Final Report

Development of non-biological pollination options for protected cropping using emerging technologies

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Public summary

Australia's protected growing spaces for fruits and vegetable crops are on the rise due to its highly valued produce and market. However, the decline in natural pollinators and inability to import bumblebees render pollination to be left by chance or require manual methods. Consequently, manual pollination is becoming unviable due to its high costs, inefficiency, and intractability. Polybee aims to solve this problem by introducing autonomous pollination using drones.

Polybee collaborated with Western Sydney University (WSU) to conduct a strawberry pollination trial in a controlled glasshouse at Hawkesbury campus. The experiment aimed to compare four treatments: no pollination (Control), hand pollination, blowfly pollination, and drone-based aerodynamic controlled pollination (ACP).

The drone pollination system was configured to map the glasshouse, set flight boundaries, establish a ground control station, and schedule daily pollination. The experiment occurred twice in August and September 2022, using separate glasshouse chambers as replicates.

WSU's research scientist aided in data collection, analysis, and reporting across treatments and replicates. The first experiment showed drone pollination outperforming no pollination, while blowfly and hand pollination had the best results with the heaviest fruits. The second drone experiment faced challenges due to a botrytis fungal infection causing higher fruit abortion rates, limiting the control fruit's development to under 50%, insufficient for statistical analysis.

The diminished drone pollination yields are hypothesized to be linked to the specific strawberry variety employed in the study, namely Lowanna, characterized as a non-commercial variety. It produces fewer, larger berries due to a smaller flush, leading to less pollen dispersal onto central stigmas.

Trials were also run for tomato pollination in glasshouses. In collaboration with Perfection Fresh, Polybee has conducted pollination trials on snacking and truss tomatoes in Perfection Fresh's glasshouse in Two Well, South Australia. The trial was conducted over one row each for snacking variety (Tastery) and truss variety (Endeavour) between October 2022 to August 2023. Insights into the practical applicability of the two pollination techniques under examination were drawn from the experiments. In the case of endeavor variety, the fruits produced through ACP consistently yield equal or better results when compared to those obtained through manual pollination. This observation suggests that ACP has the potential to facilitate self-pollination in both, endeavor and tastery varieties. The downwash generated by the drones' propellers proves to be sufficiently effective in inducing flower vibrations, thus leading to the dislodging of pollen from anthers onto the stigmas.

Keywords

Aerodynamically Controlled Pollination (ACP)

Manual Pollination

Tastery Variety

Endeavor Variety

Autonomous pollination

Introduction

Polybee, a Singapore-based company supported by Hort Innovation's Pollination fund, has introduced an innovative approach termed Aerodynamically Controlled Pollination (ACP). This method aims to facilitate the pollination of self-pollinating crops through the precise manipulation of turbulent airflow from the drone's downwash to facilitate pollen dispersal of self-fertile crops. By harnessing this technology, the potential exists to significantly enhance both productivity and profitability within the protected cropping industry. Notably, the Australian protected cropping sector commands an impressive annual production value of 1,232 billion AUD. In a collaboration with Western Sydney University (Hawkesbury) and Perfection Fresh Pty Ltd, Polybee has conducted pollination trials on strawberry and two distinct tomato crop varieties. The outcomes of this trial were compared against the conventional manual pollination involving insect and hand pollination for strawberries and, blowers or whacking sticks for tomato. The results obtained offer proof of concept for the viability and effectiveness of ACP on the two crops.

Methodology – Strawberry Pollination

This section reports on the methodology of the pollination trial conducted at Western Sydney University (WSU) Hawkesbury Campus between 27th July – 7th September 2022. In this experiment, we conducted trials involving five distinct treatment groups: the Control group, ACP group, bagged group, hand-pollinated group, and fly-pollinated group. The focus of our experimentation at Western Sydney University (WSU) was the Lowanna strawberry variety. These strawberries were cultivated across six rows within a climate-controlled glasshouse chamber measuring 13.5 meters by 8.0 meters. The experiment was conducted concurrently in two distinct glasshouse chambers at WSU, with each chamber serving as an experimental replicate. For a visual representation of the treatment timeline, please refer to the accompanying figure.

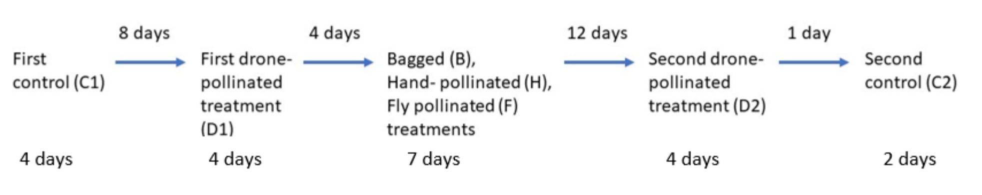


Figure 1*: Timeline of experiment. Flowers were tagged for control between 27th – 30th July 2022 and 6th – 7th September 2022. Bagged, hand- and fly-pollination were conducted concurrently between 15th – 21st August, ACP experiments conducted by Polybee fall between 8th – 11th August 2022 and 2nd to 5th September 2022.*

Control Group: In the control group, flowers were left unpollinated and uncovered, serving as a baseline for comparison. Data were collected at two different points in the experiment: first, 8 to 11 days prior to the initial Aerodynamically Controlled Pollination (ACP) treatment, and second, after the conclusion of the second ACP treatment.

Aerodynamically Controlled Pollination (ACP): ACP was carried out twice (D1 and D2) on specified dates (Figure 1). A drone was employed to pollinate the strawberry plants by maintaining a consistent speed for a predetermined duration. The drone traversed each row twice.

Bagged Group: This group served a dual purpose: as a control for both hand- and fly-pollinated groups and as a comparison to control groups C1 and C2 to verify the absence of bagging effects.

Hand-Pollination: Manual pollen transfer from one flower to another occurred on the same day of flowering, utilizing a paintbrush.

