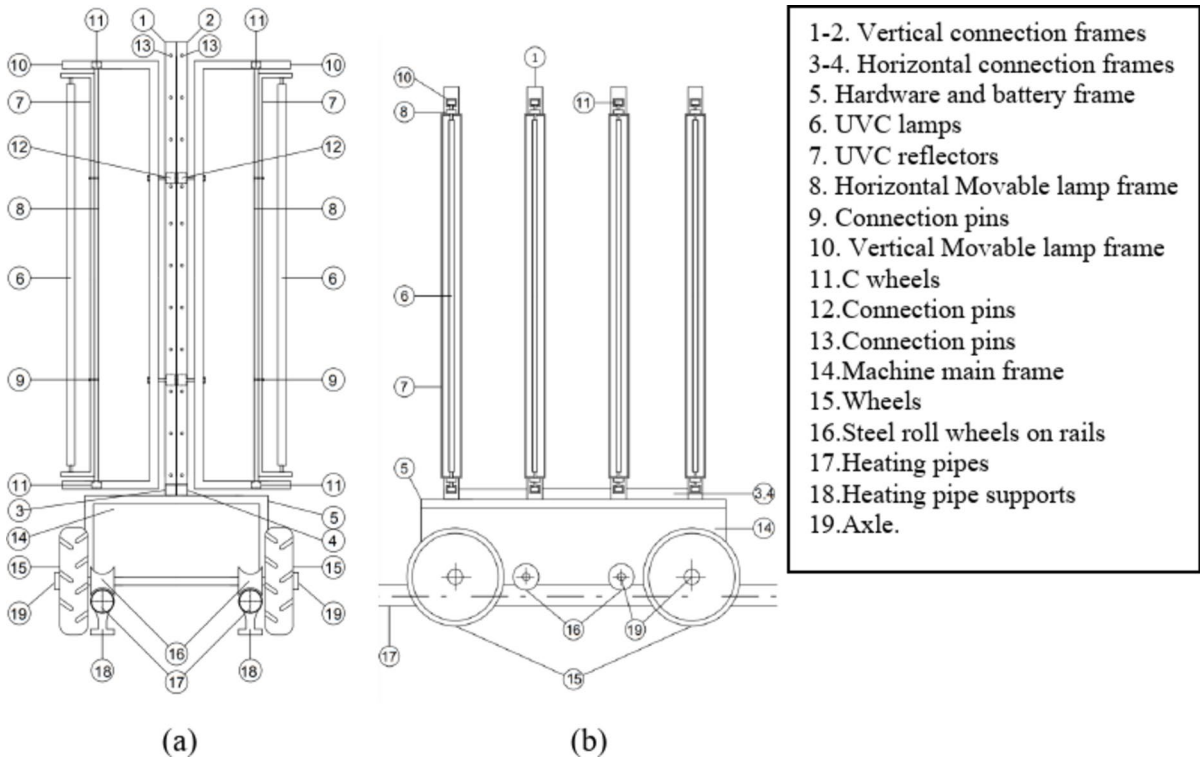


Fig. 1. Technical drawing showing the front (**a**) and side (**b**) views of the UVC machine that was developed and tested.

