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# An Autonomous Dual-Fan Pollination Device: Mathematical Modeling, Trajectory Optimization, and Distribution Analysis for Enhanced Crop Yield

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**Abstract: The decline of natural pollinators, exacerbated by climate change and pesticide use, poses a critical threat to global food security. Innovative solutions are essential to mitigate these challenges and ensure sustainable agricultural practices. This study addresses the urgent need for effective, autonomous pollination systems to enhance crop productivity and resilience. This research introduces a novel artificial pollination device designed for autonomous pollen collection and dispersal. It features a custom 3D-printed funnel, a suction fan, precise artificial pollination brushes, and a blowing fan to ensure robust performance in various agricultural settings. The primary objective is to evaluate the device's accuracy and efficiency under both controlled and environmental conditions. The device was tested in a model testbed using turmeric and mustard seeds as pollen simulants. Initial tests achieved a 61% success rate, which improved to 79% after a hardware upgrade. Further analysis using the Tracker: Video Analysis and Modeling Tool, Python, and AI tools revealed a cone-shaped pollen distribution range influenced by environmental factors. Optimized dispersion angles led to a pollen dispersal rate of 93-100%. Under typical Los Angeles weather conditions, the device's adjusted success rate was 87.6%. This innovative artificial pollination system marks a significant leap forward in agricultural technology. It offers a scalable solution for crop pollination and urban farming, enhancing productivity in controlled environments. Future research will focus on integrating advanced sensors and AI algorithms to optimize the device's positioning and movement in dynamic field conditions, further improving accuracy and efficiency.**

***Keywords:*** *Artificial Pollination; Autonomous Pollination Systems; Crop Yield; Sustainable Agriculture; 3D-printed Pollination Device.*

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## I. INTRODUCTION

Pollinator populations are crucial to the health and sustainability of our ecosystems and agriculture, yet they are in a state of alarming decline. These vital species, including bees, butterflies, and other insects, are responsible for pollinating 87.5% of the world's flowering plants and about 35% of global food crops [1]. Despite their importance, current conservation efforts have struggled to solve the decline of these populations, which continue to face threats from habitat loss, pesticide use, and climate change. This ongoing decline poses a severe risk to biodiversity and food security. The situation is projected to worsen, with some studies estimating that at least 40% of pollinator species could be at risk of extinction in the coming decades [2]. As the pressure on pollinator populations intensifies, there is an urgent need to create innovative and advanced technologies to support pollinator health, decrease pesticide usage, and mitigate the impacts of climate change. Addressing these challenges is essential to ensuring the continued availability of food crops in an ever-growing population and maintaining ecological balance.

### A. *Pollinator Health*

Pollinator populations around the world are facing alarming declines that threaten biodiversity and disrupt ecosystem balances. Many plants depend on these pollinators for reproduction, highlighting the seriousness of this global issue [1], [3]. Among the most affected are various bee species: about 25% of native bee species are at risk of extinction, with over 52% experiencing population declines [4], [5]. This includes honeybees (Apis mellifera), vital for agricultural pollination, which have been severely impacted by Colony Collapse Disorder (CCD)—a phenomenon where worker bees abandon the hive, leading to its collapse [6]. Similarly, populations of wild bees like the bumblebee (Bombus spp.) are dwindling; the rusty

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patched bumblebee (Bombus affinis), for instance, is now listed as an endangered species in the United States [7].

Other crucial pollinators, such as monarch butterflies (Danaus plexippus), are also in peril. Known for their extensive migratory patterns, these butterflies have seen their numbers decline by approximately 81% due to habitat loss and pesticide use [8]. Moreover, moths, beetles, and some bird species like hummingbirds are facing similar pressures, all of which are vital for pollinating a variety of plants [9]. The decline of these species poses severe risks, affecting not only plant reproduction but also the broader food webs that rely on these plants.

### B. *Increase in Pesticide Use*

The decline in pollinator populations has created a vicious cycle that worsens the problem of pesticide use in agriculture. As pollinators decline, their natural role in controlling pests also diminishes, leading to increased pest pressures on crops. In response, farmers are often compelled to use more pesticides to protect their yields from these pests. This increased pesticide use can further harm pollinator populations, creating a negative feedback loop [10], [11].

Farmers facing reduced pollination services may also turn to synthetic chemicals to compensate for the lack of natural pollinators. The reliance on chemical pesticides not only threatens pollinators but also affects soil health and biodiversity. For example, neonicotinoid pesticides have been shown to impair foraging behavior, reproduction, and immune systems in bees, contributing to colony collapse disorder (CCD) and population declines in other pollinator species. Neonicotinoid exposure is directly correlated with large-scale and long-term decline in wild bee species distributions across the United Kingdom [12].

### C. *Climate-Induced Challenges*

Climate change significantly exacerbates the decline of pollinator populations. It alters the distribution and abundance of both pollinators and the plants they pollinate, leading to several negative impacts [3].

One major issue is phenological mismatch, where changes in temperature and precipitation disrupt the timing of flowering in plants and the activity periods of pollinators. This mismatch reduces the availability of food resources, leading to decreased survival and reproduction rates among pollinators [13]. Consequently, disruptions in the timing of interactions between plants and their pollinators are expected, which may lead to declines in both pollinator populations and the plants that depend on them [14].

Moreover, shifts in climate patterns can cause geographic range shifts for both plants and pollinators. These shifts may lead to spatial mismatches, further exacerbating the decline of pollinator populations and disrupting essential ecosystem services critical for agricultural productivity and biodiversity conservation [15].

### D. *Global Food Security*

The decline of pollinators, specifically bees, poses a significant threat to global food security, ecosystem health, and the economy. Pollinators are indispensable for the growth of many flowering plants, including a substantial portion of the crops that humans depend on for food. Without them, the production of fruits, vegetables, nuts, and other essential crops could significantly decrease, potentially leading to food shortages and higher prices. According to the National Institute of Food and Agriculture, approximately 75% of the world's flowering plants and about 35% of the world's food crops depend on animal pollinators to reproduce [9].

The reduction in pollination services can lead to decreased crop yields, impacting food availability and increasing prices. This is particularly concerning for global food systems, where the demand for pollinator-dependent crops is rising. Research has shown that crops dependent on animal pollination contribute significantly to the global food supply and the economy [16]. A decline in pollinator populations can therefore significantly affect the availability of nutritious foods, leading to increased prices and reduced food security [17].

The economic impact of pollinator decline extends beyond food production. The agricultural industry relies heavily on pollination services, and a decline in pollinators can lead to increased costs for farmers who must invest in alternative pollination methods or face reduced yields [18]. This can result in higher prices for consumers and reduced profitability for farmers, further straining the agricultural economy.

## II. LITERATURE SEARCH

Given the critical role of pollinators in agriculture and the alarming decline in their populations, there is an urgent need to explore alternative methods to ensure crop pollination. Traditional approaches, such as the use of managed bee colonies, have proven insufficient in addressing the scale of the problem [19]. This has led to increased interest and research in artificial pollination techniques as a viable solution to sustain agricultural productivity.

### A. *Artificial Pollination Process*

Pollination is a critical reproductive mechanism in angiosperms, involving the transfer of pollen grains from the anther (male gametophyte) to the stigma (female gametophyte) of a flower [20]. This biotic or abiotic-mediated process is integral to the formation of fruits and seeds, which constitute the primary yield of many agricultural crops. Insect pollinators, particularly honeybees, are the predominant agents of biotic pollination. However, the recent decline in pollinator populations globally has highlighted the urgency for alternative pollination strategies.

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Artificial pollination has emerged as a viable solution, wherein the pollen is manually or mechanically collected from donor flowers and applied to the recipient flower's stigma, thereby facilitating fertilization and subsequent fruit and seed development [21]. Techniques for artificial pollination can range from simple hand pollination using brushes to sophisticated mechanical pollinators and drones equipped with pollen dispensers.

The primary objective of artificial pollination is to emulate the natural pollination mechanisms, thereby ensuring consistent and reliable fertilization and subsequent fruit set [22]. Artificial pollination can enhance crop yield stability and sustainability, even amidst significant declines in natural pollinator populations by providing a controlled and targeted approach to pollen collection and transfer.

*B. Existing Artificial Pollination Methods*

A range of artificial pollination devices have been explored and implemented in various agricultural contexts. These include hand pollination, where workers manually transfer pollen from one flower to another, as well as the use of mechanical devices such as pollen blowers or sprayers to distribute pollen over crop plants [23]. While effective in certain situations, these methods can be labor-intensive, time consuming, and limited in their scalability.

As an alternative, the development of robotic pollination systems has gained traction in recent years. These systems, often utilizing autonomous vehicles or drones, are designed to autonomously navigate crop fields and apply pollen to individual flowers, potentially offering greater efficiency and coverage compared to manual methods [24], [25]. The use of drones, in particular, has emerged as a promising approach, as these aerial platforms can access hard-to-reach areas and provide more comprehensive coverage of crop fields. With their ability to navigate crop fields with precision, drones equipped with pollen-dispensing mechanisms can deliver pollen directly to individual flowers, mimicking the natural pollination process carried out by insects [26].

Source [27] mentions a "chicken-and-egg" problem when it comes to developing artificial pollination systems. The systems often rely on pollen as an input, making them uneconomical without a readily available and affordable pollen source. However, collecting pollen becomes economically unviable without the widespread adoption of artificial pollination systems. This highlights the need for a holistic approach that addresses both the technological and supplychain aspects of artificial pollination.

Table I presents a comparative analysis of various artificial pollination devices. Each device is evaluated based on its name, description (including what it is and two examples), pollen collection method, pollen dispersal method, the necessity of external pollen, level of autonomy, and any gaps in pollination.