Fly-Pollination: A total of 260 blowflies were released into the glasshouse to freely interact with open strawberry flowers. These treatments were conducted concurrently, with hand-pollinated flowers subsequently being covered to prevent any interference by flies.

Harvesting: Strawberries were harvested once they reached 95% ripeness on one side (Figure 2), as indicated by specific visual criteria (Figure 3). The team recorded harvest dates, fruit weights, and categorized the strawberries into classes A to E based on the extent of underdeveloped flesh.

Figure 2: *Mature fruit that is ready to harvest*

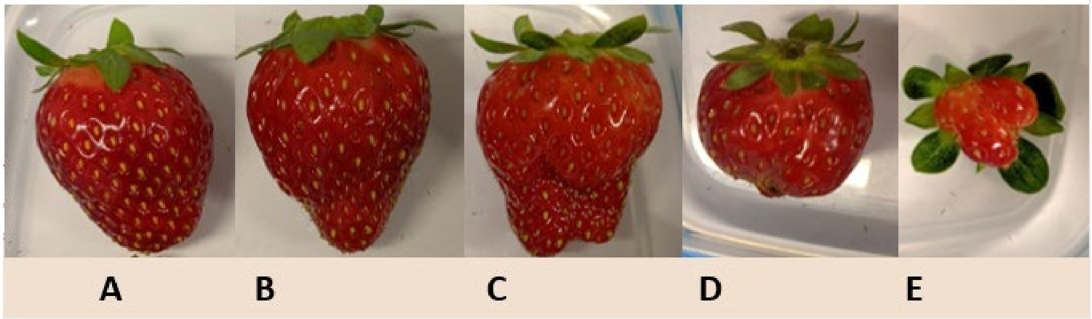


Figure 3**:** Strawberry grading system. Class A is the most well-developed fruit with uniform achene swelling and Class E is the most underdeveloped fruit.

Results and Discussion – Strawberry Pollination

The weight and class (quality) of each strawberry were collected at harvest. The raw data was grouped into their respective experimental groups and analyzed to compare the results between the different treatment groups and replicates of the two glasshouse chambers. Fruit quality and weight based on the number of ACP treatments and development time were evaluated in the following sections.

<u>Fruit abortion and data selection</u>

Data collected from the ACP treatment and control groups between September 2nd and 7th was excluded from the analysis. This decision was made because fruits from flowers that opened in September exhibited a notably higher abortion rate compared to the earlier ACP and control groups in August. This increase in abortion rates was attributed to a botrytis fungal infection that occurred in late September. Consequently, the number of fully developed control fruits dropped to under 50%, rendering the sample sizes insufficient for inclusion in statistical analyses (Appendix A - Table 1, Figure 4).

<u>Effect of number of treatments on ACP efficacy</u>

During the initial experiment conducted between August 8th and 11th, 2022, Aerodynamically Controlled Pollination (ACP) treatment was administered over four days, with daily samples comprising 10-15 flowers in each glasshouse chamber. The Kruskal-Wallis test was employed to assess statistically significant differences among the treatment groups regarding fruit weight and class. The results (Kruskal-Wallis chi-squared = 20.602, df = 3, p-value = 0.00013) indicate a significant variance in fruit weight between flowers pollinated for 3-4 days (days 1 and 2) and those pollinated for 1-2 days (days 3 and 4). However, within the two groups (flowers pollinated for 3-4 days vs. flowers pollinated for 1-2 days), no significant difference in fruit weight was observed, suggesting that a higher number of ACP treatments per flower leads to increased fruit weight.

Based on these findings, the data from flowers that opened on days 1 and 2 were specifically compared with fly pollination for efficacy. Notably, differing results were obtained in the two chambers due to variations in the glasshouse's orientation to the sun, influencing temperature and humidity fluctuations. Additionally, the prevalence of fungal infections in each chamber potentially impacted strawberry quality. Subsequently, the data of ACP-treated flowers that commenced on days 1 and 2 were combined as ACP-treated flowers (D1) for subsequent analyses to ensure a consistent sample size across treatment groups (Figure 6).

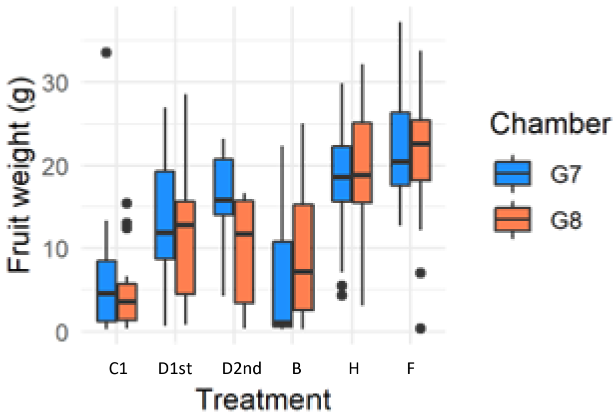


Figure 4: *Weight of strawberries from control (C1), ACP treated day 1 (D1st), ACP treated day 2 (D2nd), bagged (B), hand-pollinated (H), and fly-pollinated (F) treatments.*

<u>Fruit quality</u>

Fruit quality, determined by shape and uniformity at harvest, was categorized into five classes (Class A to Class E). Fly-pollinated flowers resulted in the development of all fruits, while control flowers without pollination (C1) and bagged flowers experienced over a 25% abortion rate. Hand-pollinated flowers exhibited somewhat lower quality, with A and B grade strawberries comprising 50% of the group. In contrast, most ACP-treated fruits fell within the C to E grade range, as depicted in the consolidated results (Figure 5).