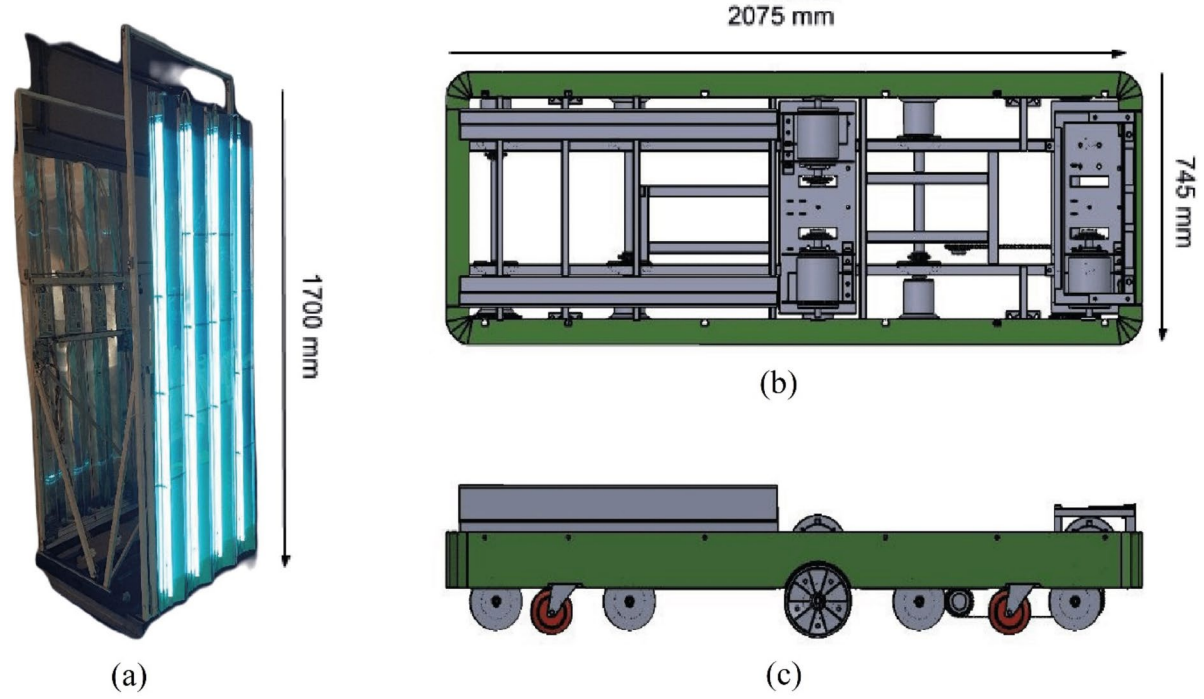


Fig. 2. The primary sizes of the UVC machine: (**a**) general view of the UVC machine developed, (**b**) bottom view of the machine, (**c**) side view of the machine (photos and drawings not on scale).

remote control of machine movement and lamp operation. The system operates on a real-time operating system, FreeRTOS. For programming the microcontroller, the C++programming language was used. Web and mobile applications were developed using JavaScript and mobile SDKs. The user interface is cloud-based, allowing control from any location with an internet connection.

UVC measurement method and sensor usage

For the measurement of UVC radiation between 220 and 280 nm, a Delta Ohm HD 2102.2 model data logger and a LP471UVC sensor were utilized. This device is capable of measuring UVC radiation in various units. The UVC sensor was positioned approximately 1.5 m above the ground, at the midpoint of the lamps, with a distance of about 15 cm between the lamps and the sensor. This setup simulates the distance from the machine to the crop leaves in an actual greenhouse. Measurements were taken at night, as illustrated in Fig. 3, to replicate the conditions of UVC application in greenhouses during nighttime.

Testing of the UVC machine and speed calibration

After assembling all components and manufacturing the machine, it was tested on heating rails in a trial greenhouse. The UVC light was measured and recorded for different machine speeds, which were controlled via PWM from a mobile phone using a Wi-Fi connection. The speed of the machine was calibrated using a chronometer, converting PWM values into meters per second (m/s). A table was created to correlate UVC measurements with machine speeds in m/s.

For testing, the primary independent variable was the PWM speed, with four levels: 900, 1000, 1200, and 1300. The dependent variable was the UVC dose measured for a single lamp. The UVC intensity was recorded at various distances and machine speeds using a calibrated sensor placed at the height of the crop canopy. Measurements were conducted under controlled environmental conditions, ensuring no interference from external light sources. Each measurement was repeated three times to account for variability, and the average values were used for further analysis.

The motor driver board for the UVC machine is illustrated in Fig. 4. The device, "Brushless Motor Controller, 5V-36V 350 W DC Brushless Motor Board Safe Motor Controller BLDC PWM Driver Board," is designed to control and drive the BLDC with a power range of 5 V to 36 V and a maximum output of 350 W. This device operates using PWM to manage motor speed by adjusting the duty cycle of the PWM signal, as noted by Yuniarto et al.[27,28].