Table 1: Comparative Analysis of Various Pollination Devices

| Device Name | Description (what is + two examples) | Pollen Collection Method | Pollen Dispersal Method | External Pollen | Autonomy | Gaps in Pollination Devices |
|---|---|---|---|---|---|---|
| Artificial Pollination Brushes [27] | Brushes specifically designed for artificial pollination, which are used to manually transfer pollen from one flower to another. These brushes can vary in size and material to suit different types of plants. Examples: 1. Soft bristle brush for small flowers such as tomato blossoms. 2. Electric pollination brush designed for larger flowers like squash or melon plants. | Manual collection by gently brushing the stamens of flowers to gather pollen on the bristles. | Pollen is manually transferred to the stigma of flowers by brushing the collected pollen onto the receptive parts of the plant. | No | Low, requires manual operation. | Labor intensive, risk of cross-contamination, not suitable for large-scale operations |
| Bubbles [28] | An innovative method utilizing soap bubbles to carry and transfer pollen to flowers. This method leverages the gentle and widespread dispersal capabilities of bubbles. Examples: 1. A handheld bubble blower with a pollen-infused solution for home gardens. 2. An automated bubble machine capable of creating | Pollen is manually mixed with a soap solution in the bubble blower's reservoir. | Bubbles are blown into the air, carrying pollen, and burst upon contact with flowers, depositing the pollen. | Yes | Medium can be semi automated. | Environmental impact of soap solution, limited precision, potential for uneven distribution |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | thousands of pollen-carrying bubbles for large-scale agricultural use. | | | | | |
| Dry Pollination Hand Gun [27] | A handheld device designed to blow dry pollen directly onto flowers. This method is precise and efficient for targeted pollination. Examples: 1. Manual squeeze bulb hand gun suitable for small-scale operations. 2. Battery-operated pollen blower that can cover larger areas, such as orchards or fields. | Pollen is manually loaded into the device's chamber. | When the trigger is activated, the device blows the pollen onto the flowers through a directed nozzle. | Yes | Medium, requires user operation. | Limited area coverage, dependency on user skill, potential pollen wastage |
| Mister [29] | A device that creates a fine mist containing pollen, which is sprayed onto flowers. This method ensures even distribution of pollen and is effective in enclosed environments. Examples: 1. Handheld misting bottle for small gardens. 2. Automated misting system designed for use in greenhouses or large fields. | Pollen is mixed with water or another suitable liquid carrier in the device's reservoir. | The pollen-laden mist is sprayed onto the flowers, ensuring the pollen adheres to the floral surfaces. | Yes | Medium to high, depending on automation level. | Risk of pollen clumping, dependency on weather conditions, potential equipment clogging |
| Leafblowers [30] | Originally designed for clearing leaves, these devices have been adapted for pollination by using the high-velocity air to blow pollen onto flowers. Examples: 1. Handheld leaf blower for garden use. 2. Backpack leaf blower with extended reach for use in orchards or large fields. | Pollen is manually or mechanically loaded into the blower's intake or a specially designed attachment. | The high-velocity air from the blower disperses the pollen over a wide area, reaching multiple flowers simultaneously. | Yes | Low to medium, requires user operation. | Potential damage to delicate flowers, uneven pollen distribution, noise pollution |
| Devices with Electrostatic Charge [31] | Devices that use electrostatic charges to attract and disperse pollen. These devices can be handheld or mounted on agricultural equipment. Examples: 1. Handheld electrostatic sprayer for small farms. 2. Tractor-mounted electrostatic pollinator for large-scale farming. | Pollen is charged and attracted to the device's collection plates. | The electrostatically charged pollen is dispersed onto flowers, adhering to their surfaces due to opposite charges. | Yes | Medium to high, depending on the setup and size of the device. | Requires careful calibration, potential for equipment malfunction, limited effectiveness in high humidity conditions |
| Robots [27], [32] | Automated ground vehicles designed for pollination in agricultural settings. These robots can navigate fields autonomously and perform precise pollination tasks. Examples: 1. Autonomous rovers with robotic arms that mimic natural | Pollen is collected through mechanical means or manually loaded into the robot's | The robotic arms or nozzles of the robot accurately disperse pollen onto the target flowers, guided by sensors and AI | Yes | High, can be fully autonomous advanced AI and sensor systems. | High initial cost, maintenance complexity, dependency on accurate sensors and AI algorithms |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | pollination. 2. AI-guided pollination robots equipped with cameras and sensors for efficient operation in greenhouses or open fields. | storage compartment. | algorithms. | | | |
| BrambleBee Robots [27], [33] | Autonomous ground-based robot for pollinating bramble plants in greenhouses | Built-in pollen collector | Precise application to individual flowers | No | Fully autonomous | Limited to Greenhouse |
| Unmanned Aerial Vehicles (UAV) [34] | Unmanned aerial vehicles equipped with specialized equipment for pollination tasks, capable of flying over large areas and precisely dispersing pollen. | Details Below | Details Below | Details Below | regulatory restrictions & battery limitations | Details Below |
| UAV DJI Agras T40 [27], [35] Spraying Dry Pollen Mechanism | Commercial UAV for spraying in open fields, including spraying fertilizers and pesticides, seeding, and pollination. | No pollen collection mechanism | Spraying of pollen | Yes | Semiautonomous | No pollen collection mechanism |
| UAV XAG ”Electronic Bees” [27], [36] Spraying Liquid Pollen Mechanism | Drone that sprays micron-level pollen liquid onto fruit trees for precise pollination | Built-in pollen collector | Collected pollen blended with a solvent to produce pollen liquid, which is uniformly sprayed over fruit trees | No | Semiautonomous | Open field |
| UAV Polybee [27], [37] Vibration mechanism | Solution incorporates aerodynamically controlled pollination (ACP), a proprietary contactless mechanism for self-pollination, using off-the-shelf drones. | No pollen collection required | Dispersal with vibration motion | No | Fully autonomous | Limited to Greenhouse |
| UAV Dropcopter [27], [38] downwash air flow mechanism | Commercial UAV for supplemental orchard pollination | No pollen collection mechanism | Disperses pollen through downwash air flow | Yes | Semiautonomous | Limited to Orchard, No pollen collection mechanism |

*C. Significance of Research*

The significance of this research lies in its innovative methods of artificial pollination, offering a comprehensive solution that allows for the collection and dispersal of pollen in a single flight cycle. The absence of these differentiating aspects in current methods and the need for them are highlighted through the comprehensive comparative analysis of various artificial pollination devices, as demonstrated in Table I.

This analysis highlights several critical areas where current technologies require significant improvement. One of the primary challenges identified is the development of reliable and efficient pollen collection and delivery mechanisms. Many existing systems depend on manual or semi-automated pollen collection processes, which are labor-intensive, time-consuming, and ultimately limit the scalability of the technology.

Ensuring the viability of pollen during collection, storage, and application presents a significant challenge. There is a pressing need for methods that can maintain pollen viability over extended periods, especially in systems reliant on external pollen sources. Additionally, the precision and targeted application of pollen to individual flowers remains a challenge, with some systems relying on broad-spectrum spraying or misting approaches. The use of an advanced control system to enable precise, flower-level pollination would mark a significant advancement in this field.

The comparative analysis also highlights the necessity for systems capable of operating in diverse environments, ranging from greenhouse facilities to tall orchard trees. Adaptability to various crop types, canopy structures, and environmental conditions is crucial for the widespread adoption of drone-based pollination technologies.

This research aims to bridge this gap by developing an innovative solution that enhances the level of autonomy in pollen extraction, storage, and targeted dispensing, requiring no human intervention. By increasing the degree of autonomy, this research seeks to reduce labor costs and improve the reliability and consistency of the artificial pollination device. The focus is on advancing autonomous pollen collection mechanisms, precision pollination techniques, and adaptable systems that can operate effectively in diverse agricultural settings. These improvements will contribute significantly to the scalability and effectiveness of artificial pollination technologies, ensuring their broader adoption and impact in various agricultural environments.

The research proposal focuses on developing an innovative artificial pollination device designed to address the existing gaps in current pollination methods. This solution features a 3D-printed funnel paired with a 5V fan, which directs airflow to collect pollen onto the device. The pollen is stored on artificial pollination brushes within the device. When the device moves to the next flower, a second blower fan (5V or 9V) disperses the pollen onto the flower, ensuring efficient and targeted pollination.

## III. PROPOSED SOLUTION

The proposed solution specifically addresses the gaps identified in current artificial pollination methods by advancing capabilities in autonomous pollen collection, precision pollination, and environmental adaptability. This section discusses the criteria, constraints, materials, hardware, software tools, subsystems, and assembly of the novel artificial pollination system developed to meet these needs.

➢ *Criteria and Constraints*

The project must meet specific criteria to ensure its effectiveness and feasibility. The system should be easily mountable to existing drones, UAVs, and other agricultural technologies. It needs to efficiently collect pollen from flowers using a suction fan and accurately disperse it through a blower fan to maximize pollination rates. While moving from one flower to another, the pollen should be stored on artificial pollination brushes. The pollination method should be relatively targeted, ensuring precision in pollinating flowers, and should be adaptable to various crop types and field conditions. The design must be cost-effective for large-scale agricultural use. Additionally, it should minimize interference from fans, winds, and drone propellers, ensuring successful artificial pollination. Safety is paramount, so the system must be safe for crops and the environment, avoiding any damage to plants or unintended ecological consequences. Scalability is also crucial, allowing the design to be implemented across different sizes of agricultural operations.

Several constraints must be considered in the design process. The system must work within the limitations of current UAV and robotic technologies, including battery life, weight capacity, and the amount of pollen it can carry. Both turmeric and mustard seeds will be used as simulated pollen for testing purposes. Rigorous testing on a model testbed will be indispensable to validate the system’s capabilities under simulated conditions. Lastly, the design must adhere to environmental protection laws and guidelines. No human intervention is allowed for the collection and dispersal of the pollen in any form.

➢ *Materials and Software Tools*

Table II tabulates the component names, function, software, hardware, and microcontroller used to create this artificial pollination device.

➢ *System Design and Function*

The proposed system aims to address the challenges of artificial pollination by integrating various components into a cohesive and efficient solution. The system is designed to mimic the natural pollination process using a combination of custom-designed hardware and software. See Fig. 1.

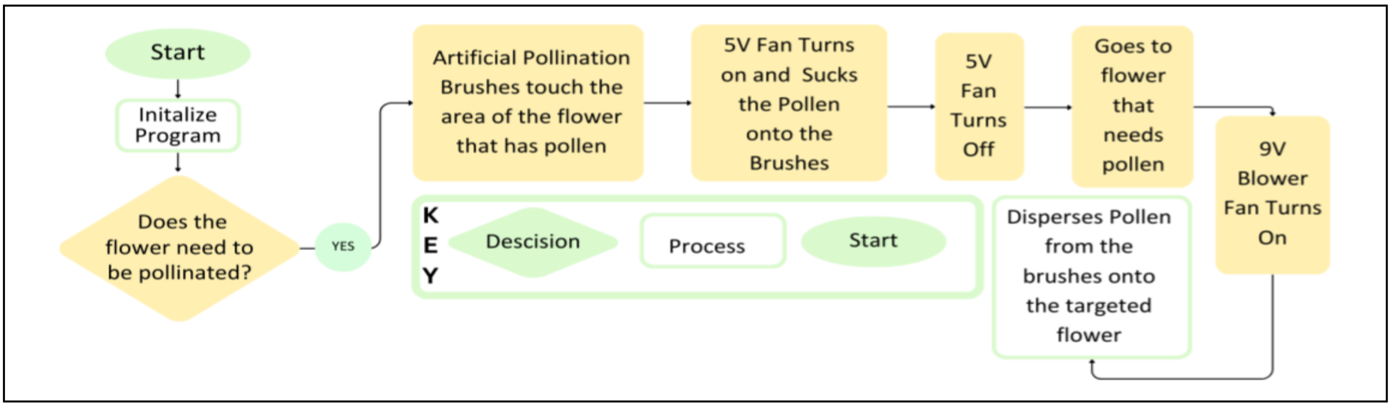


Fig 1: Flowchart of the Artificial Pollination Process

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The system consists of several key components: a custom 3D-printed funnel, a suction fan, a blowing fan, and artificial pollination brushes. These components work together to create a vacuum effect that collects pollen from the pistil, stores it on artificial pollination brushes, and disperses it onto the reproductive parts of flowers. The system's architecture (Fig. 2) is designed to ensure optimal airflow and pollen transfer efficiency.

