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Remote-Controlled Drone-Based Spray Pollination System for Greenhouse Bitter Gourd Cultivation

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Abstract:

Background: Agriculture is globally essential yet faces numerous challenges due to the rapid growth of human population and declining pollinator populations, highlighting the need for innovative solutions.

Aim: This aimed to design and to develop a remote-controlled drone-based spray pollination system for greenhouse bitter gourd cultivation.

Design: The drone was developed through Research and Development (R&D) design, including prototype designing, functionality testing, and adaptability and acceptability evaluation.

Results: This study successfully designed a drone-based spray pollination system, achieving a 92% success rate in fertilizing female bitter gourd flowers. The data collection involved the participation of six respondents who completed the evaluation questionnaire. The evaluation ratings indicated a high acceptability level, with an overall mean rating of 3.91 and a standard deviation of 0.29, as well as a high adaptability level, with an overall mean rating of 4.00 and a standard deviation of 0.13, respectively. These findings showcase the prototype's potential for advancement in agricultural robotics.

Conclusion: The drone-based spray pollination system, using a pollen concentration water suspension, was concluded to have high levels in all the following aspects: functionality, adaptability, and acceptability. This highlights that the drone is reliable and effective.

Implication: The prototype's potential extends to addressing environmental challenges and advancing agricultural productivity and sustainability through drone-based pollination technology.

Keywords: pollinator populations, agricultural technology, spray technology.

I. INTRODUCTION

Agricultural production serves as the lifeblood of economies and sustenance for countless communities globally, providing economic stability and nourishment. However, a critical challenge emerges from the data presented by the PSA: the number of people grew 1.4 percent faster than the amount of food we could produce, which was 0.5 percent. This significant disparity brings attention to the critical need for innovative solutions to bridge the gap between rapid population growth and the sustainable cultivation of essential food resources (Department of Agriculture, 2022). Consequently, addressing this disparity becomes imperative to combat hunger and propel economic and social development (Sustainable Development Goals 2 and 9), as SDG 2 focuses on ensuring food security and sustainable agriculture, while SDG 9 aims at fostering inclusive and sustainable industrialization and infrastructure. Conversely, both goals are essential for boosting agricultural productivity and supporting food systems. Likewise, concerted effort towards elevating crop production on a global scale is crucial (Ritchie *et al.*, 2023). In this context, pollinators like bees, wasps, moths, butterflies, and flies play a crucial role in aiding fruits, seeds, and new plants growth by transferring pollen. The decline in bee and pollinator populations, as indicated by Smitley *et al.* (2019) and Mull *et al.*, (2022), is caused by many factors, including losing their habitat, getting harmed by pesticides, dealing with parasites and diseases, improper beekeeping practices, climate change, competition among introduced and native bee species, and having poor nutrition. These emphasize how these factors are related, affecting both agriculture and environmental sustainability.

Bees, on the other hand, have a crucial function in the pollination process, as they collect nectar and pollen from flowers (Khalifa *et al.*, 2021). Based on the results from Khalifa *et al.* (2021), areas with diverse bee habitats showed increased levels of pollination and high-quality crop yield. Additionally, in the study of Tayal *et al.* (2020), the concept of artificial pollination is introduced, utilizing manual flower vibration devices such as electronic toothbrushes that mimic

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insect buzzing. The study also reported a high fruiting rate due to consistent pollination via flower vibration, highlighting the potential of electric toothbrushes in artificial buzz pollination. Furthermore, in 2022, Alyafei *et al.* stated that spray pollination is a technique used to pollinate plants, specifically fruit trees, to increase crop yield and improve fruit setting. Furthermore, the study revealed that using a concentration of 3.0 g/L of pollen grains in a water suspension spray was an effective method of pollinating date palm trees, showing a more cost-effective process compared to traditional labor-intensive methods.

Building on these advancements, Seker *et al.* (2021) presented an autonomous drone-based pollination system that achieved a high success rate of 97.1% in flower detection and attempted pollination, with a notable flower survival rate of 93% across multiple trials. The quadrotor, equipped with onboard computers and vision systems, autonomously navigates and transfers pollen between targeted flowers without causing damage. Furthermore, Blain (2018) emphasizes the significance of Dropcopter, a US-based company utilizing multi-rotor drones for plant pollination, highlighting that drone-based pollination systems have the potential to increase crop yields by up to 60% during years marked by suboptimal bee activity. In a complementary study by Hiraguri *et al.* (2023), they introduced a study employing a convolutional neural network for autonomous drone-driven pollination research, achieving a robust 87.3% validation accuracy in discerning suitable flowers. The drone's AI classifier, with a 70% accuracy threshold, proved crucial, leading to fruit set rates exceeding 60%.