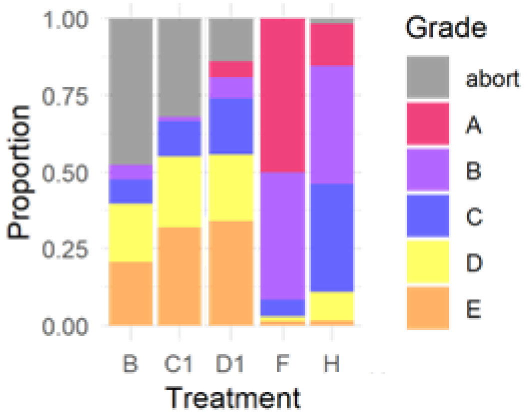


Figure 5: *The stacked bar plot that represents the proportion of fruit quality in each treatment group. This is the combined data from two chambers.*

<u>Fruit weight</u>

The weight of fruits from the first control (C1), the first ACP treatment (D1), bagged (B), hand-pollinated (H), and fly-pollinated (F) treatments are significantly different (Kruskal-Wallis test, Chamber G7: $\chi2= 57.461$, df = 4, $p<0.05$; Chamber G8: $\chi2 = 72.937$, df = 4, $p<0.05$). When the post hoc test was performed, the fly- and hand-pollinated fruits were significantly heavier than the fruits from bagged and control treatments despite no weight difference between hand- and fly-pollinated treatments (Figure 6).

Furthermore, there were no significant differences between control and bagged treatments. In addition, the results indicated that ACP treated fruits of chamber 7 are significantly heavier than control and bagged fruits (Figure 7). However, there was no significant difference in ACP treated and bagged flowers in chamber 8 (Figure 7). It could be due to the different extent of fungal infection in each glasshouse chamber.

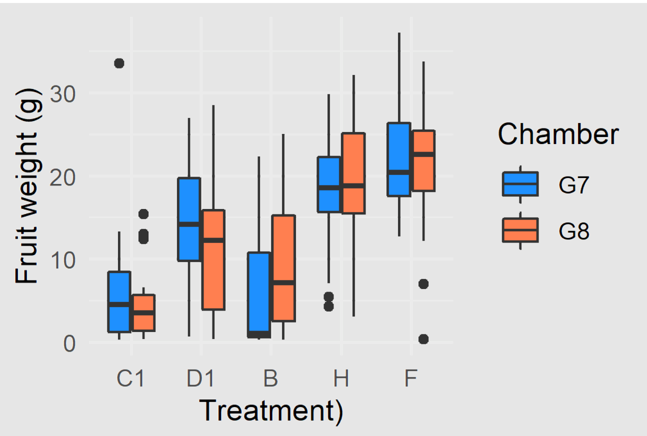


Figure 6: *Weight of strawberries from control (C1), ACP treatment day 1 and 2 (D1), bagged (B), hand-pollinated (H), and fly-pollinated (F) treatments.*

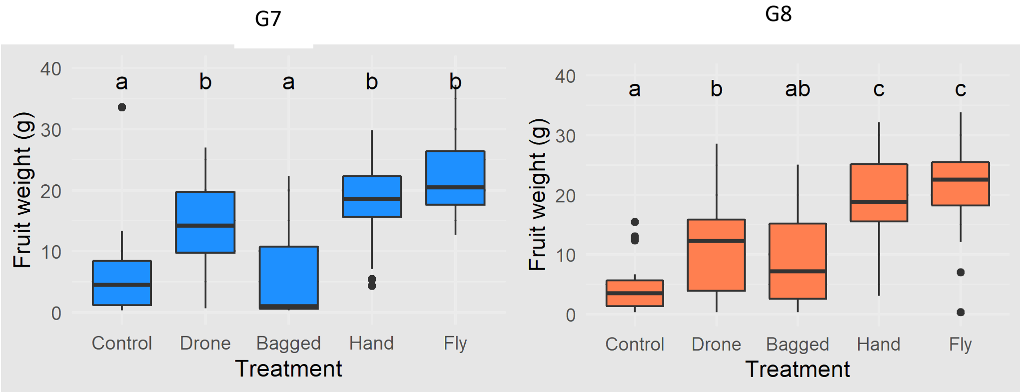


Figure 7: *The boxplots illustrate the weights of strawberries as in Figure 6 with a multiple comparison test. The left (blue) plot represents data from chamber G7, and the right (orange) is from chamber G8. The different letters indicate a significant difference at p≤0.05 in each chamber.*

<u>Development time</u>

The time that the flowers take to develop into fruit exhibits a similar trend to that of the fruit weight. The treatments had a significant impact on fruit development time (Kruskal-Wallis test, Chamber G7: $\chi 2= 57.794$, df = 4, $p<0.05$; Chamber G8: $\chi 2 = 67.029$, df = 4, $p<0.05$). When examining this time difference using Dunn's multiple comparison test, the fly- and hand-pollinated flowers took the least time to develop into mature fruits than the rest of the treatments. There was no significant difference in fruit development time between the control and bagged treatment, but the ACP treated fruits had statistically shorter development time than the control flowers in chamber 7 (Figure 8). There was also no difference in development time between hand-pollinated and fly-pollinated treatment. This result applies to both strawberry chambers.

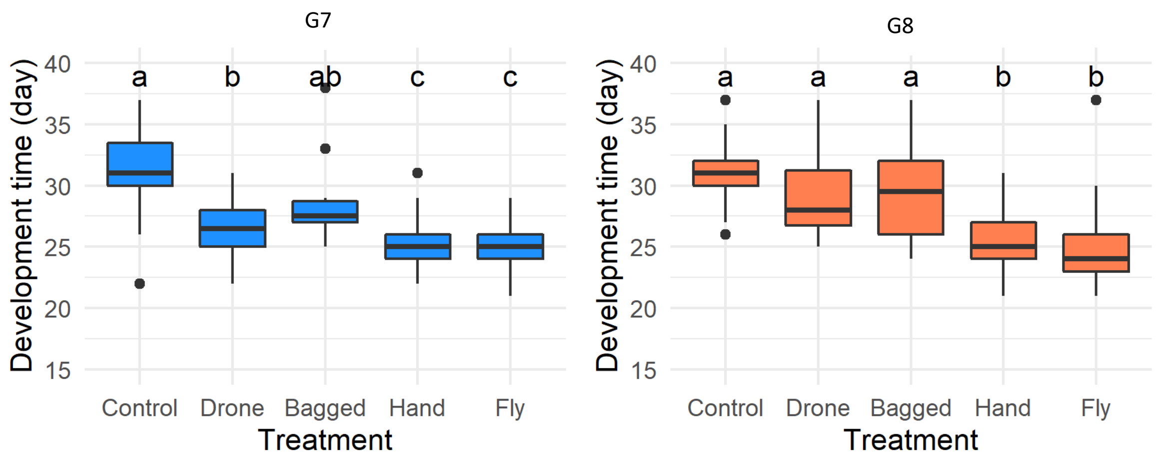


Figure 8: *The boxplots represent the length of time that strawberry flowers in chambers 7 (left) and 8 (right) took to develop into mature fruits with Duun's multiple comparison test. Different letters indicate a significant difference at p≤0.05 in each chamber.*