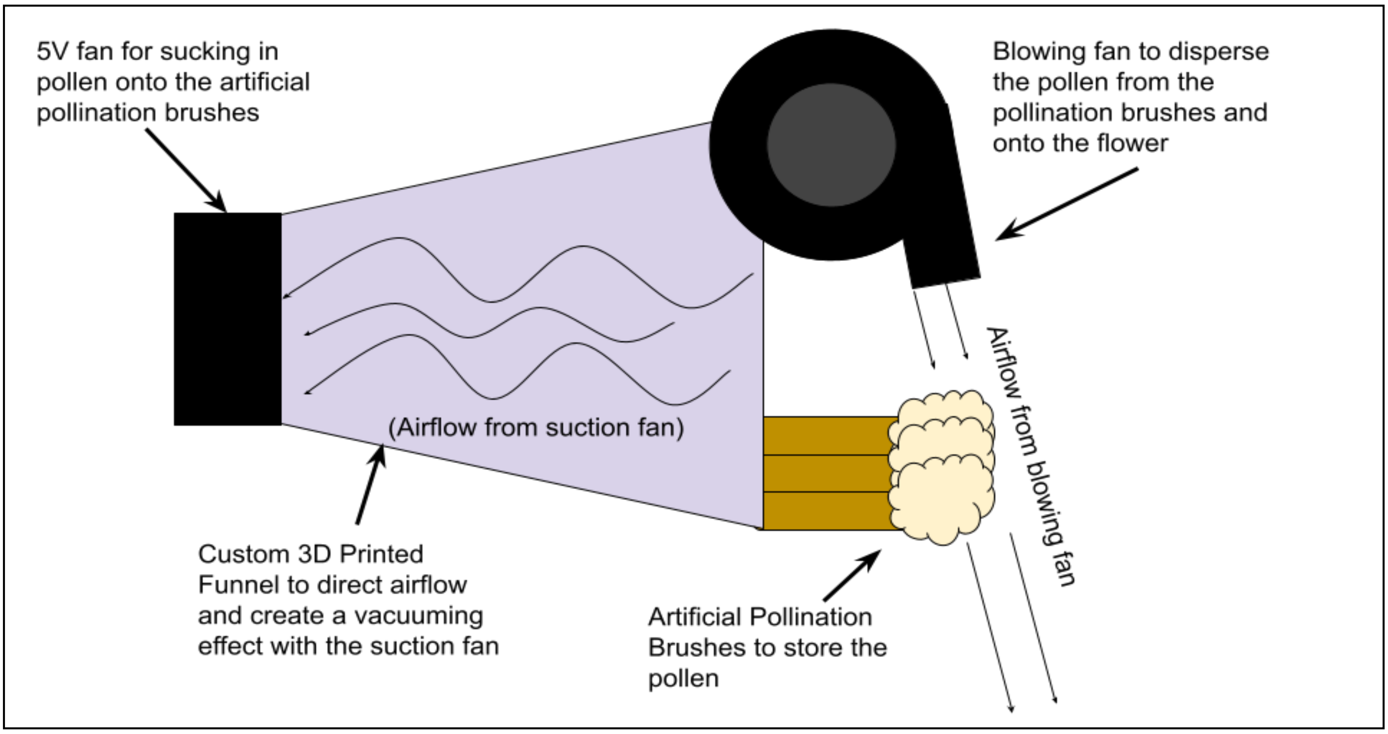


Fig 2: System Architecture Diagram

The full CAD model of the system is presented in Fig. 3, and the final prototyped device is depicted in Fig. 4.

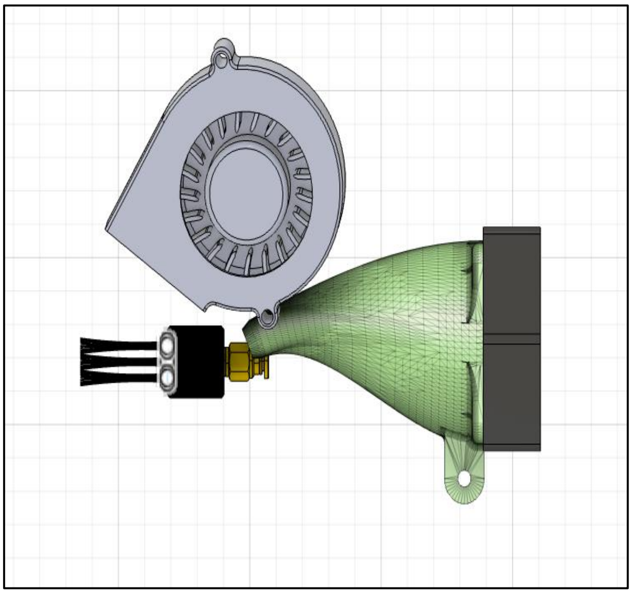

Fig 3: CAD Model of the System


Fig 4: Final Device

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Table 2: Description of Components, their Functions, Associated Software and Hardware

| Component Name | Function | Software | Hardware |
|---|---|---|---|
| Custom 3D Printed Funnel | Directs airflow onto the artificial pollination brushes as part of the vacuum system that efficiently collects pollen from the reproductive parts of the flower | None | 3D Printer (e.g., Ender V3) with PVC filament for customized funnel design with optimized suction angles |
| Suction Fan | Combined with the 3D-printed funnel, this fan creates a vacuum effect that efficiently extracts pollen from the reproductive parts of the flower and stores it on the artificial pollination brushes on the device | Arduino IDE, mBlock IDE | Arduino/mBlock Microcontroller, 5V suction fan |
| Blowing Fan | Disperses the pollen from the artificial pollination brushes onto the reproductive parts of the flower | Arduino IDE, mBlock IDE | Arduino/mBlock Microcontroller, 5V blowing fan |
| Artificial Pollination Brushes | Retains the pollen until it is ready to be dispersed | None | Specialized artificial pollination brushes |

## IV. METHODOLOGY

### A. *System Design and Development*

➢ *Component Design and Fabrication*

- *3D Printed Funnel*

The funnel was modified from an existing CAD Model on Thingiverse [33] using CAD software, specifically Fusion 360. The design includes a slanted slope to direct airflow effectively toward the artificial pollination brushes. PVC filament was selected for its durability and suitability for 3D printing. The funnel was printed using a 3D printer (e.g., Ender V3). The print settings were optimized to ensure precision and strength, with specific attention to layer height and infill density. After printing, the funnel was cleaned and all supports were removed. The surface was smoothed to ensure optimal airflow.

- *Suction Fan and Blowing Fan*

5V Fans were chosen based on airflow requirements and compatibility with the microcontroller system (Arduino). The suction fan was installed at the base of the funnel to create the vacuum effect. The blowing fan was positioned to disperse the collected pollen from the brushes. Electrical connections were made to the Arduino/mBlock microcontroller. However, it is important to note that later in the experiment, the 5V blowing fan was replaced with a 9V fan to enhance accuracy.

- *Artificial Pollination Brushes*

Brushes were utilized to hold pollen effectively. The material chosen ensures gentle contact with flowers to avoid damage. Brushes were attached to the system at the point where the airflow directs the pollen. The positioning was calibrated to maximize pollen collection and dispersal efficiency.

### B. *Software Development*

The software developed for this system focuses on controlling the fans either autonomously or via remote control. The control algorithms enable the suction and blowing fans to activate based on predefined conditions detected by the farmer's sensor readings or UAV technology. This design ensures ease of use and reliability for a variety of agricultural setups. By using commands within the Arduino IDE and mBlock IDE, the fans can be programmed to operate automatically when certain environmental parameters are met or can be manually controlled by the user, providing flexibility and adaptability to different pollination scenarios.

## V. PRELIMINARY TESTING PHASE - EVALUATING THE PERFORMANCE OF HARDWARE COMPONENT

### A. *Purpose*

The primary objective of this first testing phase was to evaluate the device's capability to collect pollen and store it on artificial pollination brushes, and then to assess its effectiveness in dispersing the pollen onto the reproductive parts of the flowers. This round of testing is purely to understand the efficiency and accuracy of the device as a whole, including all of its features and capabilities.

### B. *Experimental Setup*

The artificial pollination system was tested in a 8 feet by 6 feet model test bed with artificial flowers. Turmeric was used to simulate pollen. The test bed was divided into four sections, each with a different type of artificial flower. The device was placed on a turntable to simulate UAV/Robot behavior, ensuring efficient pollen collection and transfer. See Fig. 5.

Each test trial lasted for a maximum of 1 minute, during which the entire pollination process had to be completed. This time constraint ensured the system's efficiency and suitability for real-world agricultural applications.

### C. *Actual Testing and Data Collection*

This round of testing focused on verifying whether the device could successfully collect and disperse turmeric (used as a pollen simulant). Table III presents sample data and the data table used for determining the accuracy rate of the technology during this phase.

Table 3: Testing Criteria

| Is the device powered on? | Can it collect pollen from the pistils? | At least half of the sample stored on pollination brushes? | Dispersed from brushes onto the pistil of another flower? | Pollination completed under a minute? |
|---|---|---|---|---|
| Y/N | Y/N | Y/N | Y/N | Y/N |
| Y/N | Y/N | Y/N | Y/N | Y/N |
| Y/N | Y/N | Y/N | Y/N | Y/N |