While there is an increasing interest in the advancement and application of autonomous drone-based pollination as a solution to address pollinator decline, there is also a significant lack of studies on remote-controlled drone-based spray pollination systems for greenhouse bitter gourd cultivation. Current studies tend to focus on the feasibility and technical aspects of drone-assisted pollination, such as drone design, navigation, and pollen delivery mechanisms. However, there is a significant scarce of comprehensive examination regarding the impact of different factors, such as drone flight patterns, pollen release mechanisms, and environmental conditions within greenhouse settings, on the overall effectiveness of pollination. Additionally, in a 2019 article from Kerala Agricultural University, it is mentioned that bitter gourd, scientifically classified as a cross-pollinated crop, heavily relies on external agents, particularly insects like bees, to transfer pollen between flowers for successful reproduction. Cross-pollinated plants such as bitter gourds are crucial for their genetic growth and development of seed and fruits. However, problems occur during the rainy season, together with the murky skies and increased rainfall. In these situations, the decreasing bee activity may be affected where insufficient pollen transfer between flowers can negatively impact the quality and crop yield for bitter gourd plants. Additionally, a study conducted in Indonesia (Suhri *et al.*, 2022), stated that the presence of insect pollinators has increased the fruit production rate by 390%, indicating that a decline in these pollinators can significantly affect and reduce the crop for bitter gourd plants. Moreover, in 2023, Nakweya emphasized that small farms and agricultural fields in and near tropical areas cultivating crops such as coffee, cocoa, mangoes and bitter gourd, are particularly vulnerable to crop declines due to climate change affecting pollinator loss. Bitter gourd holds significant economic value in the Philippines, especially in Region XII, where it is a staple vegetable. This underscores the importance of exploring alternative pollination methods to ensure food security. Thus, the objective of this study was to design and develop a remote-controlled drone-based spray pollination system for greenhouse bitter gourd cultivation.

This study specifically (a) designed and constructed a drone-based spray pollination system tailored for greenhouse bitter gourd cultivation; (b) developed the program logic for the prototype; (c) tested the functionality of the constructed drone system;(d) determined the percentage of fertilized flowers; and(e) evaluated the adaptability and acceptability of the drone-based pollination system. Drone-based pollination systems present a promising remedy to the decreasing bee populations for pollination, which are susceptible to factors such as climate change, habitat loss, and pesticide usage. Moreover, utilizing a drone- based pollination system enhances agricultural efficiency, reduces resource usage, and fosters innovation, aligning with SDG 9's objective of promoting economically and environmentally sustainable development. Furthermore, drone-based pollination increases pollination rates, leading to increased yields in greenhouse bitter gourd cultivation, ensuring efficient, consistent, and precise pollination. This parallels the essential goals of ending hunger and achieving food security outlined in SDG 2. In addition, this drone-based pollination system does not aim to replace bees and other insects in pollination but rather serves as a supplementary solution to support natural pollination processes. Given the impact of climate change, which has reduced bee populations, the adaptability of these drones to various environmental conditions becomes particularly crucial. Moreover, this study offers agricultural industries increased efficiency and profits through enhanced yields in greenhouse bitter gourd cultivation, while farmers benefit from reliable pollination in the face of declining bee populations and unpredictable weather conditions.

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II. MATERIALS AND METHODS

2.1 Materials

The researchers selected a set of essential materials for the development of the remote-controlled drone-based spray pollination system. The drone's structure incorporated lightweight, durable materials like aluminum or carbon fiber. Brushless DC motors, matched with appropriate propellers, facilitate controlled and targeted spray pollination. Arduino, a versatile microcontroller platform, is employed for coding the drone's program logic. The flight controller manages motor outputs and sensor inputs, while electronic speed controllers regulate motor speed. Lithium polymer batteries power the drone, with a power distribution board ensuring efficient energy distribution. Furthermore, a radio transmitter (Radiolink T8FB) and a receiver for remote control communication are essential for maneuvering the drone within the greenhouse, while the GPS facilitates accurate navigation. An onboard computer interprets remote commands. Frame mounting hardware, wiring, connectors, and power connectors such as XT60 are crucial for securing components and establishing electrical connections. An antenna is used for radio and video transmission. Additionally, propeller adapters ensured secure attachment, and a specially designed spray nozzle with a 0.4-mm size, along with a 550-mL mini container tank, holds the pollen reservoir. In collecting pollen from a male bitter gourd flower, a small, clean brush was used to gently brush the stamen of the flower, and the collected pollen was stored in a dry container. Subsequently, the pollen grains, weighing 0.75 grams, and the distilled water, weighing 250 milliliters, were combined to be able to transfer to the drone's tank for spraying. The weighing scale utilized was analytical.