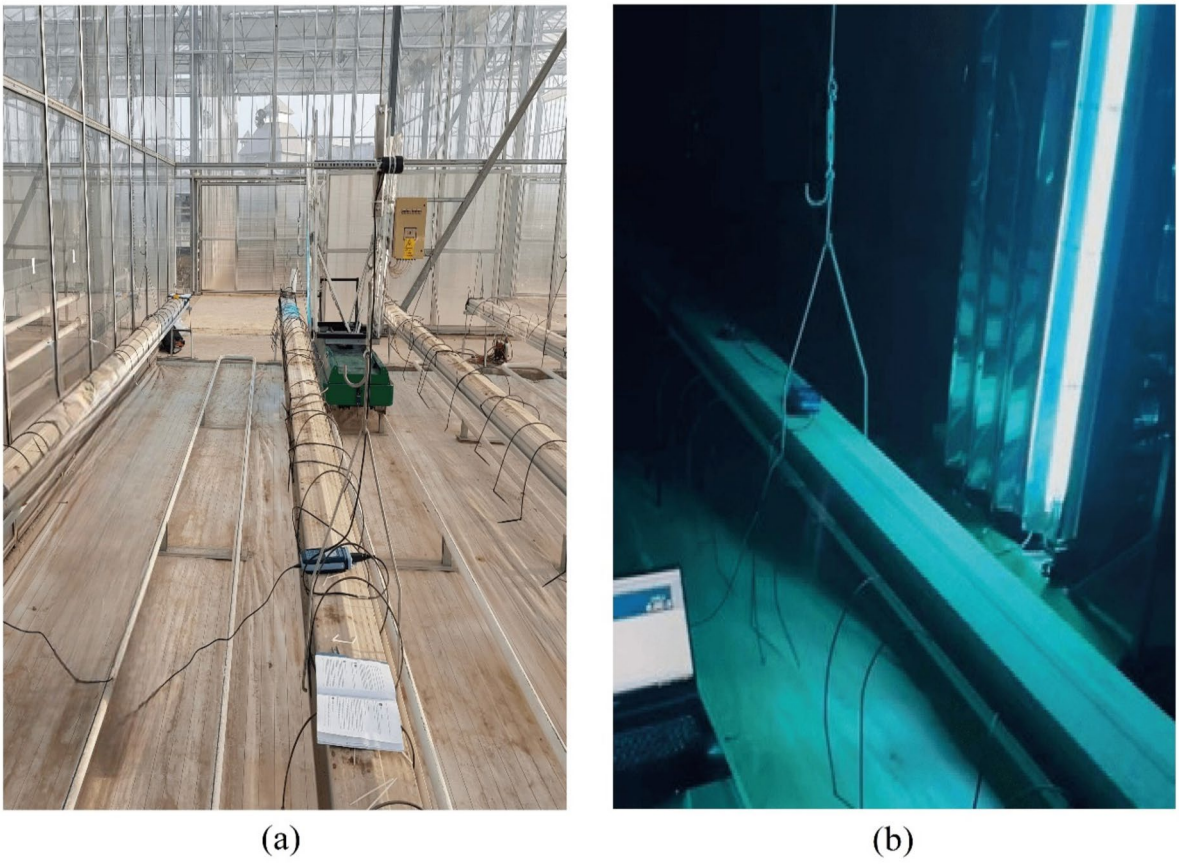


Fig. 3. Measurement Setup in the Greenhouse with rail heating pipes during the day(**a**) and measurements at night while the UVC machine is in action(**b**).

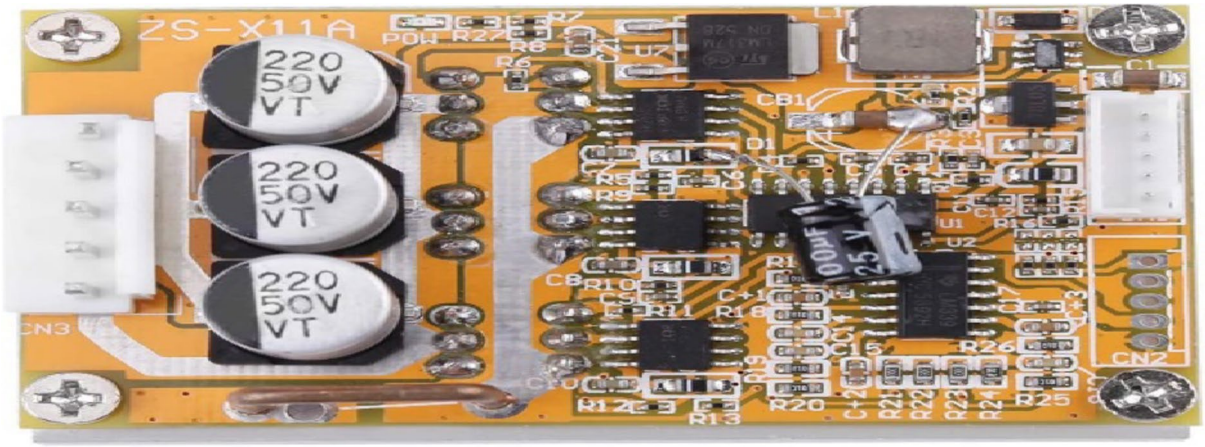


Fig. 4. The BLDC motor driver board with power regulation and control circuitry.