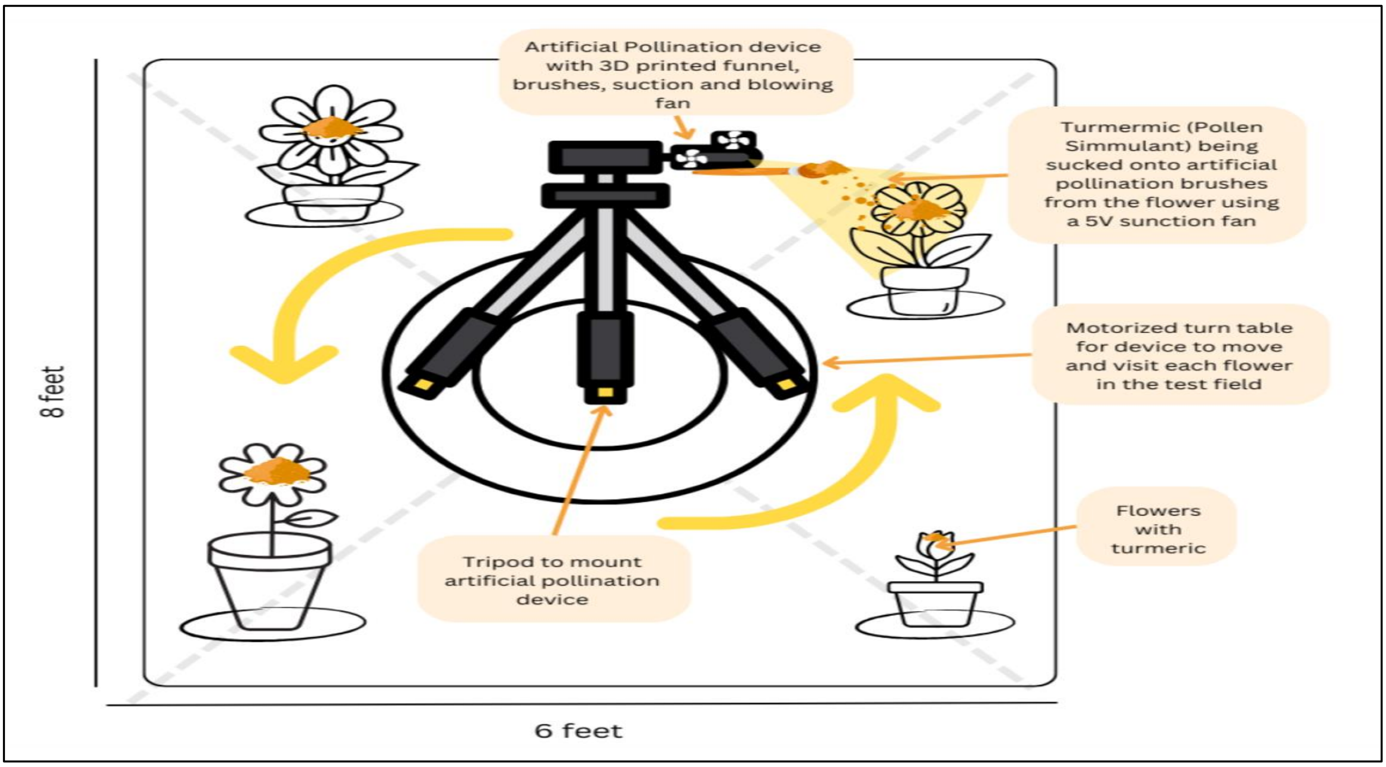


Fig 5: Testbed for Preliminary Round of Testing

D. *Data Analysis*

➢ *Descriptive Analysis*

After conducting 100 test trials using the criteria outlined in Table II, the overall accuracy rate for pollen collection was determined to be 61%. Of the collected pollen, 61% was successfully dispersed.

To calculate the success rates, a point-based system was used. Each row in Table II represents an individual test trial, and each column within a row corresponds to a specific criterion. Each criterion met earns one point, with a maximum of 4 points possible per row (one point per column). The success rate for each row is calculated as follows:

- If a row earns 4 out of 4 points, the success rate for that trial is 100%.
- If a row earns 3 out of 4 points, the success rate for that trial is 75%.
- If a row earns 2 out of 4 points, the success rate for that trial is 50%.
- If a row earns 1 out of 4 points, the success rate for that trial is 25%.
- If a row earns 0 out of 4 points, the success rate for that trial is 0%.

After calculating the success rate for each row, the average success rate of all rows is taken to determine the final overall accuracy rate. This average represents the overall performance across all test trials.

However, it is important to note that this rate includes all the features of the artificial pollination device listed in the Table II. During testing, it was immediately identified that the criteria of completing pollination within one minute could not be met due to the low power of the dispersal fan. The 61% accuracy could be improved by enhancing the dispersal mechanism.

➢ *Inferential Analysis*

Additionally, the confidence interval was calculated to ensure the reliability of the results. A confidence interval provides a range of values, calculated from the data observed, that is likely to contain the true value of an unknown population parameter. In this case, a 95% confidence interval was used, meaning we can be 95% confident that the interval from 0.56197 to 0.65803 captures the true proportion of successful artificial pollination by the

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UAV. This statistical method is crucial because it not only gives an estimate of where the true value lies but also the certainty or probability of it falling within a specific range, allowing the data analyst to make more informed decisions and assessments based on the data collected.

- *Success Proportions of Artificial Pollination System at 95% Confidence Interval (CI)*

- ✓ $n$ = number of trials
- ✓ $\hat{p}$ = probability of artificial pollination
- ✓ Mean = 0.61
- ✓ $z^*$ = standard deviation

- *Conditions*

- ✓ 10% Condition:

  - $n \leq \frac{1}{10}N \quad \Rightarrow \quad 100 \leq \frac{1}{10}N$

- ✓ Large Counts:

  - $n\hat{p} \geq 10 \quad \Rightarrow \quad 100 \times 0.61 \geq 10$
  - $n(1-\hat{p}) \geq 10 \quad \Rightarrow \quad 100 \times 0.39 \geq 10$

- *Confidence Interval Calculation*

- ✓ $\hat{p} \pm z^* \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$
- ✓ $0.61 \pm 1.96\sqrt{\frac{0.61 \times 0.39}{100}}$
- ✓ $0.61 \pm 0.04803$
- ✓ (0.56197,0.65803)

This calculation means that we are 95% confident that the true proportion of times this device can successfully carry out the full process of artificial pollination lies between 0.56197 and 0.65803.

This testing phase demonstrated that, under random conditions without specific adjustments for angle and distance from the flowers, the efficiency of the hardware and its components achieved a success rate of 61% when operating the device.

## VI. FINAL TESTING PHASE: ANALYSIS OF POLLINATION PARTICLE MOTION FOR OPTIMIZING ARTIFICIAL POLLINATION DEVICE PLACEMENT

### *A. Purpose*

The primary objective of the second round of testing was to collect detailed data on the movement of pollen, simulated by mustard seed particles, after being dispersed by a newly added 9V blowing fan. Upgrading from a 5V to a 9V fan was intended to improve the accuracy of the pollination device's dispersal capabilities. This phase involved capturing slow-motion footage of the mustard seeds in motion and subsequently analyzing the recordings in the tracker software titled Tracker: Video Analysis and Modeling Tool. The analysis aimed to generate graphs and range measurements, providing insights into the dispersion patterns and behavior of the particles. The purpose of this analysis is to optimize the placement and efficiency of artificial pollination devices, ensuring effective and precise pollination, which is crucial for improving crop yields and supporting agricultural productivity.

### *B. Experimental Setup*

The testing setup was modified to effectively track the particles. Due to the relatively small size of turmeric particles, mustard seeds were selected for this phase. Mustard seeds are heavier and larger, making them easier to track with the software used for analysis. The added weight difference justified upgrading the fan from a 5V blower to a more powerful 9V blowing fan. Additionally, observations from previous rounds of testing proved that upgrading the blowing fan may increase the accuracy of that component from 61% to a higher percentage.

Each pot in the setup measured 2 inches in height, with an additional 1 inch for the flower, totaling 3 inches in height. The leftmost flower had a diameter of 2.5 inches, the middle flower had a diameter of 3.5 inches, and the rightmost flower had a diameter of 1.35 inches. All flowers were spaced 3.5 inches apart from each other. The middle flower was positioned 3.5 inches away from the pollination stand, while the two side flowers were 4.95 inches away. The stand held the device 6 inches above the ground.

Approximately 1/4 teaspoon of mustard seeds (equivalent to 125-150 seeds) was pre-loaded onto the artificial pollination brushes for each test run, as this is typically what is collected by the suction fan. See Fig. 6 for the testbed diagram and Fig. 7 for pictures of the actual testbed.

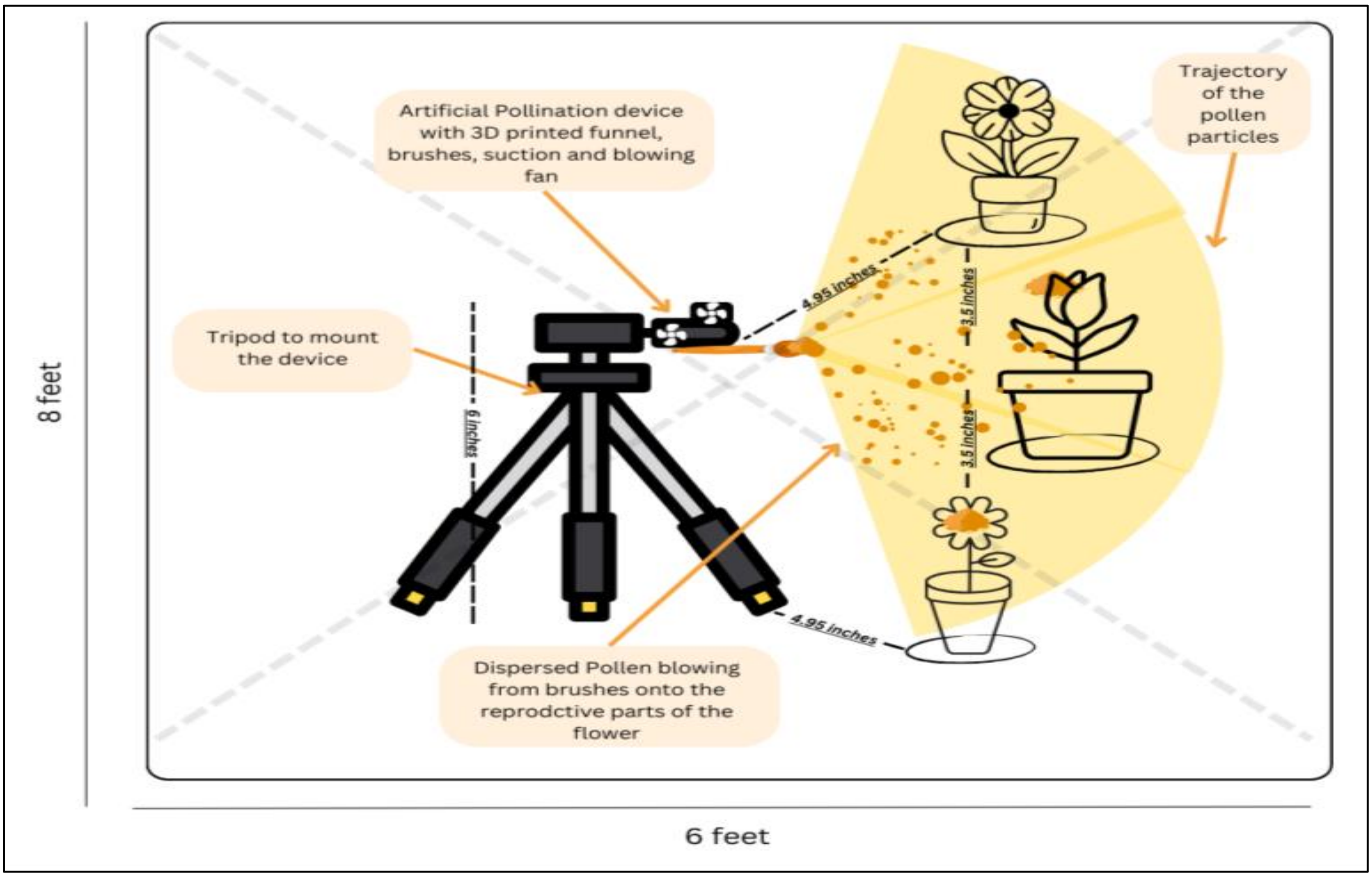


Fig 6: Model Testbed for Tracking the Motion of the Pollen Particles

Fig 7: Photos of Actual Testbed for Tracking the Motion of the Pollen Particles.