2.2 Research Design

The researchers utilized a Research and Development design (R&D), which involved a systematic approach to generating new knowledge through investigation, experimentation, and analysis. It involved various techniques, including literature review, experimentation, prototyping, and iterative refinement in developing innovative solutions to address specific needs or challenges (Kenton, 2024). A study by the OECD (2015) classified research and development (R&D) into three categories. These categories were basic research, which involved obtaining fundamental knowledge without immediate practical application; applied research, which concentrated on exploring specific practical objectives; and experimental development, which involved systematic work for creating new products or enhancing existing ones. Utilizing a research and development framework was ideal in this case, with a specific focus on applied and experimental development, as it allowed for a systematic method for innovating a remote-controlled drone pollination system to address the declining pollinator populations.

2.3 Procedure

2.3.1 Designing and Constructing the Drone-Based Spray Pollination System

The researchers designed a drone-based spray pollination system by utilizing SketchUp software by first creating a 3D model of the drone and considering the system requirements, such as the payload capacity, to ensure that it can carry the necessary pollen while maintaining an optimal flight time and agility for efficient coverage of crop fields. Additionally, a spray nozzle with a 0.4-mm size was integrated into the design to ensure efficient pollen distribution. Moreover, the remote-control system was modeled to ensure efficient coverage of crop fields and to avoid collisions for safety. Lastly, researchers used SketchUp to select power sources that provide energy efficiency and long-duration flights, ensuring that the drone could operate for extended periods while conducting pollination tasks.

In constructing the prototype, the researchers selected materials such as aluminum or carbon fiber frames, brushless DC motors, and propellers that aligned with the design requirements for the drone-based spray pollination system. Flight controllers and lithium polymer batteries were integrated in ensuring the efficient energy distribution for prolonged operational capability. Furthermore, the inclusion of frame mounting hardware, wiring, connectors, power connectors, and a mini container tank for the necessary pollen solution were essential for the prototype's functionality. Additionally, the researchers enhanced the prototype by incorporating components like antennas, propeller adapters, and a specially designed sprayer, which collectively optimized the system for effective spray pollination.

Figure 1: Prototype Design

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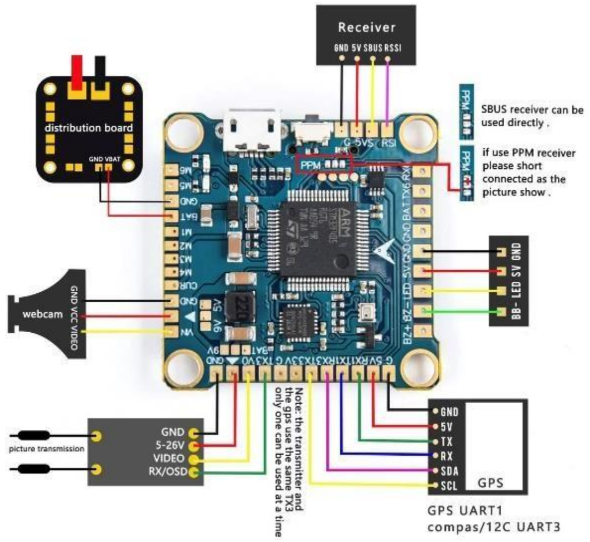