Electrical and control system

The board is equipped with several safety features to protect both the motor and the board itself. These features include overcurrent protection, overvoltage protection, and thermal protection. Additionally, there is reverse polarity protection to prevent motor damage from incorrect polarity connections. This aspect is crucial when selecting BLDC motors for robotics applications.

One area where BLDC motors excel is in control system performance, specifically in torque and position control for one-wheel self-balancing vehicles[29]. The board is compact and easy to install, compatible with various types of brushless DC motors. It is suitable for a range of applications, including electric vehicles, drones, and industrial machinery[30].

Remote control and software infrastructure

The Particle Photon is a compact and cost-effective development board with Wi-Fi capability, making it ideal for IoT applications[31–33]. It features a microcontroller, Wi-Fi module, and multiple digital/analog inputs and outputs, enabling seamless interaction with sensors, actuators, and other devices. The board is programmable via Particle's web-based IDE or using C++and JavaScript, and supports integration with third-party software tools (Alsekh & Hagem, 2021).

The software development follows a modular architecture to ensure scalability, real-time control, and secure cloud integration. The system consists of three main components: an embedded system software, a cloud-based API, and a user interface. The embedded software, developed in C++, manages motor control, sensor data acquisition, and safety monitoring. The RESTful API (Node.js) processes sensor data and executes remote commands, while the user interface, built using JavaScript, HTML and CSS, enables real-time visualization and remote device management. The system operates using a state-machine-based architecture, where UVC lamp activation and machine movement adjust dynamically based on pre-programmed schedules and real-time sensor feedback, optimizing UVC dose application. Supplementary File 1 illustrates the overall software architecture and data flow.

The diagrams for the microcontroller block and its electrical connections (pinout) are presented in Fig. 5.

Motor movement is controlled by several pins, each serving a specific function:

D0: Controls forward movement by triggering the motor to move forward. D1: Controls backward movement, activating the motor to move backward. D2: Manages the operational state of the motor. It starts the motor when an 'On' command is received and stops it with an 'Off' command. D3 and D: Used for sensor inputs, these pins handle interrupts that track the motor's rotation count. They trigger interrupts when they receive signals to change the motor's direction. D5: Controls the opening and closing of lamps on the right side of the machine. D6: Controls the opening and closing of lamps on the left side of the machine. DAC pin: Regulates the motor speed in an analog manner. The value written to this pin using "analogWrite( )" determines the speed of the motor.

The motor's operation is managed via the D2 pin, which is initially set to a high (HIGH) state. When the motor is running, either the D0 or D1 pin is activated based on the command for forward or backward movement. Speed and direction changes for the motor are facilitated through analog signals sent via the DAC pin. Rotation signals from the sensors then control the direction changes of the motor and increase the rotation count.

Statistical analysis

All statistical analyses were conducted using SPSS v.23. Statistical analyses were performed to evaluate the relationship between PWM speed, exposure time, and UVC dose. A one-way analysis of variance (ANOVA) was conducted to determine whether there were statistically significant differences in UVC dose across different PWM speed settings. Additionally, a multivariate analysis of variance (MANOVA) was applied to assess the combined effect of PWM speed and exposure time on UVC dose distribution. Normality of the data was tested using the Shapiro-Wilk test before conducting ANOVA and MANOVA. The significance level was set