### *C. Data Collection through Tracker: Video Analysis and Modeling Tool and Desmos Graphing Tool*

The data captured from this final testing phase showed that the flower pot directly in front of the pollination device was able to capture 36 mustard seeds, which is approximately 24 to 28.8% of the pollen on the brushes. The left flower, with a diameter of 2.5 inches, captured 3 pollen particles (less than 1 percent), and the right flower captured no pollen particles. The video clips recorded in slow motion were uploaded into the tracking software called Tracker: Video Analysis and Modeling Tool. Initially, the coordinate plane was set at the point where the artificial pollination brushes made contact. Calibration was performed to ensure the correct units were set to inches, and it was noted that the pollination device was positioned 6 inches off the ground.

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- **The Tracker:** Video Analysis and Modeling Tool setup is illustrated in Fig. 8.

A total of 250 data points were collected, tracking 18 particles. Since the tracking software does not support a Z-axis, the Z-axis measurements were manually calculated using a ruler, making them approximate. The data was stored in a table format with columns for the x, y, and z coordinates. A sample of this data is presented in Table IV - Subset Of Collected Data For Particle Tracking. The final data was transferred to a spreadsheet and then graphed. The coordinates for the first 18 pollen particles shown in Fig. 9.

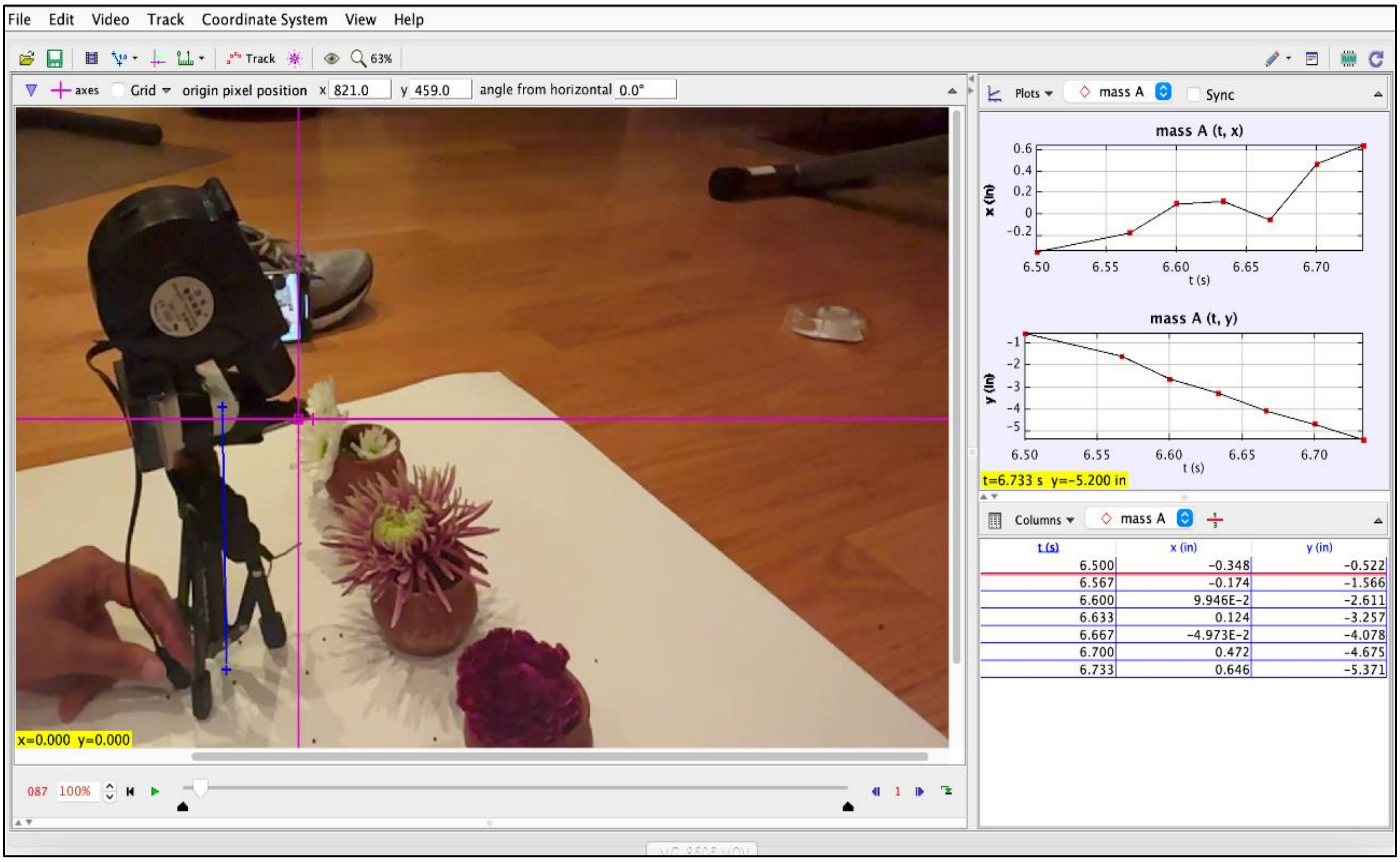

Fig 8: Tracker: Video Analysis and Modeling Tool Software Set Up

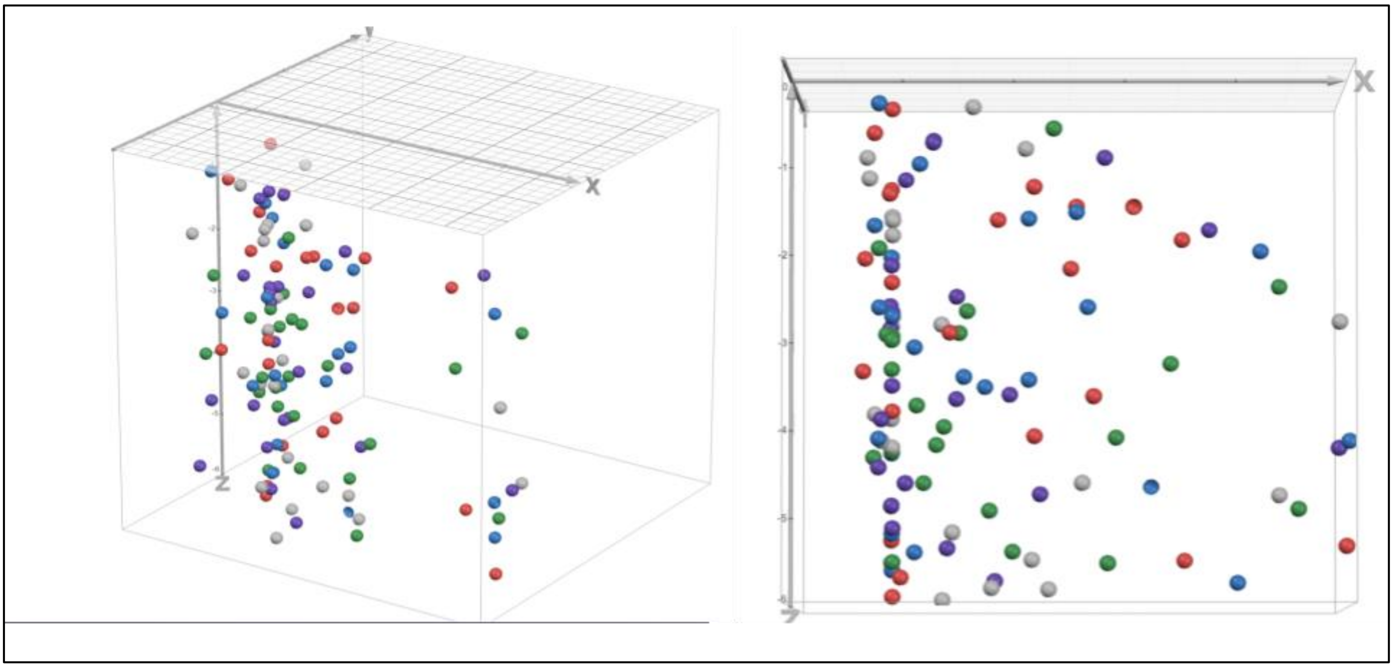

Fig 9: Coordinates for the first 18 Pollen Particles (Bird's Eye View and Side View)

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Table 4: Subset of Collected Data for Particle Tracking

| x | y | z |
|---|---|---|
| 0.000000 | 0.467410 | 0.000000 |
| 0.025126 | 0.410408 | -0.030151 |
| 0.050251 | -0.706142 | -0.060302 |
| 0.075377 | 1.248737 | -0.090452 |
| 0.100503 | -1.151471 | -0.120603 |
| 0.125628 | 0.369438 | -0.150754 |
| 0.150754 | 2.129398 | -0.180905 |
| 0.175879 | 0.783011 | -0.211055 |
| 0.201005 | -0.398296 | -0.241206 |
| 0.226131 | -0.224928 | -0.271357 |
| 0.251256 | 0.694946 | -0.301508 |
| 0.276382 | -0.863461 | -0.331658 |
| 0.301508 | -0.228877 | -0.361809 |
| 0.326633 | 0.648003 | -0.391960 |
| 0.351759 | 1.255195 | -0.422111 |
| 0.376884 | 0.398792 | -0.452261 |
| 0.402010 | -1.002734 | -0.482412 |
| 0.427136 | 0.588639 | -0.512563 |
| 0.452261 | 0.867044 | -0.542714 |
| 0.477387 | -1.484662 | -0.572864 |

To address the initial data's limited representation, 1,000 additional data points were artificially generated using Python on Google Colab. 10. Therefore, 75% of the data is synthetic/AI generated, while 25% is originally collected. However, the synthetic data is designed to closely follow the patterns and motions observed in the original data. The synthetic data fills in gaps along the mustard seeds' paths and introduces new trajectories that mirror the patterns and angles of the collected data points. The new and improved dataset is illustrated in Table V. Fig. 10 presents a side-by-side comparison of the synthetic data versus the actual data.