Figure 2: Schematic Diagram

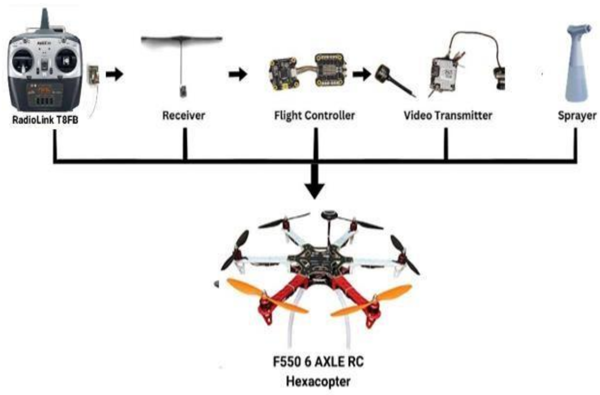

Figure 3: Network Model

2.3.2 Developing the Program Logic

The program logic involved a systematic series of steps initiated by the remote operator. When the user initiated takeoff through the remote-control system, the microcontroller signaled the flight controller to activate the brushless DC motors and stabilize the drone. As the user navigated the drone to the target flower, the microcontroller communicated with the onboard computer, ensuring the accurate translation of remote commands into adjustments of the drone's position. When the drone was positioned over the target flower, the microcontroller prompted the activation of the pollen dispensing mechanism for a specified duration, controlled by micromotors, based on the user’s input. This activation was initiated by the user lowering down the switch CH7 on the remote control system. The microcontroller would inform the user if the battery was running low, which would trigger the Return to Home (RTH) feature, prioritizing the safe return of the drone.

Once the pollination has been completed, the microcontroller would direct the drone to navigate back to the launch point, facilitating a smooth and controlled landing, and subsequently turned off the drone by the user, concluding the pollination mission.

Figure 4 shows the system flow of the developed prototype.

2.3.3 Testing Drone System Functionality

With the prototype being constructed, the researchers began testing its functionality in a controlled environment. They utilized the FeelFPV simulator software in testing the drone. The software provided a realistic simulation of flight physics, allowing the researchers to simulate drone piloting experiences. This facilitated rigorous testing of the drone’s performance, responsiveness, and stability, which enabled them to practice flying and to test various maneuvers without risking damage to actual hardware.

The researchers employed testing tools in examining the parts of the drone such as a multimeter to measure voltage, current, and resistance in electrical circuits, and a battery tester in ensuring that the drone's batteries are functioning without errors. This had helped the researchers identify any performance issues or malfunction.

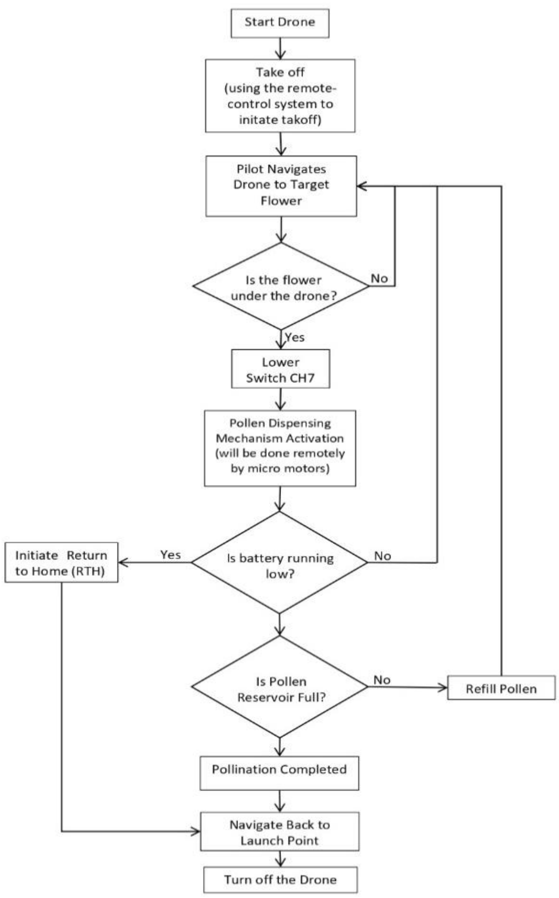

Figure 4: System Flow

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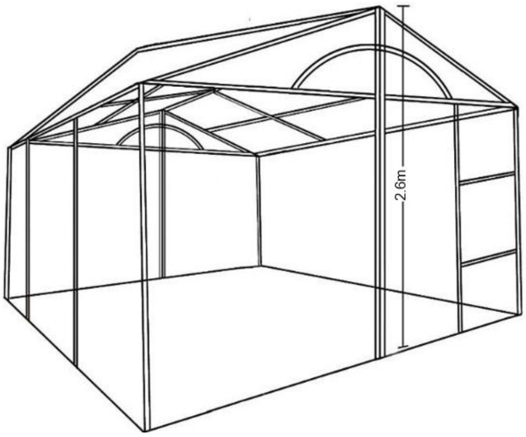
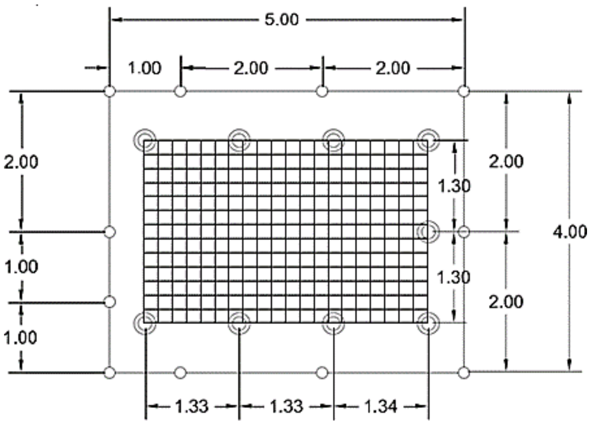