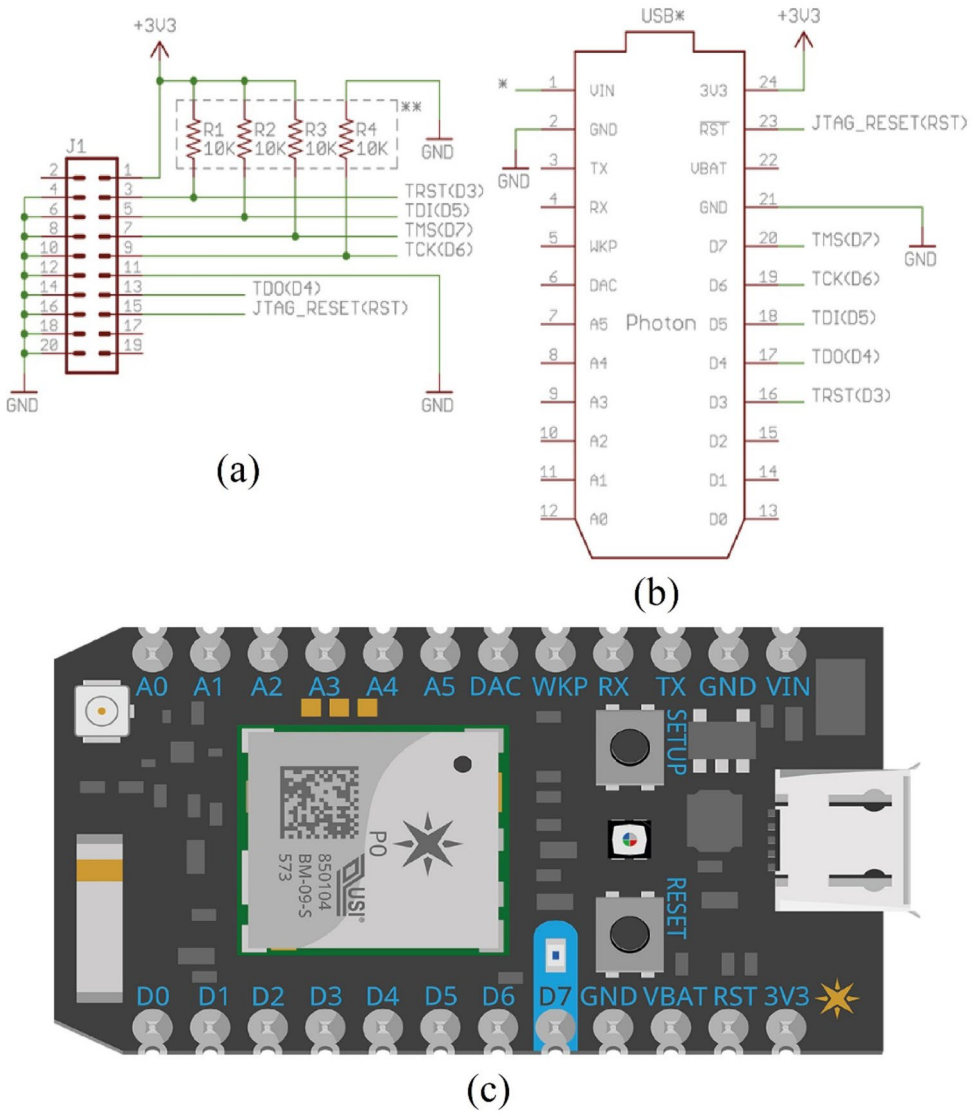


Fig. 5. (**a**) Joint Test Action Group interface connector with optional pull-up resistors for signal stabilization, (**b**) pin layout, and (**c**) physical pinout of the Particle Photon board showing analog, digital, and power pins along with setup and reset buttons.

at $p < 0.05$. Regression analysis was performed to model the relationship between PWM speed and UVC dose accumulation. An initial linear regression analysis did not yield statistically significant results ($p > 0.05$), so a quadratic regression model was applied, providing a better fit.

Results and discussion

Cloud-Based control system and user interface

The logging screen and user interface are presented in Fig. 6. The cloud-based control system was successfully implemented, allowing real-time logging of UVC exposure data and remote management of machine operations. The web and mobile applications provided intuitive control, enabling users to adjust PWM settings, activate lamps, and monitor sensor feedback seamlessly.

The interface is completely cloud-based, allowing control from anywhere with an internet connection. Access to the interface is secured through a password registered on the microcontroller.

The system demonstrated low-latency performance, with an average command execution delay of 150 ms, ensuring instantaneous response to user inputs. The integration of the Particle Cloud API facilitated stable communication between the microcontroller and remote applications, enabling secure and reliable data transmission. Utilizing Particle API JS and mobile SDKs allows developers to integrate complex functionalities with minimal code, streamlining the process of remote device management. The RESTful nature of the Particle Cloud API supports a variety of operations, such as turning devices on or off, retrieving sensor data, and updating device configurations. These functions are executed through standard HTTP methods, ensuring high compatibility with various technologies and ease of integration with existing systems.