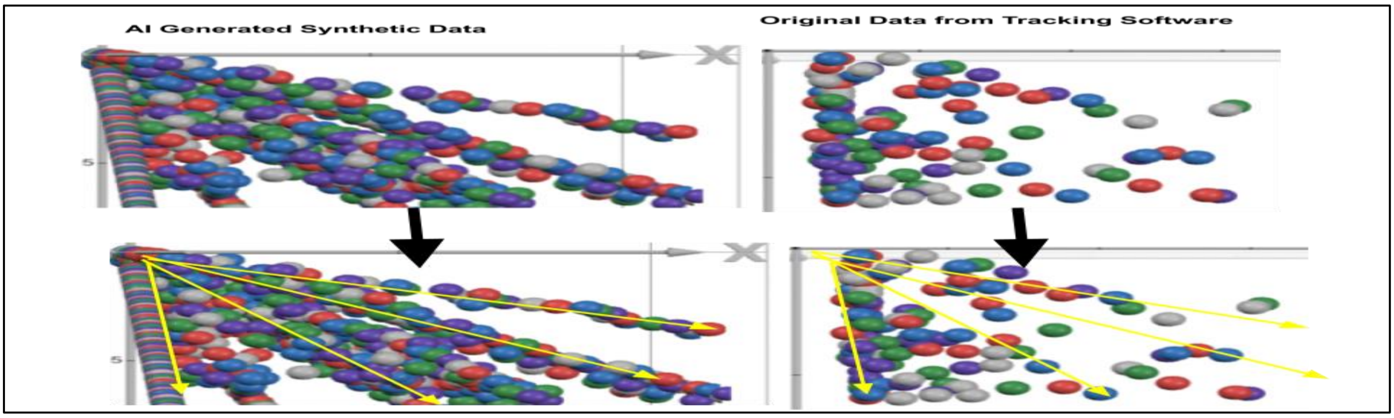

Fig 10: Zoomed Out View of Original and AI-Generated Coordinates (Bird's Eye View and Side View)

Table 5: AI Generated Data of Particle Tracking

| x | y | z |
|---|---|---|
| 3.969849 | -0.995210 | -4.763819 |
| 3.994975 | 0.855502 | -4.793970 |
| 4.020101 | 0.293608 | -4.824121 |
| 4.045226 | 0.778864 | -4.854271 |
| 4.070352 | 0.013840 | -4.884422 |
| 4.095477 | 2.172533 | -4.914573 |
| 4.120603 | -0.060196 | -4.944724 |
| 4.145729 | -1.810132 | -4.974874 |
| 4.170854 | 0.927721 | -5.005025 |
| 4.195980 | -0.053587 | -5.035176 |
| 4.221106 | 0.275196 | -5.065327 |
| 4.246231 | 0.244153 | -5.095477 |

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar1299

| | | |
|---|---|---|
| 4.271357 | -1.743951 | -5.125628 |
| 4.296482 | 0.308864 | -5.155779 |
| 4.321608 | -1.359134 | -5.185930 |
| 4.346734 | 0.810215 | -5.216080 |
| 4.371859 | -0.006111 | -5.246231 |
| 4.396985 | -0.280494 | -5.276382 |
| 4.422111 | -0.217364 | -5.306533 |
| 4.447236 | -1.956118 | -5.336683 |
| 4.472362 | 1.591194 | -5.366834 |

*D. Data Analysis*

➢ *Original vs. Synthetic Data*

The comparison of the original and synthetic data is shown in Fig. 11. Both datasets follow a similar pattern, indicating that the synthetic data is an accurate representation of the original data.

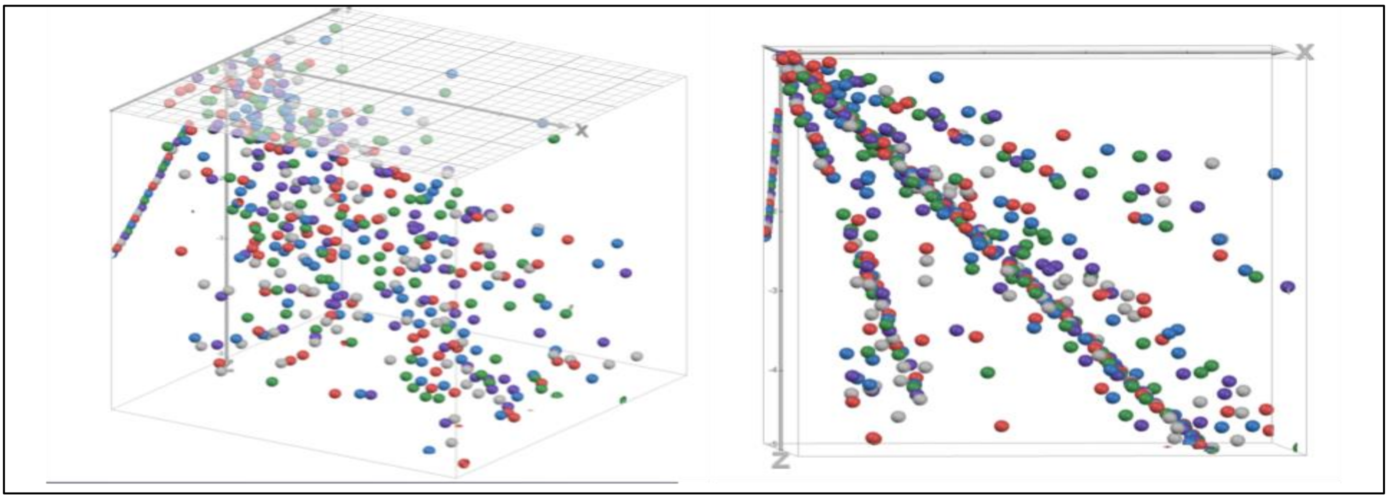

Fig 11: Original and AI-generated Coordinates (Bird's Eye View and Side View).

## VII. MODELING POLLEN PARTICLE MOTION: DEVELOPING THE CONE-SHAPED ARTIFICIAL POLLINATION RANGE

The data collected from the previous round of testing revealed a cone-shaped range. Based on this data, the range of a cone that best fits these points was approximated. The parameters of the cone are as follows:

*A. Understanding the Cone Parameters*

➢ *The Cone Parameters are as Follows:*

- **Radius (r)**: 4 units
- **Height (h)**: 6 units
- **Slant Height (s)**: 7.2111 units (calculated using the Pythagorean theorem)
- **Volume (V)**: 100.531 cubic units
- **Lateral Surface Area (L)**: 90.6174 square units
- **Base Surface Area (B)**: 50.2655 square units
- **Total Surface Area (A)**: 140.883 square units

*B. Determining the Orientation Angles*

To determine the angles that the apex of this cone makes with the x-axis, y-axis, and z-axis, we use trigonometric functions.

➢ *Angle with the $\boldsymbol{x}$-axis ( $\boldsymbol{\alpha}$ ):*

$$\cos(\alpha) = \frac{r}{s} = \frac{4}{7.2111}$$
$$\alpha = \cos^{-1}\left(\frac{4}{7.2111}\right) \approx 56.31°$$

➢ *Angle with the $\boldsymbol{y}$-Axis ($\boldsymbol{\beta}$):*

$$\cos(\beta) = \frac{h}{\sqrt{r^2 + h^2}} = \frac{6}{\sqrt{4^2 + 6^2}}$$
$$\beta = \cos^{-1}\left(\frac{6}{\sqrt{4^2 + 6^2}}\right) \approx 84.53°$$

➢ *Angle with the z-axis ($\gamma$):*

$$\cos(\gamma) = \frac{h}{s} = \frac{6}{7.2111}$$
$$\gamma = \cos^{-1}\left(\frac{6}{7.2111}\right) \approx 33.69°$$

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➢ *Apex Angle (δ):*

$$\tan(\delta/2) = \frac{r}{h} = \frac{4}{6}$$

$$\delta = 2\tan^{-1}\left(\frac{4}{6}\right) \approx 67.38°$$

➢ *Implementing the Angles:*

The cone can be mounted on a gimbal or a similar adjustable mechanism to achieve the desired angles as illustrated in Fig. 12.

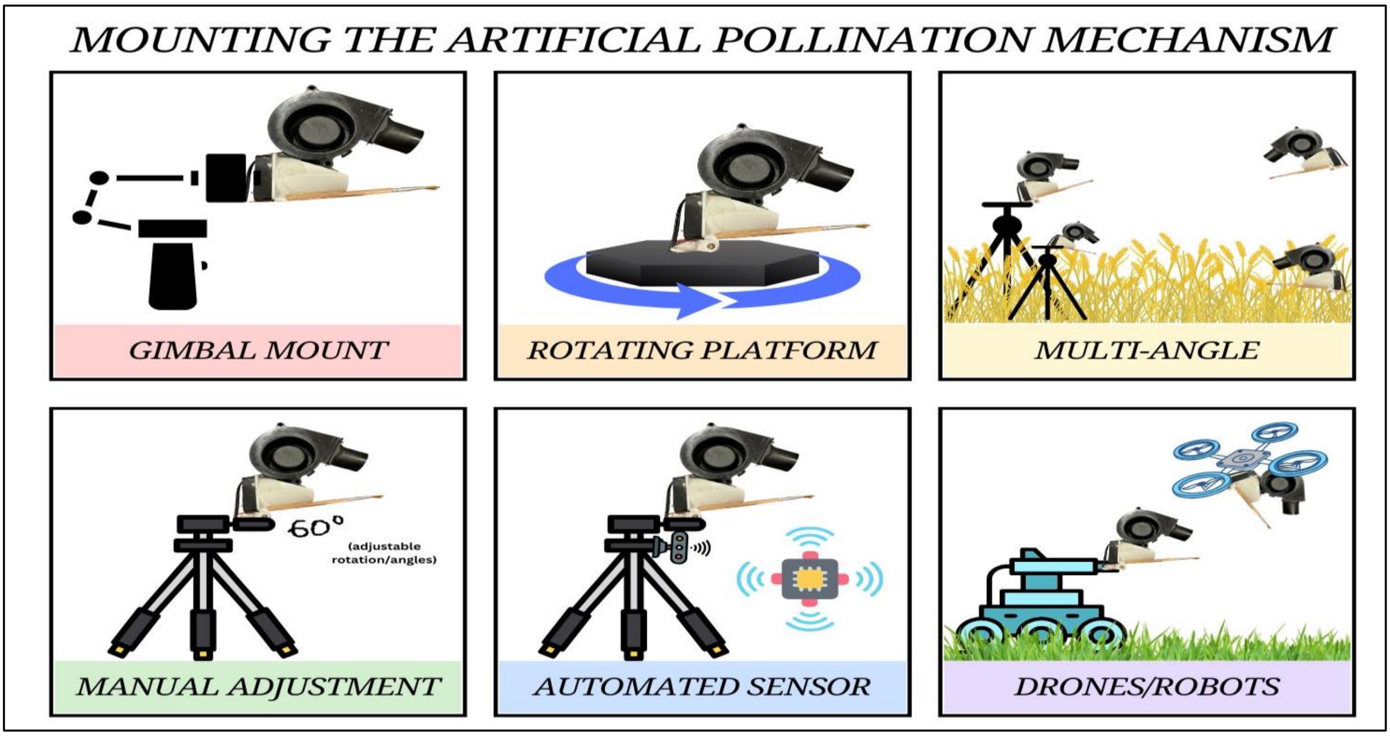


Fig 12: Mounting the Artificial Pollination Mechanism)

*C. Trajectory and Distribution Analysis*

Assuming the mustard seeds follow a parabolic path under the influence of gravity and the initial velocity imparted by the fan, we can analyze the trajectory and distribution.

- Initial Velocity: Let v0 be the initial velocity of the seeds when blown off the brushes. The horizontal and vertical components of the velocity are v0x = v0 cos(θ) and v0y = v0 sin(θ), where θ is the angle of release relative to the horizontal.
- Trajectory Equation: The trajectory of the seeds can be modeled by the parametric equations:

$$x(t) = v_{0x}t = v_0 \cos(\theta)t$$

$$y(t) = v_{0y}t - \frac{1}{2}gt^2 = v_0 \sin(\theta)t - \frac{1}{2}gt^2$$

- Range: The horizontal range R can be calculated as:

$$R = \frac{v_0^2 \sin(2\theta)}{g}$$

- Distribution Pattern: The seeds' distribution will depend on the initial velocity, angle of release, and environmental factors such as wind and air resistance.
- Distribution Coverage: The cone-shaped range ensures a broad distribution of pollen over a wide area. The base radius of 4 units provides substantial coverage, ideal for maximizing pollination efficiency.