Figure 5: Greenhouse



2.3.4 Determining the Percentage of Fertilized Flowers

In assessing the effectiveness of the drone-based spray pollination system, the researchers determined the percentage of fertilized flowers. The percentage of fertilized flowers was calculated by comparing the number of successfully fertilized female flowers to the total number of flowers pollinated by the drone system. This comprehensive evaluation provided insights into the system's efficacy in facilitating successful pollination in greenhouse bitter gourd cultivation. The researchers used standard statistical methods to analyze the data and draw conclusions regarding the performance of the drone system.

$$\%Fertilized\ Flowers = \frac{No.of Female Flowers Fertilized}{Total Number\ of Flowers\ Pollinated} \times 100\%$$

2.3.5 Evaluating Adaptability and Acceptability

The researchers gathered feedback from the qualified electronic engineers after testing and refining the drone system.

2.3.5.1 Respondents and Sampling Technique

The purposive sampling technique was utilized by the researchers in selecting a particular set of respondents to successfully gather feedback from the qualified experts. This approach proved beneficial as it allowed the researchers to choose a sample representative of the qualities or attributes they aimed to investigate, with a clear understanding of the characteristics of interest (Dovetail Editorial Team, 2023). The evaluators were required to meet the following criteria: (a) a degree holder of an engineering course (preferably electronics and communication engineering); (b) employed and have at least three years of work experience; and (c) reside in Region XII, Philippines.

2.3.5.2 Research Instrument

In comprehensively assessing the prototype's performance and usability, the researchers employed a questionnaire as their research instrument, which consists of a 5-point Likert scale. In addition, pilot testing was conducted in refining the questionnaire and ensuring its clarity and effectiveness, enabling them to calculate Cronbach's alpha for internal validity.

2.4 Data Analysis

In collecting the data, this study used a survey questionnaire distributed among the evaluators. The responses in the evaluation were then assessed for their weighted mean using an interpretation table adapted from the study of Mutiara *et al.* (2016). The response sets were divided into five nominal categories labeled as 1 = strongly agree; 2 = disagree; 3 = neutral; 4 = agree; and 5 = strongly agree. In facilitating the interpretation of the responses, each category was associated with very low level, low level, moderate level, high level, and very high level respectively.

Table 1: Interpretation for the Level of Acceptability and Adaptability

Rating	Range	Descriptor	Interpretations
5	4.50-5.00	Strongly Agree	Very high level
4	3.50-4.49	Agree	High level
3	2.50-3.49	Neutral	Moderate level
2	1.50-2.49	Disagree	Low level
1	1.00-1.49	Strongly Disagree	Very low level

2.5 Ethical Consideration

The researchers followed set guidelines to ensure the research was conducted responsibly. Firstly, permission was obtained from the principal and the location owner before conducting the study. It was made sure that the use of the drone system would be utilized responsibly, causing no harmful effects on the environment involved. Moreover, it was ensured that any generated waste was appropriately disposed of throughout the entirety of the process. Furthermore, the privacy and confidentiality of evaluators were strictly protected, with data used exclusively for academic purposes. To ensure safe data handling, strict protocols were put in place to keep and manage all of the data that was gathered.

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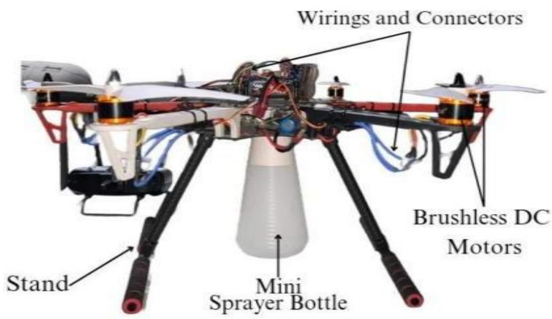
Transparency and accountability were guiding concepts that supported ethical standards in research techniques and fostered trust throughout the whole study.