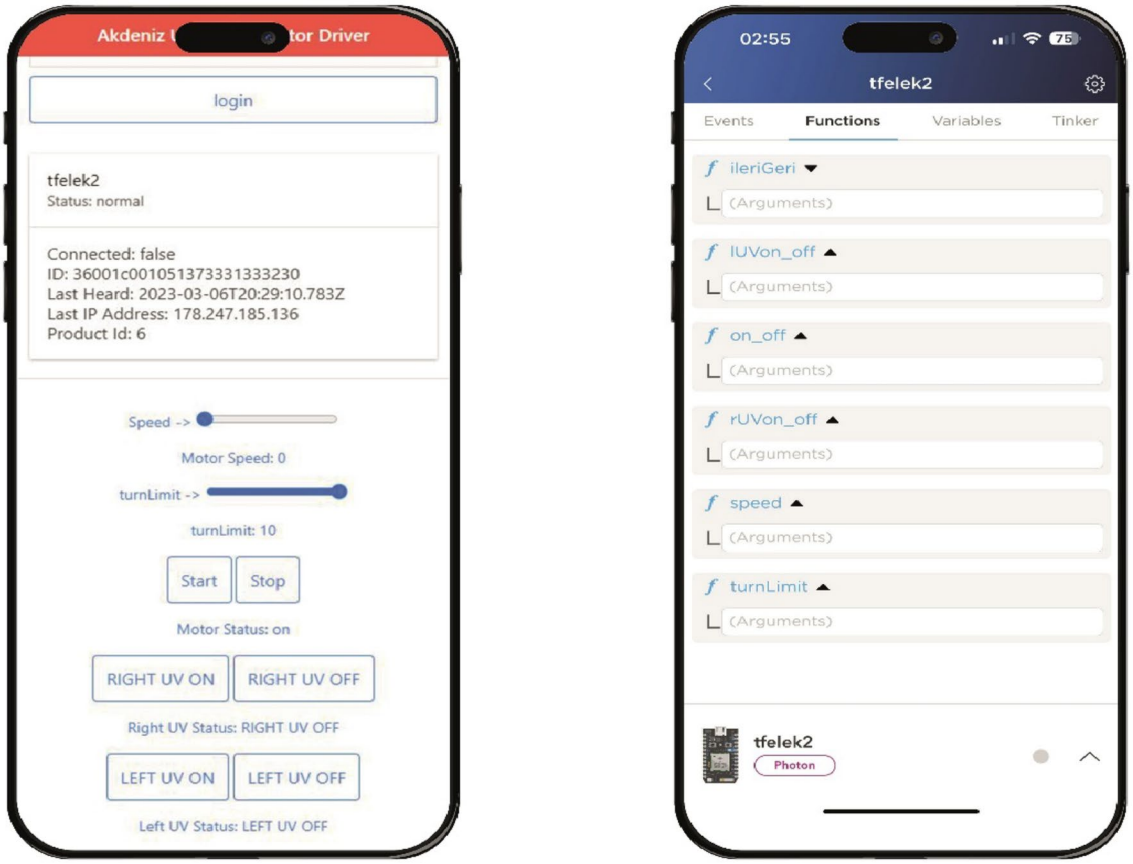


Fig. 6. (**a**) Screens used for logging and (**b**) the user interface for controlling functions of the developed software.

PWM, Speed (m/s)	UVC Dose (J/m²) – 1 Lamp	UVC Dose (J/m²) – 2 Lamps	UVC Dose (J/m²) – 3 Lamps	UVC Dose (J/m²) – 4 Lamps	Total Exposure Time (s)
900, (0.12)	50 ± 4.07	95 ± 5.75	110 ± 7.05	200 ± 8.14	15
1000, (0.16)	38 ± 4.28	63 ± 6.06	100 ± 7.42	150 ± 8.57	12
1200, (0.2)	18 ± 3.16	35 ± 4.47	43 ± 5.48	75 ± 6.33	10
1300, (0.25)	13 ± 2.74	23 ± 3.88	31 ± 4.75	53 ± 5.49	8

Table 1. Measured UVC doses and the approximate UVC exposure time of the light sensor.

The integrated interface not only enhances user experience by providing immediate feedback and control but also guarantees that all communications are encrypted and secure. This system architecture is designed to be scalable and efficient, capable of accommodating a growing number of devices without compromising performance. Through this integration, a user-friendly dashboard is provided, offering comprehensive control over connected devices and enabling effective application management from any location.