This cone was cut on paper and assessed by conducting the same experimental setup. See Fig. 6. From the 1/4 teaspoon of mustard seeds (120-150 seeds), only 35 seeds did not fall within the cone's range when positioned at the specified angles, resulting in a 65% to 75% accuracy rate. During all 100 test trials, approximately 15-30 mustard seeds landed on the center flower each time, proving that when positioned at 56.31 degrees with the x-axis and 84.53 degrees with the y-axis, and 33.69 degrees with the z-axis the cone range accurately predicted the distribution of the mustard seeds for the flower directly below. The accuracy rate for the probability of the flower getting pollinated if there is 1/4 of a teaspoon is 97%. This consistency demonstrates the effectiveness of the cone-shaped pollination range in targeting specific areas for pollen distribution.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar1299

*D. Confidence Interval for Proportion of Mustard Seeds within Cone's Range*

- To calculate the confidence interval for the proportion of mustard seeds that fell within the cone's range, we follow these steps:
- $n = 100$ (number of trials)
- $\hat{p} = 0.97$ (probability of artificial pollination when 1/4 tsp of pollen is collected by the suction fan)
- Mean → 0.97
- $z^* = 1.96$ (z-value for 95% confidence interval)

➢ *Conditions*

- 10% Condition:

✓ $n \leq \frac{1}{10}N \quad \Rightarrow \quad 100 \leq \frac{1}{10}N$

- Large Counts:

✓ $n\hat{p} \geq 10 \quad \Rightarrow \quad 100(0.97) \geq 10$
✓ $n(1-\hat{p}) \geq 10 \quad \Rightarrow \quad 100(0.03) \geq 10$

➢ *Confidence Interval Calculation*

✓ $\hat{p} \pm z^* \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$

$\Rightarrow \quad 0.97 \pm 1.96\sqrt{\frac{0.97 \times 0.03}{100}}$

$\Rightarrow \quad 0.97 \pm 1.96\sqrt{0.000291}$

$\Rightarrow \quad 0.97 \pm 0.0335$

$\Rightarrow (0.9365, 1.0035)$

Since a proportion cannot exceed 1, the upper bound is adjusted to 1. Thus, the 95% confidence interval for the proportion of mustard seeds that fell within the cone's range is approximately 93.7% to 100%.

This means that under the condition where the device collects 1/4 of a teaspoon of pollen and the blowing fan voltage is increased from 5V to 9V, the accuracy of pollen dispersal increases from 61% to 97%. This significant improvement demonstrates the effectiveness of optimizing fan power in enhancing pollen dispersal. Consequently, the overall device accuracy is elevated to 79%.

## VIII. TRAJECTORY ANALYSIS OF POLLEN PARTICLES WITH WEATHER CONDITIONS

Knowing that the success rate is 79%, it is now essential to uncover how different factors, especially wind, will affect the success rate and accuracy of pollination. Using trajectory and vector analysis will help determine the paths of pollen particles when dispersed by the fan.

*A. Definitions of Variables*

- $v_0$: Initial velocity of the particle
- $\theta$: Launch angle of the particle (33.69°)
- $w_0$: Wind speed (10 mph ≈ 4.47 m/s, typical LA weather conditions)
- $\alpha$: Wind angle with respect to the horizontal (30°, typical LA weather conditions)
- $g$: Acceleration due to gravity (9.8 m/s²)
- $t$: Time
- $x(t)$: Horizontal position of the particle at time $t$
- $y(t)$: Vertical position of the particle at time $t$
- $V_m$: Initial velocity vector without wind
- $V_w$: Wind velocity vector
- $R_v$: Resultant velocity vector with horizontal wind
- $R_s$: Resultant velocity vector with wind at an angle

*B. Ideal Case (No Wind)*

This is the case where no wind effects the movement and trajectory of the particles.

➢ *Initial Velocity Components*

- Horizontal: $v_0\cos\theta$
- Vertical: $v_0\sin\theta$

In projectile motion, the initial velocity $v_0$ of the pollen particles can be broken down into horizontal and vertical components based on the launch angle $\theta$. These components are essential for analyzing the motion of the particles and predicting their trajectory.

The horizontal component of the initial velocity is given by $v_0\cos\theta$. This represents the portion of the initial velocity that is directed along the horizontal axis. It determines how far the pollen particles will travel horizontally.

The vertical component of the initial velocity is given by $v_0\sin\theta$. This represents the portion of the initial velocity that is directed along the vertical axis. It determines how high the pollen particles will rise and the influence of gravity on their motion.

➢ *Position Equations*

- Horizontal position: $x(t) = v_0\cos\theta \cdot t$
- Vertical position: $y(t) = v_0\sin\theta \cdot t - \frac{1}{2}gt^2$

The position equations describe the location of the pollen particles at any time $t$ after they are dispersed. These equations account for the initial velocity components and the effect of gravity on the vertical motion.

The horizontal position equation $x(t) = v_0\cos\theta \cdot t$ calculates the horizontal distance $x$ traveled by the pollen particles over time. It is derived from the horizontal component of the initial velocity, $v_0\cos\theta$, multiplied by the time $t$. Since there is no horizontal acceleration, this distance increases linearly with time.

The vertical position equation $y(t) = v_0 \sin\theta \cdot t - \frac{1}{2}gt^2$ calculates the vertical distance $y$ traveled by the pollen particles over time. It includes two components: the initial vertical motion $v_0 \sin\theta \cdot t$ and the effect of gravity $-\frac{1}{2}gt^2$. The first term represents the upward motion due to the initial vertical velocity, while the second term accounts for the downward acceleration due to gravity, causing the particles to fall over time.

By using these position equations, the trajectory of the pollen particles can be determined at any given time $t$, allowing for accurate predictions of their landing positions.

*C. Case: Wind is Horizontal to the Machine*

➢ *Initial Velocity Components (Without Wind)*

- $V_m = \langle v_0 \cos\theta, v_0 \sin\theta \rangle$

The initial velocity $V_m$ of the pollen particles can be expressed as a vector with horizontal and vertical components. The horizontal component is $v_0 \cos\theta$ and the vertical component is $v_0 \sin\theta$.

➢ *Wind Velocity Components*

- $V_w = \langle w_0, 0 \rangle$

The wind velocity $V_w$ is assumed to be horizontal, represented by $w_0$ in the horizontal direction and 0 in the vertical direction.

*D. Resultant Velocity Components*

- Horizontal: $v_0 \cos\theta + w_0$
- Vertical: $v_0 \sin\theta$

The resultant velocity components are calculated by adding the wind's horizontal component to the initial horizontal velocity and keeping the vertical component unchanged. Thus, the horizontal component becomes $v_0 \cos\theta + w_0$ and the vertical component remains $v_0 \sin\theta$.

*E. Resultant Velocity Vector*

- $R_v = \langle v_0 \cos\theta + w_0, v_0 \sin\theta \rangle$

The resultant velocity vector $R_v$ is obtained by combining the adjusted horizontal and unchanged vertical components, resulting in $\langle v_0 \cos\theta + w_0, v_0 \sin\theta \rangle$.

*F. Equations of Motion with Horizontal Wind*

- Horizontal Position: $x(t) = (v_0 \cos\theta + w_0) \cdot t$
- Vertical Position: $y(t) = v_0 \sin\theta \cdot t - \frac{1}{2}gt^2$

The equations of motion with horizontal wind are modified to account for the wind's effect. The horizontal position equation becomes $x(t) = (v_0 \cos\theta + w_0) \cdot t$, incorporating the additional horizontal velocity from the wind. The vertical position equation remains unchanged as $y(t) = v_0 \sin\theta \cdot t - \frac{1}{2}gt^2$, since the wind does not affect the vertical component.

## IX. SUMMARY: HORIZONTAL WIND

When the wind is horizontal (with angle $\alpha = 0^\circ$), the resultant horizontal velocity of the particles increases by the wind's horizontal component, while the vertical component remains unaffected by the wind. The trajectory equations are modified accordingly to incorporate the effect of the horizontal wind.

## X. CASE: WIND IS AT AN ANGLE ($A \neq 0^\circ$)

*A. Wind Velocity Components*

- $\langle w_0 \cos\alpha, w_0 \sin\alpha \rangle$

When the wind is at an angle $\alpha$, the wind velocity $V_w$ can be decomposed into horizontal and vertical components. The horizontal component is $w_0 \cos\alpha$ and the vertical component is $w_0 \sin\alpha$.

*B. Resultant Velocity Components*

- Horizontal: $v_0 \cos\theta + w_0 \cos\alpha$
- Vertical: $v_0 \sin\theta + w_0 \sin\alpha$

The resultant velocity components are found by adding the wind's horizontal and vertical components to the corresponding initial velocity components. Thus, the horizontal component becomes $v_0 \cos\theta + w_0 \cos\alpha$ and the vertical component becomes $v_0 \sin\theta + w_0 \sin\alpha$.

*C. Summary of Resultant Velocity ($R_s$)*

- $R_s = \langle v_0 \cos\theta + w_0 \cos\alpha, v_0 \sin\theta + w_0 \sin\alpha \rangle$

The resultant velocity vector $R_s$ is obtained by combining the adjusted horizontal and vertical components, resulting in $\langle v_0 \cos\theta + w_0 \cos\alpha, v_0 \sin\theta + w_0 \sin\alpha \rangle$.

*D. Equations of Motion with Wind*

- Horizontal position: $x(t) = (v_0 \cos\theta + w_0 \cos\alpha) \cdot t$
- Vertical position: $y(t) = (v_0 \sin\theta + w_0 \sin\alpha) \cdot t - \frac{1}{2}gt^2$

The equations of motion with wind at an angle are modified to account for the wind's effect. The horizontal position equation becomes $x(t) = (v_0 \cos\theta + w_0 \cos\alpha) \cdot t$, incorporating the additional horizontal velocity from the wind. The vertical position equation becomes $y(t) = (v_0 \sin\theta + w_0 \sin\alpha) \cdot t - \frac{1}{2}gt^2$, incorporating the additional vertical velocity from the wind and the effect of gravity.

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In summary, when the wind is at an angle $\alpha$, both the horizontal and vertical components of the resultant velocity are affected by the wind, altering the trajectory equations to reflect these changes.

## XI. APPLICATION WITH WEATHER CONDITIONS

### A. *Example Weather Condition*

In this example, specific weather conditions are considered to analyze the motion of pollen particles. The parameters used are:

- Wind speed ($w_0$): 10 mph ≈ 4.47 m/s (Los Angeles,
- California (LA) weather conditions)
- Wind angle ($\alpha$): 30° (LA weather conditions)
- Initial velocity ($v_0$): 10 m/s
- Launch angle ($\theta$): 33.69

### B. *Resultant Velocity Components*

- To determine the resultant velocity components, the initial velocity and wind velocity components are combined:
- Horizontal: v0 cosθ + w0 cosα
- 10cos33.69◦ + 4.47cos30◦ 10 · 0.8321 + 4.47 · 0.866
- 8.321 + 3.872 ≈ 12.193m/s
- Vertical: v0 sinθ + w0 sinα
- 10sin33.69◦ + 4.47sin30◦
- 10 · 0.5547 + 4.47 · 0.5
- 5.547 + 2.235 ≈ 7.782m/s

The calculations show the resultant horizontal velocity as approximately 12.193 m/s and the resultant vertical velocity as approximately 7.782 m/s.