III. RESULTS AND DISCUSSION

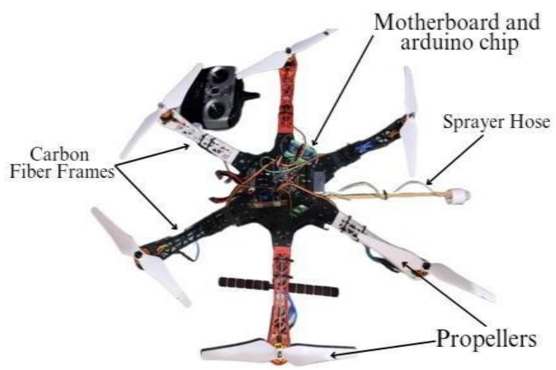
3.1 Design of the Drone-based Spray Pollination System

The researchers successfully designed and constructed a drone-based spray pollination system. Initially, the process began with the design phase, carefully considering the optimal configuration of the prototype while considering the placement of the spray system. Following this, it proceeded in integrating the selected design into the drone, ensuring seamless compatibility and functionality. Lastly, necessary codes into the drone were installed, enabling it to execute its pollination tasks effectively.

(a) Front view



(b) Back view



(c) Top view

Figure 6: Prototype

Figure 6 shows that model of the drone, Hexacopter (F550 6 AXLE RC), which consists of a tank, sprayer nozzles and a controller. During flight mode, the controller manipulates the overall operational status of the drone's sprayer and monitors its condition. Take off, landing and triggering of the sprayer nozzles are the functions of the remote control. In 2020, Susitra *et al.* mentioned that utilizing Hexacopter which has 6 propellers with sprayer system are more stable and durable during the spraying process in agricultural fields compared to that of Quadcopter which has 4 propellers and it's more economical than an Octocopter which has 8 propellers.

3.2 Program Logic of the Prototype

The discussion below follows the program logic of the prototype and its interpretation.

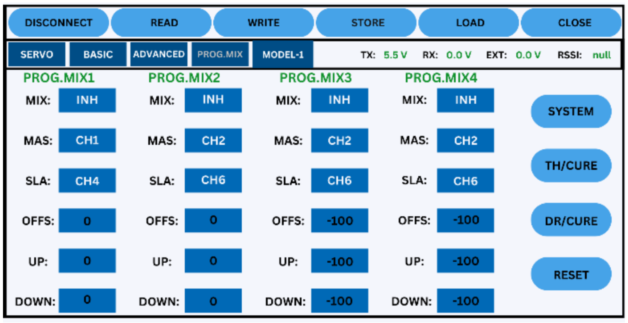


Figure 7: Prototype Programming

In the prototype program, the RadioLink-En app was used to enable drone control using a Bluetooth connection to the RadioLink T8FB(BT) remote control. This modification allowed for real-time monitoring of the drone's movements. Moreover, comprehensive connection setup options were provided in the main menu. These options displayed specifications, including transmitter and receiver battery voltage and signal strength, as well as basic servo statistics for each channel. Additionally, the Elevon structure simplified control in the drone system by combining elevator and aileron operations, while the Attitude Mode (D/R) adjusted control sensitivity to adapt to multiple flying conditions. Furthermore, the V-Tail arrangement improved maneuverability by replacing two surfaces arranged at a V-angle for conventional stabilizers.

```
const int relayPin = 7;    // Pin connected to the relay module
const int receiverPin = 2; // Pin connected to the receiver output

void setup() {
  pinMode(relayPin, OUTPUT);
  pinMode(receiverPin, INPUT);
}

void loop() {
  int receiverValue = pulseIn(receiverPin, HIGH); // Reads the PWM signal from receiver
  if (receiverValue > 1500) { // Example threshold value
    digitalWrite(relayPin, HIGH); // Activate relay/sprayer
  } else {
    digitalWrite(relayPin, LOW); // Deactivate relay/sprayer
  }
}
```

Figure 8: Coding for Sprayer

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In developing the sprayer functionality for the pollination system, the initial step was defining constants and allocating specific PINs to components such as relays and receivers. Consequently, in the setup function, pin modes were configured to specify whether each pin would operate as an input or output. Within the main loop, the program utilized the pulseIn() function to read PWM signals from the receivers, assessing the intensity of control signals from the remote controls. These values were then aggregated to evaluate the overall strength of the control signal. When the combined value exceeded a predefined threshold, typically 100, it activated the relay, thereby initiating the sprayer. Conversely, if the combined value fell below the threshold, which was 0, the relay was deactivated, terminating the sprayer's operation. The coding facilitated the drone's responsiveness to remote control signals, enabling the timely activation of the sprayer for pollination purposes.