Methodology – Tomato Pollination

This section summarizes the pollination trial and operations conducted at Perfection Fresh's facility at Two Wells, South Australia between October 2022 – August 2023.

Polybee has leveraged its technology by integrating off-the-shelf drones (DJI Air2s) with the follow physical specifications: Diagonal Size: 302mm; Weight: 595g. The software involves the use of a vision-based system to detect April Tags (similar to a QR code) for drone localization in an indoor system. This allows the flights to be fully autonomous. In addition, Polybee has developed its proprietary Android-based mobile application, known as Navibee. Navibee serves as a tool for monitoring and controlling autonomous drone operations, directly from the convenience of a mobile phone application.

The experiment conducted at Perfection Fresh's glasshouse involved two distinct treatment groups: the Manual-pollinated group and the ACP (drone-pollination) group. The experimental scope and methodology are presented in the tables below.

Experiment 1

Variety	Tastery (Snacking)
Location	Glasshouse 3B
Length of row	100 m
Treatment: ACP	Row No. 326
Treatment: Manual Pollination	Remaining 57 rows
Total rows under trial	58
Plant density/row	800 plants

Table 1: Experimental scope for Tastery, a snacking variety. The experiment was conducted in Glasshouse 3B with a total of 58 rows under the trial. One row (Row 326) was allocated for ACP and the remaining rows were pollinated manually based on Perfection Fresh's standard operating procedure for pollination.

Experiment 2

Variety	Endeavour (TOV)
Location	Glasshouse 2A
Length of row	100 m
Treatment: ACP	Row No. 155
Treatment: Manual Pollination	Remaining 61 rows
Total rows under trial	62
Plant density/row	600 plants

Table 2: Experimental scope for Endeavor, a truss on vine (TOV) variety. The experiment was conducted in Glasshouse 2A with a total of 62 rows under the trial. One row (Row 326) was allocated for ACP and the remaining rows were pollinated manually based Perfection Fresh's standard operating procedure for pollination.

For each tomato variety, a dedicated row was designated for Aerodynamically Controlled Pollination (ACP) using drones (Row 155 for Endeavor and Row 326 for Tastery). The pollination process involved the drones hovering over the tomato plants at a fixed speed of 0.5 meters per second, resulting in a total duration of 2 seconds to cover a 1-meter plot. During this operation, the drone effectively pollinates one side of the row as it enters and proceeds to pollinate the other side during its return journey (Figure 2).

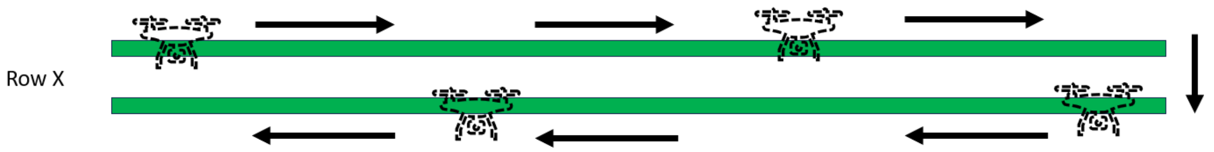


Figure 1: The two green solid lines make up one row of plants with two sides. The drone will enter from one side of the row when ACP operations commence and return from the other side to cover pollination for the entire row.

The entire pollination path is preplanned, ensuring efficient coverage of the designated area. The drone initiates its flight autonomously, taking off from the ground and following the preconfigured route until it reaches its endpoint (Figure 2). This entire process is initiated and overseen by the user, who sends the operation command through the Navibee application.