UVC dose measurement and PWM speed calibration

Measurement results are presented in Table 1 below. During trials, PWM values of 900, 1000, 1200, and 1300 were selected, as higher or lower PWM values (or speeds in m/s) were deemed either too slow or too fast. A human walking speed was considered to determine appropriate UVC application doses. Additionally, the rate of change in UVC dose per second was analyzed to assess the impact of different PWM speeds on dosage efficiency. The mean rate of change and its 95% confidence interval (CI) were calculated for each speed setting. The results indicate that higher PWM values lead to a reduced rate of increase in UVC dose per second, emphasizing the inverse relationship between machine speed and accumulated UVC exposure.

To evaluate the relationship between PWM speed and UVC dose, a one-way ANOVA test was performed. The results indicated a statistically significant effect of PWM speed on the applied UVC dose ($p < 0.05$), confirming that variations in speed influence the overall dosage distribution. Moreover, a multivariate analysis of variance (MANOVA) was performed to evaluate the interaction between PWM speed and exposure time on UVC dose

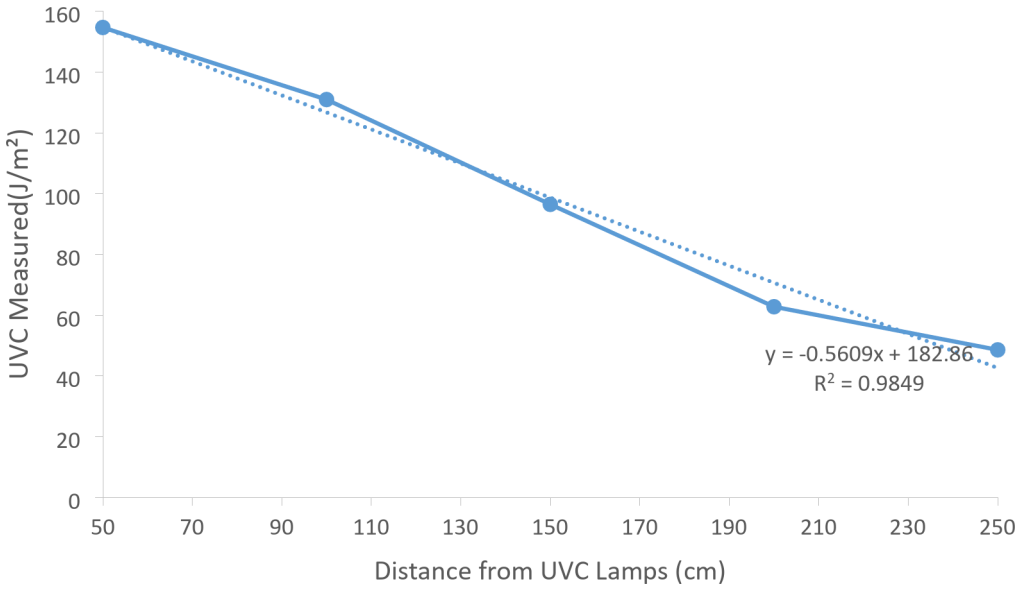


Fig. 7. Effect of distance from lamps on UVC dose delivered.

levels under various lamp configurations. The MANOVA results confirmed that both PWM speed and time significantly influence the total UVC exposure (Wilks' Lambda = 0.0198, $p < 0.05$).

The number of lamps can be increased or decreased based on the required UVC doses and the specific crops being treated. Furthermore, a regression analysis was performed to model the relationship between PWM speed and UVC dose. The initial linear regression model did not yield statistically significant results ($p > 0.05$, low R^2), suggesting a non-linear association between these variables. Consequently, a quadratic regression model was employed, yielding an improved fit and confirming the inverse relationship between PWM speed and UVC dose per second, which follows a non-linear trend. As the machine's speed increases, the UVC dose naturally decreases. Conversely, a slower speed leads to a higher dose, which can delay the treatment of infected plants. This delay may be critical in preventing the spread of diseases or pests. Therefore, it is recommended that a PWM setting of 900 or 1000 be used, as these speeds are close to a normal walking pace. These findings suggest that PWM settings of 900 or 1000 are optimal for ensuring effective UVC doses, as these speeds provide a balance between treatment efficacy and practical application constraints in greenhouse environments. Moreover, the statistical analyses reinforce the inverse relationship between machine speed and accumulated UVC exposure, highlighting the importance of speed control in achieving the desired dosage levels. This is particularly relevant when these devices are operated on rails in greenhouses by human operators. To achieve the total UVC dose needed to eradicate a specific disease or pest from the crops, increasing the frequency of machine traffic can be effective.