3.3 Functionality Test

The functionality of the prototype underwent thorough examination by employing specialized tools and software. Each component of the drone underwent rigorous testing to assess its individual performance and overall contribution to the system. This section will detail the functionality of the drone using a comprehensive table presentation.

Table 2: Functionality of the Prototype Components

No.	Component	Functional	
		Yes	No
1	Propellers	✓	
2	Motors	✓	
3	Battery	✓	
4	Remote Control	✓	
5	Flight Controller Board	✓	
6	Frame	✓	
7	Arduino	✓	

The table provides a detailed summary of the results obtained from comprehensive tests conducted on the prototype of a remote-controlled drone-based spray pollination system. These tests were carried out in assessing the functionality and performance of various components within the drone system. The findings from these evaluations reveal a high degree of reliability and efficiency across all tested components, indicating their ability to effectively contribute to the overall functionality and operational success of the drone.

3.4 Percentage of Fertilized Flowers

The researchers calculated the percentage of fertilized flowers in order to accurately assess the performance of the drone system when it comes to pollinating bitter gourd flowers. In getting the results of this assessment, the researchers compared the number of female flowers that were successfully fertilized by the total number of flowers that were pollinated. The results are displayed in Table 3.

Table 3: Percentage of Fertilized Flowers

Total No. of Female Flowers	Flowers Successfully Fertilized	Flowers Not Fertilized	%Fertilized Flowers
26	24	2	92%

The percentage of fertilized flowers demonstrated the effectiveness of the drone-based spray pollination system. The findings showed that there were 24 successfully fertilized flowers out of the 26 female flowers that were pollinated. This evaluation yields a positive result as it has a 92% success rate, highlighting the capability of the drone system in successfully fertilizing female bitter gourd flowers. These findings are consistent with the previous study of Alyafei *et al.* (2022), as it was stated that employing a drone for spraying pollen concentration in water suspension had effectively enhanced fruit setting in date palm trees, leading to an acceptable fruit set percentage.

3.5 Adaptability and Acceptability of the Drone-Based Pollination System

In ensuring the validity of the questionnaire, the following are the results for the Cronbach's alpha. Additionally, engineering experts evaluated the acceptability and adaptability of the prototype according to predefined criteria. Tables 4 and 5 present the discussions and implications for the results of the evaluation.

A survey questionnaire with a 5-point Likert scale was used to evaluate the prototype which has two sections with a total of 17 questions. The first section evaluates the prototype's acceptability, focusing on the user experience, simplicity of usage, and design. Meanwhile, the second section examines adaptability under varying conditions, feature adjustability, and portability. To ensure the questionnaire's validity, a pilot test was conducted. Cronbach's alpha coefficient was calculated for each section to assess internal consistency, a measure of reliability. The level of acceptability section yielded a Cronbach's alpha of 0.94, which can be interpreted as excellent. The level of adaptability section is also highly reliable, with a Cronbach's alpha of 0.73.

Table 4: Level of Acceptability of the Prototype

Indicator	M	SD	Interpretation
1. Understanding the functionality of the prototype was easy.	5.00	0.00	Very high level
2. I am satisfied with the performance of the prototype.	3.67	0.52	High level
3. I am likely to recommend this prototype to others.	4.00	0.00	High level
4. The prototype was intuitive	4.33	0.52	High level

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and easy to use.			
5. The prototype design/layout is intricate and well-thought-out.	3.83	0.75	High level
6. The wire management of the prototype is satisfactory.	2.50	0.55	Moderate level
7. The features of the prototype are relevant to its purpose.	4.33	0.52	High level
8. The different parts of the prototype are easy to navigate.	3.50	0.55	High level
9. Overall, I am satisfied with the prototype	4.00	0.00	High level
Overall Weighted Mean	3.91	0.29	High level