### C. *Resultant Velocity Vector*

The resultant velocity vector $R_s$ combines these components:

- $R_s = \langle 12.193, 7.782\rangle$

### D. *Equations of Motion*

With the resultant velocity components, the equations of motion are:

- Horizontal position: $x(t) = 12.193 \cdot t$
- Vertical position: $y(t) = 7.782 \cdot \mathrm{t} - \frac{1}{2} \cdot 9.8 \cdot t^2$

These equations describe the horizontal and vertical positions of the pollen particles over time. The horizontal position equation $x(t) = 12.193 \cdot t$ incorporates the resultant horizontal velocity, while the vertical position equation $y(t) = 7.782 \cdot \mathrm{t} - \frac{1}{2} \cdot 9.8 \cdot t^2$ includes the resultant vertical velocity and the gravitational acceleration.

By using these equations, the position of the pollen particles at any given time $t$ can be calculated to determine their trajectory and where they will fall.

## XII. CONFIDENCE INTERVAL AND NEW SUCCESS RATES

To calculate the new success rates with wind influence, we will apply a confidence interval to the success rate data.

- $n = 30$ (Number of Trials)
- $p\hat{} = 0.876$ (observed success rate in pollen dispersal when 1/4 teaspoon of pollen is collected by the suction fan)
- Mean → 0.876
- $z* = 1.96$ (z-value for 95% confidence interval)

### A. *Conditions*

➢ *10% Condition:*

- $n \leq \frac{1}{10}N \quad \Rightarrow \quad 30 \leq \frac{1}{10}N$

➢ *Large Counts:*

- $np\hat{} \geq 10 \quad \Rightarrow \quad 30(0.876) \geq 10$
- $n(1-p\hat{}) \geq 10 \quad \Rightarrow \quad 30(0.124) \geq 10$

### B. *Confidence Interval Calculation*

- $$\hat{p} \pm z^* \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$$

$$\Rightarrow \quad 0.876 \pm 1.96\sqrt{\frac{0.876 \times 0.124}{30}}$$

$$\Rightarrow \quad 0.876 \pm 1.96\sqrt{0.0036144}$$

$$\Rightarrow \quad 0.876 \pm 1.96 \cdot 0.0601$$

- $$\Rightarrow \quad 0.876 \pm 0.117$$

- ® (0.759,0.993)

### C. *Adjusted Success Rate with Wind Influence*

The sample weather conditions were plugged into the simulated testbed, yielding an 87.6% accuracy in pollen dispersal when 1/4 teaspoon is collected by the suction fan, which is a typical amount. This results in a 5% decrease in the success rate due to wind influence. However, since the cone range and conditions are known, farmers can mitigate these effects. Consequently, the final success rate of the overall device is adjusted to 74.3%.

### D. *Summary*

The new success rates considering the wind influence, with a 95% confidence interval, range from approximately 75.9% to 99.3%. This adjustment shows how weather conditions, specifically wind speed and angle, can impact the effectiveness of pollination. By understanding these effects and using trajectory analysis, farmers can better predict and

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manage pollination success under varying weather conditions. The final success rate of the overall device is 74.3%.

# XIII. DISCUSSION

## A. *Summary of Performance Metrics*

Table VI shows percentages that reveal several key insights about the performance and potential of the artificial pollination system developed in this study.

Table 6: Summary of Performance Metrics

| Description | Percentage |
|---|---|
| Initial accuracy rate of pollen collection and dispersal | 61% |
| Accuracy of pollen dispersal after upgrading blowing fan to 9V | 93.7% |
| Overall device accuracy under optimal (no wind) conditions after optimal positioning based on mathematical modeling and trajectory analysis | 79% |
| Device accuracy under varying wind conditions based on mathematical modeling and trajectory analysis | 74.3% |
| Sample Calculation - Accuracy under typical Los Angeles weather conditions | 87.6% |

## B. *Summary of Findings*

The findings from both rounds of testing provide a comprehensive understanding of the artificial pollination system's capabilities and limitations. Key findings include:

- **Overall Performance:** The first round of testing showed that the device could successfully collect and disperse pollen simulant (turmeric) with an overall accuracy rate of 61%. This indicates that the hardware components, including the suction and blowing fans, function effectively in controlled environments.
- **Impact of Hardware Optimization:** Enhancing the blowing fan from 5V to 9V significantly increased the dispersal accuracy to 93.7%. This substantial improvement demonstrates the critical role of hardware optimization in enhancing the system's effectiveness, raising the overall device accuracy to 79%.
- **Pollination Pattern:** The second phase of testing highlighted a cone-shaped distribution pattern of mustard seeds, influenced by wind, the blowing fan, and drone propellers. Testing in a controlled environment simulating typical field conditions confirmed the effectiveness of the optimized hardware configuration.
- **Accuracy and Precision:** The device maintained a base accuracy of 79%. However, performance slightly declined by about 5% under varying wind conditions, resulting in a final success rate of 74.3%. This demonstrates the device's robustness and adaptability to real world agricultural environments.
- **Trajectory and Distribution Insights:** Particle motion analysis revealed predictable trajectories influenced by gravity and initial velocity. Under typical Los Angeles weather conditions (10 mph wind speed, 30-degree wind angle), the adjusted accuracy was 87.6%. This indicates the device's reliable performance in specific environmental settings.
- **Statistical Confidence:** A 95% confidence interval for pollen dispersion success rates was calculated, ensuring the reliability of results. The interval ranged from 93.7% to 100% for mustard seeds within the cone's range, supporting the validity of the findings and the potential for consistent performance in practical applications.

The proposed artificial pollination system stands out due to its unique capability to autonomously collect, store, and disperse pollen without any human intervention. This represents a significant advancement over traditional manual pollination methods and other existing robotic solutions, which often require some level of human oversight. The integration of suction and blowing fans enables our device to achieve a higher accuracy rate of 79% under optimal conditions, compared to the 60-70% accuracy observed in other automated pollination technologies. This fully autonomous operation not only reduces labor costs but also enhances efficiency and precision in pollination processes, addressing a critical gap in the current agricultural technology landscape.

Overall, the findings confirm that the artificial pollination system is a viable solution to address the challenges posed by the decline of natural pollinators, climate change-induced crop degradation, increasing use of pesticides, and global food security. The system's innovative approach and robust performance in controlled tests demonstrate its potential for real-world agricultural applications.

Based on the observed findings, we can place the machine at different angles and locations, allowing farmers and other users to substitute various parameters and analyze the trajectory of the pollen particles by plugging these values into mathematical equations. By doing so, we can optimize pollination success and increase crop yield. To achieve this, various options can be considered:

- **Adjustable Gimbal System:** An adjustable gimbal can be used to precisely control the angle and direction of the machine dispersing pollen. This allows for finetuning the trajectory of pollen particles.
- **Rotating Platform:** A rotating platform can help change the location of the machine, enabling dispersal from different positions within the field.
- **Multi-Angle Dispersal System:** This system uses multiple fixed positions at various angles around the field, allowing users to switch between these positions to analyze different trajectories.

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- **Manual Adjustment Mechanism:** A simpler, manual adjustment mechanism that allows for changes in both angle and location by manually repositioning the machine.
- **Automated Sensor-Based System:** An automated system that uses sensors to analyze wind speed, direction, and other environmental factors to adjust the angle and position of the pollen machine automatically.
- **Mounted on Drones or Robots:** The machine can be mounted on drones or robots, allowing for flexible movement and precise control over the dispersal process. This mobility ensures that the machine can cover larger areas and adapt to different field conditions.

These setups are illustrated in Fig. 12 to help visualize how each method works, ensuring that the best configuration is chosen to maximize pollination efficiency.

### C. Strengths and Limitations

➢ *The Artificial Pollination System Developed in this Study Showcases Several Notable Strengths.*

- **Innovation:** The system introduces a novel integration of suction and blowing fans, enabling fully autonomous pollen collection and dispersal in a single flight cycle. This represents a significant advancement over traditional methods, which often require manual intervention and lack the precision of our approach.
- **Precision and Control:** The device provides precise control over the pollination process, which is particularly beneficial for high-value crops. This precision ensures optimal pollen distribution, enhancing the likelihood of successful pollination and increasing crop yields.
- **Data-Driven Optimization:** The detailed analysis of pollen dispersion patterns using motion tracking software provided valuable insights that inform system optimization. Data collected during testing allows for further refinements, ensuring the device continuously improves in accuracy and efficiency.
- **Broad Applications:** The device's baseline efficiency of 61% in controlled environments indicates reliable hardware performance. Its broad potential applications, including large-scale crop pollination, urban farming, and precision agriculture, highlight its significance in addressing global food security challenges.

Despite these strengths, the study has some limitations. Testing was conducted in controlled environments, which may not fully replicate the complexities of actual agricultural fields. The system's accuracy relies on precise positioning, which could be challenging in dynamic field conditions. Additionally, while the study used turmeric and mustard seeds as pollen simulants, testing with actual pollen from various crops is necessary for comprehensive validation. Furthermore, the impact of extreme weather conditions was not evaluated, which could affect the system's performance in real world applications.

### D. Future Research Directions

Future research should focus on validating the artificial pollination system in diverse real-world agricultural environments, testing with actual pollen from various crops to ensure comprehensive applicability. Integrating advanced sensors and AI algorithms to optimize the device's positioning and movement in dynamic field conditions can enhance accuracy and efficiency. Additionally, investigating the system's performance under extreme weather conditions and examining its economic feasibility and scalability will be vital for widespread adoption. By addressing these areas, future research can enhance the system's effectiveness, resilience, and practicality in real-world agricultural applications.

### E. Conclusion

The artificial pollination device shows great promise for large-scale agricultural applications, especially in controlled environments where conditions can be managed to optimize efficiency. The ability to enhance pollination accuracy through hardware improvements and to account for environmental influences highlights the device's potential to address critical challenges in modern agriculture, such as the decline of natural pollinators and the need for sustainable crop production methods.

### F. Future Applications

The artificial pollination system developed in this study holds significant potential for a variety of future applications. In large-scale crop pollination, the system can enhance yields and reduce reliance on dwindling natural pollinator populations. Urban farming systems can benefit from this technology by ensuring effective pollination in controlled environments, leading to increased productivity in city-based agriculture. The system's adaptability to diverse environmental conditions makes it suitable for precision agriculture in remote or harsh environments where traditional pollination methods are impractical. Additionally, integrating this system with other smart farming technologies could create comprehensive solutions for sustainable and efficient agricultural practices, contributing to global food security and resilience against climate change impacts.

## AUTHOR CONTRIBUTION

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation

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