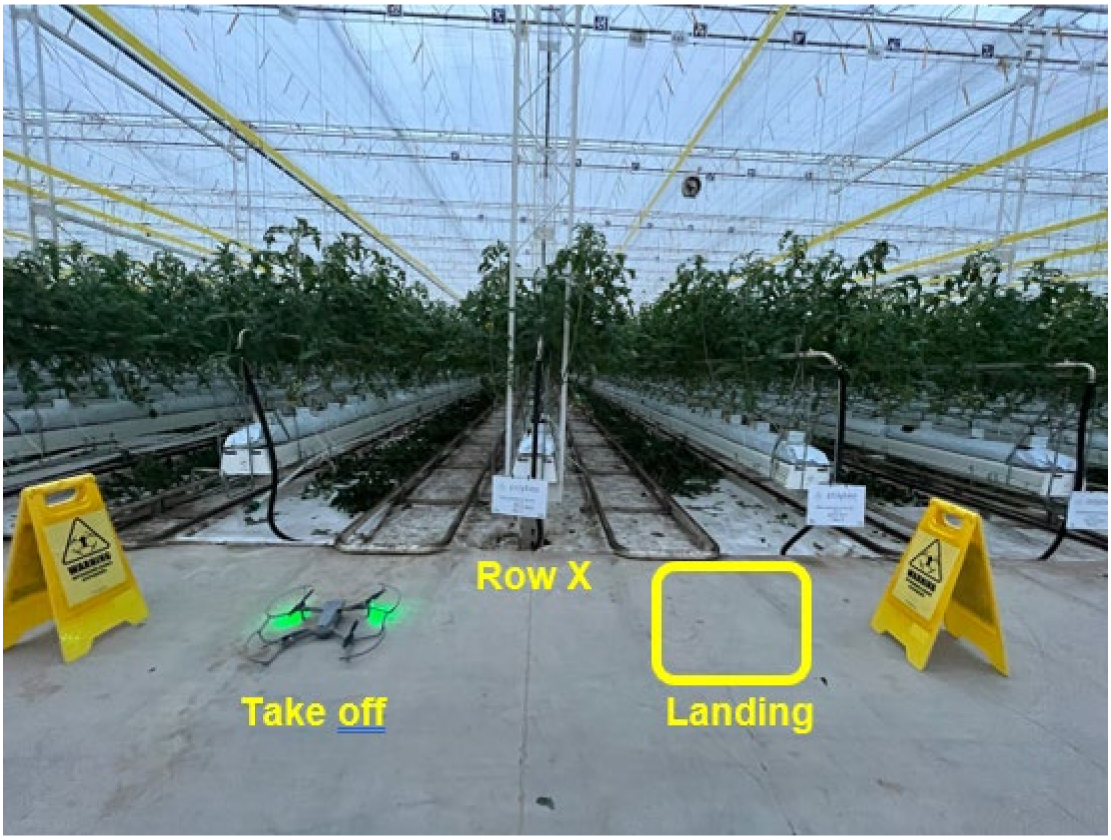


Figure 2: Using Row X as an example, the drone takes off from its position as shown and pollinates the left side or Row X while flying into the row and pollinates the right side of Row X while exiting the row before landing in the area demarcated by the yellow box.

The remaining rows allocated for each of the trialed tomato varieties were subjected to Perfection Fresh's conventional method of manual pollination. In this method, a manual laborer employed a trolley scissor lift to access the rows. Using whacking sticks, the laborer performed a controlled impact on the upper section of the trellising cables while moving along the row. This deliberate action induced vibrations in the plants, facilitating the pollination of the flowers.

The harvested fruits were collected after six to eight weeks when the fruits are ripe, and the yield results were collected and tabulated.

Results and Discussion – Tomato Pollination

Data was collected at harvest, specifically focusing on the total yield from both the rows subjected to Aerodynamically Controlled Pollination (ACP) and those managed through manual pollination (MP). This comprehensive dataset was then organized and presented in Table 3 and 4 for both the trialed varieties. The collected data offers a comprehensive analysis of the crop's yield performance, drawing a comparison between ACP and manual pollination (MP) methods over a fourteen-week period. The central focus revolves around assessing the relative effectiveness of ACP against the average yield achieved through manual pollination methods.

Evaluating the percentage improvement figures, a fluctuating pattern emerges, revealing the extent to which ACP performed better or slightly behind the average yield obtained through manual pollination. Weeks with negative percentage improvements indicate instances when ACP yielded lower results compared to manual pollination's average. Conversely, positive percentages highlight weeks when ACP proved superior to the average manual pollination yield. This data collection approach allows for a more direct comparison of the two methods' performances.

<u>Endeavor (TOV) Variety</u>

Table 3: Raw data of the harvest yield collected weekly for Endeavor variety.

Week	Row 155 Yield ACP (kg)	Average Yield for MP/ Row (kg)	% Improvement
1	286	296	-3%
2	389	376	3%
3	347	346	0%
4	373	360	4%
5	327	324	1%
6	330	326	1%
7	279	285	-2%
8	273	283	-4%
9	349	330	6%
10	380	373	2%
11	378	370	2%
12	392	387	1%
13	420	409	3%
14	632	624	1%

From the analysis, 14 weeks of data were collected to compare yield improvements between ACP and manual pollination. Out of the 14 weeks studied, 11 weeks displayed yield improvements when using ACP (highlighted in green). However, it is important to note that three weeks had slightly lower yields compared to manual pollination (highlighted in red).

Upon closer inspection of the broader trend, it is observed that fluctuations in both negative and positive improvements remained consistent, falling within a 5% range. This consistency suggests that ACP and manual pollination yield similar results throughout the experiment.

Further examination of the data revealed an overall 1.12% improvement in average yield when comparing ACP to manual pollination over the 14-week period. This suggests that ACP is at least as effective as manual pollination with whacking sticks. However, natural variations across rows may have contributed to these improvements.

Tastery (Snacking) Variety

Table 3: Raw data of the harvest yield collected weekly for Tastery Variety.

Week	Row 326 Yield ACP (kg)	Average Yield for MP / Row (kg)	% Improvement
1	175	165	6%
2	116	132	-12%
3	194	192	1%
4	147	187	-21%
5	186	183	2%
6	204	182	12%
7	190	186	2%
8	171	181	-6%
9	182	186	-2%
10	172	171	1%
11	183	202	-9%
12	192	174	10%
13	178	179	-1%
14	125	154	-19%

From the analysis, 14 weeks of data were collected to compare yield improvements between ACP and manual pollination. During this period, seven weeks exhibited increased yields, while the remaining seven exhibited minimally lower yields.

Specific anomalies in the findings were noted during weeks 2, 4, and 14, where there were substantial differences between ACP and manual pollination, resulting in over a 10% reduction in yields for the ACP group.

When evaluating the entire 14-week period, an average yield difference of -2.58% between ACP and manual pollination was observed. When consulted with the growers, it was shared that a difference of less than 5% in yield from one row to another can be attributed to natural variance in plant health, strength, micro-climate, and crop management. This provides a summary of the overall yield outcomes between the two pollination methods during the extended experimental period. These results provide concrete evidence for the effectiveness of both pollination approaches.

In the case of both varieties, ACP consistently produced close to equal results to manual pollination across the 14 weeks, indicating the potential for self-pollination using drones. The downwash generated by the drones' propellers effectively induced flower vibrations and pollen transfer.