Table 4 presents the results of the acceptability level of the prototype among the selected evaluators. Overall, the evaluators strongly agreed that understanding the functionality of the prototype was easy (M = 5.00, SD = 0.00), suggesting that it effectively communicates its purpose and features. Djatmiko *et al.* (2021) stated that the drone as a learning medium has had a significant impact when it is applied in the learning process in extracurricular activities, as it is easy to make the students understand the system of the drone, and with drones, students can collect data to make informed decisions easily. Conversely, the results for the wire management of the prototype is rather lower (M = 2.50, SD = 0.55), suggesting that the evaluators found the wire management of the prototype unsatisfactory, indicating potential issues or shortcomings in the organization or arrangement of wires within the prototype. An article by Oscar (2023) mentioned that the orderly wiring in drones is crucial for their efficient and safe operations. In conclusion, researchers affirm a high level of the prototype's acceptability to meet the criteria and expectations of the evaluators, summarizing the findings with an overall mean of 3.91 and a standard deviation of 0.29. This indicates that it effectively fulfills its intended purpose and aligns with the project requirements.

Table 5: Level of Adaptability of the Prototype

Indicator	M	SD	Interpretation
1. The prototype can easily be adjusted to fit different user needs.	3.83	0.41	High level
2. It is easy to add new features or functions to the prototype.	4.33	0.82	High level
3. Users can change settings or how the prototype works without trouble.	3.33	0.52	Moderate level
4. The prototype can keep up with new trends or technology changes.	4.50	0.55	Very high level
5. Users can make the prototype fit different places or conditions.	3.50	0.55	High level
6. Putting together or taking apart the prototype is simple and doesn't need special tools.	4.33	0.52	High level
7. The prototype's materials are strong and can handle different kinds of weather.	4.00	0.63	High level
8. Storing, moving, and using the prototype in different places is easy.	4.17	0.41	High level
Overall Weighted Mean	4.00	0.13	High level

Table 5 presents the adaptability level of the prototype, as assessed by the selected evaluators. Collectively, the evaluators strongly agreed that the prototype is capable of staying updated with new trends or technological advancements (M = 4.50, SD = 0.55), ensuring its relevance and effectiveness over time. This aligns with Rice *et al.*'s (2022) study, where the drone-enabled autonomous pollination system demonstrates adaptability through advanced perception, path planning and flight control modules, showcasing its potential to evolve with emerging agricultural robotics advancements. Furthermore, it was emphasized by Guzman *et al.* (2022) that the drone pollinator can adapt to different drone functions and plant pollen, aiding large-scale pollination in agriculture and conservation. On the contrary, the evaluation regarding the ease of changing settings or altering the functionality of the prototype yielded neutral results, with evaluators expressing moderate satisfaction (M = 3.33, SD = 0.52). A study conducted by Chandran (2024) highlights the imperative for drone technology to facilitate easy modifications to the prototype's functionality, ensuring user-friendly operation and adaptability. Hence, researchers conclude that the drone-based pollination system demonstrates a notably high level of adaptability, as indicated by an overall weighted mean of 4.00 and a standard deviation of 0.13 based on their findings. This demonstrates its reliability in a variety of environments and conditions.

IV. CONCLUSIONS

This study successfully developed a remote-controlled drone-based spray pollination system for greenhouse bitter gourd cultivation. The program logic was used to guide the pollination process, from takeoff to landing, all managed by the microcontroller based on user input. The assessment of the drone's functionality underscored the high reliability and efficiency of its components, highlighting its important role in ensuring the overall functionality and operational success of the drone. Utilizing research and development design (R&D), the presented data showed the system's effectiveness, achieving an approximate 92% success rate in greenhouse bitter gourd cultivation. The prototype exhibited a high level of adaptability, scoring an average of 4.00, and acceptability, with an average of 3.90. These findings emphasized the efficacy of utilizing drone-based spray pollination and using a water suspension of pollen concentration for bitter gourd cultivation. Overall, the study underscored the impact of using technology to address environmental challenges and its potential for economic advancement and social development by combating hunger.

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V. RECOMMENDATIONS

Based on the study findings, the high success rate in pollinating greenhouse bitter gourd flowers highlights their potential for enhancing crop yield, while the overall prototype success suggests effective programming. Additionally, functionality testing confirmed the system's capability and adaptability to technological advancements. Positive acceptability ratings were also received, but issues with wire management suggest areas for refinement. Moreover, expanding the functionality of the drone system beyond pollination to include other agricultural tasks such as pesticide or fertilizer applications would enhance its utility and economic viability. It is imperative that the refined prototype be utilized in actual cultivation practices to validate its efficacy in real-world agricultural settings.

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