Effect of distance on UVC dose delivery

Additionally, we examined the effect of the distance between the UVC lamps and the measurement sensor on the UVC dose (see Fig. 7). This measurement was conducted with all four lamps activated for an exposure period of approximately 20 s.

As the distance between the UVC lamps and the sensor increased, the UVC dose decreased. A linear regression model was fitted to the data, yielding the equation $y = -0.5609x + 182.86$ with a coefficient of determination (R^2) of 0.9849. This indicates a strong linear relationship between distance and UVC dose within the measured range. This decrease was nearly linear up to about 250 cm. However, beyond 250 cm, the slope of the line started to change and became less steep, suggesting that the linear relationship may not hold at greater distances. Beyond 250 cm, the slope of the trendline begins to flatten, suggesting a deviation from linearity. This implies that additional measurements at greater distances are required to determine the exact dose-response relationship in extended ranges. At some point, which was not measured, the UVC sensor would likely read zero. This measurement indicates that for sanitizing materials (such as seed trays and greenhouse hand tools) in a fixed location, UVC doses can be controlled by adjusting the distance between the lamps and the materials. For effective sanitization of materials such as seed trays and greenhouse tools, an optimal placement strategy should be considered. Adjusting the number of lamps and exposure duration can further refine the UVC dose distribution, ensuring efficient microbial inactivation. Additionally, the number of lamps used and the exposure time can also be modified to optimize the sanitization process.

Comparison with existing UVC application systems

This study has resulted in the development of a technology that applies UVC light using a rail system in next-generation greenhouses. The system integrates a UVC application solution within a rail framework, automating disease management in soilless greenhouses. Previous experiments that were field-tested involved robotic

frames and drivetrain systems capable of covering large areas, such as strawberry plantations[5]. In this study, the benefits of the rail system were leveraged to achieve a more effective and controlled application of UVC light in greenhouses. Unlike conventional stationary UVC systems, the developed rail-based mechanism ensures uniform exposure across different crop heights and configurations, reducing shadowing effects and enhancing treatment consistency.

While previous UVC applications have primarily focused on post-harvest disease control, recent advancements highlight its feasibility for pre-harvest treatments in protected cultivation environments. The development of autonomous mobile UVC irradiation units, as proposed by Short et al.[10], further reinforces the potential for integrating UVC into automated disease management strategies in greenhouses and high tunnels. Our study contributes to this growing field by demonstrating a fully integrated rail-based UVC solution, capable of delivering consistent and adjustable irradiation across greenhouse crops.

Future research should focus on field validation under commercial greenhouse conditions, as well as the long-term effects of repeated UVC exposure on plant physiology and yield performance. Additionally, comparative studies with chemical and biological pest management strategies will be essential in determining the economic and agronomic viability of UVC-based disease control systems.

Conclusion

The UVC machine developed and tested here is a prototype and can be considered a semi-autonomous device for managing plant diseases in soilless greenhouses. It operated satisfactorily, fulfilling its intended purpose whether powered by batteries or a standard 220 V electricity supply. The machine utilized a standard soilless greenhouse harvest trolley as its base, which is widely available in the greenhouse logistics equipment market.

Statistical analyses confirmed that PWM speed significantly influenced the applied UVC dose ($p < 0.05$), demonstrating the inverse relationship between machine speed and accumulated UVC exposure. The machine's ability to modulate UVC intensity based on speed settings ensures precise dose application, optimizing treatment efficacy while preventing potential plant damage.

The remote control system effectively managed speed changes and lamp functionality. Additionally, the number of lamps could be increased if needed. Furthermore, the system's adaptability for surface sanitization applications, such as disinfecting seed trays and greenhouse tools, highlights its versatility beyond plant disease control.

The developed machine autonomously navigates along greenhouse rails, adjusting speed and UVC dosage as required. Currently, rail selection is determined by the user, but future Artificial Intelligence integration will enable the system to autonomously decide which rail to operate on based on real-time plant health data. This advancement will further enhance disease management efficiency while minimizing human intervention in the treatment process. This enhancement would enable the UVC treatment system to address crop diseases and pests in greenhouses without the need for human intervention. Moreover, this advancement contributes to more sustainable agricultural practices by reducing reliance on chemical pesticides while maintaining disease control efficiency. It could also facilitate data communication from climate control systems, alerting the UVC machine when treatments are required, thereby allowing for fully autonomous operation.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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Author contributions

T.F. and A.K. wrote the main manuscript text. H.B. edited the manuscript. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

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