Possible factors that could affect ACP performance

While ACP has demonstrated its potential as an innovative and effective pollination method in agricultural contexts, it is important to acknowledge that its success may not be universal across all crop varieties and conditions. The nuances of plant biology, environmental factors and specific crop characteristics can significantly impact the suitability of ACP. This discussion aims to clarify these details for future adjustments in experiments.

a. Plant physiology & Crop characteristics

The experiments were conducted on two varieties with different crop characteristics. Tastery variety, designed for snacking purposes, typically exhibits trusses that bear a considerable load of 10 to 12 fruits per cluster. In contrast, the Endeavor variety carries a smaller load of up to 5 larger fruits at most per truss. Grower insights have revealed a crucial aspect of tastery variety's floral behavior: its flowers tend to open gradually over a span of two to three weeks. Consequently, it is not uncommon for new truss to emerge before the previous one has completed the pollination process, due to the staggered opening of flowers. Nevertheless, the pollination efficacy observed in Tastery was up to grower’s standards.

b. Relative Humidity

Humidity can play a significant role in pollination for tomato plants, as it affects the efficiency of pollen transfer between the male and female reproductive structures of the flowers. At high relative humidities (RH) above 80%, pollen grains on the anthers start to stick together, reducing their dispersal and lowering pollination rates. This stickiness goes down as RH levels drop. However, at RH levels below 60%, the stigma of the flower can also dry out, lowering the rate of pollination (Langenhoven, P. 2018). The optimal RH for tomato pollination falls between 60 – 70% (Shamshiri et al., 2018b).

With the possible natural fluctuation of relative humidity throughout the day, it introduces the possibility of pollination during a period not suited for pollination. Pollination operations take place during daytime between 0900 h – 1400 h. The drone operations were done once daily during this window. However, since micro climatic data was not considered for this trial, there is a chance that ACP operations may have been conducted during a period where it is undesirable for pollination due to unfavorable humidity conditions.

Natural Variations between rows

It is crucial to recognize that, given the scale of the experiment, inherent variations in harvest patterns across different rows may arise due to the diverse microclimatic conditions within the glasshouse. These variations can lead to fluctuations in ripening speeds from week to week. Considering the focused scope of ACP application on just one row, it is prudent to approach the observed percentage improvements, whether positive or negative, with caution and an awareness of these potential natural fluctuations when compared across the other rows.

Growers Demonstration

During the growers' demonstration event held at Flavorite, Siddharth Jadhav, the Founder and CEO of Polybee, introduced the attendees to the service offered by the company. The service automates pollination and yield forecasting in the fresh produce industry using drones and AI.

The team showcased their service, which focuses on automating pollination and yield forecasting with plant stress detection and growth monitoring capabilities in the pipeline. The service is built on three proprietary technological pillars: contactless pollination method (ACP), automation of micro-drones, and an AI pipeline for yield measurement.

During the demonstration, the audience received an overview of the pollination system, consisting of drones, a controller with a smartphone, and a ground station. The system operates with simplicity, requiring just a few steps to activate the drone through the app. The performance of the ACP method, user experience enhancements such as automation and integration with the ground control system (GCS), and the scalability of the solution in terms of the number of drones per hectare, pollination window, and integration with micro-climatic parameters were discussed. The business model for Polybee's service was also presented, highlighting a combination of capital expenditure on drones and ongoing subscription fee for the automation software.

The event concluded with a vote of thanks, acknowledging the collaborative effort of the Australian ecosystem in making Polybee's advancements possible. Special gratitude was extended to Hort Innovation for their capital support and Flavorite for their role as an early adopter.

Overall, the growers' demonstration at Flavorite showcased the innovative technology developed by Polybee, emphasizing its potential to revolutionize the fresh produce industry through automated pollination, yield forecasting, and growth monitoring.

Images from the Growers Demonstration

Business Case

Market Analysis

Market Demand: In Australia, the annual production of self-fertile crops such as tomatoes $584.4m, strawberry $435.0m and capsicum $212.9m are nearly $1,232 billion AUD (as of 2019-20). Protected growing spaces for these crops are on the rise as production can potentially be increased by an order of magnitude and acreage under protected cropping is growing at double digit rates.

The demand for autonomous pollination methods in Australia, particularly for self-fertile crops like tomatoes and strawberries, is experiencing a surge driven by various compelling factors. Self-fertile crops, while not reliant on external pollinators like honeybees, can still benefit significantly from optimized pollination practices to enhance yield and quality. One key driver for the adoption of autonomous pollination methods is the pursuit of higher productivity and consistency in crop output. By ensuring more efficient and precise pollination, farmers can achieve better fruit set, larger yields, and improved fruit quality.

Moreover, the rising labor costs and labor shortages in Australia's agricultural sector have underscored the need for automation in all aspects of farming, including pollination. Autonomous pollination methods offer a practical solution to mitigate these challenges, reducing the dependency on manual labor and ensuring pollination even during peak labor shortages or adverse weather conditions.

Furthermore, consumers are increasingly valuing sustainably produced and pesticide-free fruits and vegetables, including tomatoes and strawberries. Autonomous pollination aligns with these environmental and health-conscious consumer trends by reducing the reliance on chemical pesticides and promoting sustainable farming practices.

In conclusion, the demand for autonomous pollination methods for self-fertile crops like tomatoes and strawberries in Australia is on the rise due to the potential for increased crop yields, cost-efficiency, labor savings, and alignment with eco-friendly farming practices. This growing market presents significant opportunities for innovation and investment in autonomous pollination technologies tailored to the specific needs of these crops.

Benefit Analysis

The transition to autonomous drone pollination methods for self-fertile crops, such as strawberries and tomatoes, presents a range of quantifiable and qualitative benefits over a specific time frame.

1. Quantifiable Benefits:
    a. Increased Crop Yield: Autonomous drone pollination can lead to potential increase in crop yield due to precise and consistent pollination.
    b. Cost Savings: By reducing the reliance on manual labor for pollination, autonomous drones can result in substantial cost savings over time. Labor costs, especially during peak demand, can be a significant expense in agriculture. Drones can operate consistently and efficiently, eliminating labor-related expenses.
    c. Reduced Disease Pressure: The use of autonomous drones reduces the occurrence of workers entering the rows as often. This reduction in plant human interaction may reduce the chances of spreading diseases and viruses from plant to plant.

2. Qualitative Benefits:
    a. Consistency and Quality: Autonomous drones ensure consistent and thorough pollination regardless of the weather conditions, leading to higher fruit quality and uniformity.
    b. Reduced Reliance on External Factors: Traditional pollination methods, such as relying on honeybees, are subject to weather conditions. Autonomous drones are not impacted by such external factors, providing a more reliable and predictable pollination process.
    c. Sustainability: Adopting autonomous pollination methods aligns with sustainable farming practices and eco-conscious consumer trends. It enhances a farm's environmental stewardship, contributing to a positive brand image and potentially higher prices for sustainably produced crops.

3. Time Frame

The time frame for realizing these benefits depends on several factors, including the scale of adoption, the technology's maturity, and the specific crop in question. Generally:

- Short Term (1-2 Years): Immediate cost savings from reduced labor can be expected within the first year of implementation.
- Medium Term (2-5 Years): Yield improvements and enhanced crop quality become more pronounced as the technology is refined and integrated into existing farming practices.
- Long Term (5+ Years): Sustainability benefits, and long-term ROI become increasingly evident as the use of autonomous drone pollination becomes a standard practice in self-fertile crop cultivation.

Transitioning to autonomous drone pollination methods for self-fertile crops like strawberries and tomatoes offers a compelling range of quantifiable and qualitative benefits over a specific time frame. While short-term cost savings are immediate, the full spectrum of advantages, including increased yield, improved quality, and sustainability, becomes more pronounced over the medium to long term, making this transition a strategic investment for agricultural stakeholders.

Cost Analysis

In this section, we conduct a cost analysis to assess the feasibility of autonomous drone pollination compared to traditional manual methods for tomato pollination. The goal is to gain a comprehensive understanding of resource allocation, efficiency, and effectiveness. This analysis will inform our decision-making and provide insights into the financial aspects of choosing between drone and manual pollination, using a one-hectare tomato commercial glasshouse as a unit.

Manual Pollination

This section presents the assumptions and direct cost and inputs into current manual pollination methods. Workforce and man-hours are taken from commercial growers' manpower allocation. Cost and information regarding man hours and labor requirements are feedback from commercial growers and product website.

Assumptions for Manual Pollination	Remarks
Frequency of Pollination	5 times a week, over 52 weeks
Daily Hours of Pollination	2 hours
Number of Manual Workers	4 workers for 1-hectare glasshouse
Glasshouse Characteristics	60 rows in 1-hectare glasshouse
Time to Pollinate 1 Hectare	2 hours
Pollination Tools	Whacking stick and leaf blower
Leaf Blower Cost	$639 (Husqvarna, Model: 525iB)
Battery & Charger Cost	$449 (Battery BLi300) & $279 (QC500 Battery Charger)
Labor Cost	$26 per hour

Cost Category	Description	Units	Total Amount $	Amortization Period	Amortization value (yearly)
Initial investment – CAPEX	Leaf Blower (Husqvarna, Model: 525iB)	4	$2,556.00	5 years	$511.20
	Battery (Bli300)	8	$3,592.00	2 years	$1,796.00
	Battery Charger Cost	8	$2,232.00	5 years	$446.40
Annual Operating Costs – OPEX	Labor costs (8-man hours)	1	$54,080.00	N/A	N/A
	Maintenance and repairs	1	$500.00	N/A	N/A
Total Cost (Yearly)					**$57,333.60**

Drone Pollination

This section presents the assumptions and preliminary cost and inputs into the proposed drone pollination method.

Assumptions for Drone Pollination	Remarks
Frequency of Pollination	5 times a week, over 52 weeks
Glasshouse Characteristics	60 rows in 1-hectare glasshouse
Time to pollinate 1-hectare	2.5 hours
Labour hours daily	1 hour
Overall Preliminary Costs for equipment and labor annually	**~$50,000**

The cost analysis reveals promising preliminary financial benefits associated with adopting drone pollination over manual methods. Currently, the annual cost of drone pollination stands at approximately $50,000. This value is estimated based on the cost of six drones, accessories and the labor required to scale up the technology to 1 hectare considering amortization period of 3 years for the drone and computer technology. This would offer a potential saving of $7,333.60 when compared to the annual cost of manual pollination, which is $57,333.60.

Furthermore, it is important to note that these cost savings are expected to grow in the future. As drone pollination technology matures and becomes more widely adopted, economies of scale are likely to drive down costs even further, making it an increasingly cost-effective and efficient option for agricultural pollination needs.

In summary, the cost analysis comparing manual and drone pollination methods has provided insights into their finances. Manual pollination has lower initial costs but involves significant labor expenses and potential operational issues. In contrast, drone pollination, despite its higher initial investment, saves on labor, offers precision, and ensures long-term sustainability.

The choice between these methods depends on immediate budget constraints, long-term financial viability, and the benefits like higher crop yield and better quality. It's crucial to align the decision with each farm's unique needs, goals, and resources. As technology advances, the financial landscape of pollination methods may change, so it's essential to periodically review and adapt agricultural practices accordingly.

Benefit-Cost Ratio

The benefit-cost ratio (BCR) is a crucial metric for assessing the viability and economic attractiveness of a project. In the context of our comparison between manual and drone pollination methods, the BCR reveals important insights.

For manual pollination, the total yearly cost, as calculated, amounts to $57,333.60, encompassing both capital and operational expenses. In contrast, drone pollination demonstrates a lower total yearly cost of $50,000.00, combining amortized capital costs and operational expenses. This contrast in cost efficiency translates to a BCR that favors drone pollination.

The BCR for drone pollination can be calculated by dividing the benefits (in terms of cost savings) by the costs. Specifically, the benefits in this scenario would be the difference in total yearly costs between the two methods: $57,333.60 (manual) - $50,000.00 (drone) = $7,333.60.

BCR = Benefits / Costs

BCR = $7,333.60 / $50,000.00 ≈ 0.147

A BCR of approximately 0.147 suggests that for every dollar invested in drone pollination, there is approximately half a 15% returned in cost savings when compared to manual pollination.

The significance of this BCR is that drone pollination yields considerable annual savings. Moreover, the efficiency and precision offered by drone technology can contribute to increased crop yield and quality, potentially leading to higher revenue and profitability over time. Therefore, the BCR reinforces the project's viability, indicating that adopting drone pollination methods represents a financially sound decision, with the potential for long-term cost savings and enhanced operational effectiveness.

Return on Investment (ROI)

1. Absolute economic gain

Analyzing the cost comparison between manual and drone pollination methods, one can discern a significant absolute economic gain offered by the latter. While manual pollination entails an annual expenditure totaling $57,333.60, including initial capital outlay and yearly operating costs, the adoption of drone pollination, despite its higher upfront investment, results in a substantially reduced annual cost of $50,000.00. This substantial cost difference equates to an impressive annual saving of approximately $7,333.60 when opting for drone technology. When evaluating the Return on Investment (ROI), this annual saving serves as a pivotal factor, as it can offset the initial investment in drones and associated equipment, further highlighting the economic advantages of drone pollination.

ROI = (Net Annual Saving / Initial Investment) x 100

ROI = ($7,333.60/ $50,000) x 100 ≈ 14.7%

2. Risk Mitigation

In addition to the compelling quantitative aspects of cost savings, it is imperative to delve into the qualitative analysis of drone technology's role in transforming the pollination process.

Autonomous drone pollination eliminates the recurring issues of labor shortages by providing a reliable and automated solution. This technology ensures that pollination can proceed efficiently without dependence on manual labor, mitigating the risk associated with workforce availability. The risk of inconsistencies in manual pollination, which can vary from person to person, is mitigated through autonomous drone technology. The precision and uniformity of pollination provided by drones reduces the variability and improves the overall quality of the pollination process. Growers can pollinate their crops within any suitable windows without relying on manual laborers. Autonomous technology offers the flexibility to schedule pollination at optimal times, including outside operating hours, aligning with the specific needs of the crops and reducing the risk of missing critical pollination opportunities.

Case Summary

The comprehensive analysis presented in this business case highlights the critical considerations surrounding the choice between manual and drone pollination methods in agriculture. By meticulously assessing various factors, including costs, benefits, and return on investment, we have gained valuable insights into the financial implications of each approach.

Our analysis reveals that while manual pollination incurs lower initial capital expenditures, it is burdened by substantial yearly operating costs, primarily driven by labor expenses. On the other hand, drone pollination, despite its higher upfront investment, offers significant yearly savings and operational efficiency. The Benefit-Cost Ratio (BCR) and Return on Investment (ROI) calculations further underscore the financial viability and profitability of adopting drone technology for pollination.

In summary, this business case strongly advocates for the adoption of drone pollination methods in agriculture. While the initial capital investment may seem higher, the substantial yearly cost savings, efficiency gains, and impressive ROI position drone pollination as a financially sound and sustainable choice. Moreover, the qualitative benefits, such as potential increase in crop yield and improved quality, further enhance the attractiveness of this innovative approach.

By embracing drone technology, agricultural operations can not only achieve cost-effective pollination practices but also enhance their overall competitiveness, sustainability, and profitability in a rapidly evolving industry. This business case serves as a strategic blueprint for decision-makers, guiding them toward a future of efficient, precise, and economically viable pollination practices.

Conclusion

In conclusion, our ACP (Aerodynamically Controlled Pollination) experiments on strawberries and tomatoes offer valuable insights on the efficacy of this pollination method. Notably, ACP exhibited its potential by demonstrating increased yields when compared to control groups. This finding is significant because it points to the promise of ACP as a tool for enhancing strawberry production. However, it is essential to recognize that some anomalies were observed during the study, where the effectiveness of ACP seemed to fluctuate. These anomalies underscore the need for further in-depth research to gain a more comprehensive understanding of the method's efficacy across various strawberry varieties and under different environmental conditions.

When the same method is applied to two different tomato varieties, ACP consistently yielded results closely comparable to that of manual pollination. This suggests the viability of using drones for self-pollination due to the effective downwash generated by their propellers, inducing flower vibrations and pollen transfer. This practical application of ACP in tomato pollination introduces new avenues for more sustainable and efficient pollination practices in agriculture.

By conducting further research to fine-tune ACP techniques, accounting for variables such as weather conditions, crop types, and greenhouse settings, we can pave the way for more widespread and consistent use of this innovative approach. Moreover, exploring the long-term impacts of ACP on crop quality and sustainability is essential, ensuring that it aligns with the broader goals of agricultural innovation and crop production optimization.

Outputs

Table 5. Output summary

Output	Description	Detail
Growers Demonstration	Growers' demonstration held at Flavorite on 30th May 2023 for various growers and project managers in Australia.	Collaboration with Protected Cropping Australia and Flavorite to hold a face-to-face group growers visit to demonstrate Polybee's autonomous drone pollination technology and explain the positive impacts of ACP to 30 growers at Flavorite's facility in Warragul, Victoria. Summary provided in previous milestone.
Podcast	The Protected Cropping Podcast - Autonomous Pollination with Siddharth Jadhav Podcast conducted by Sam Turner from PCA	Polybee is a Singapore based startup who have developed an autonomous solution using the latest in drone and computer vision technologies. I'm Sam Turner and welcome to the protected cropping podcast. On this week's episode we are joined by Siddarth Jadhav from Polybee. New technologies and solutions like autonomous pollinators will play an increasingly important role in Australia's protected cropping industry. With Australia's high labour costs and low margins, leaning into new technologies to help reduce cost of production will allow us to compete in diverse markets on the global stage. https://www.audacy.com/podcast/the-protected-cropping-podcast-f728e/episodes/ep-5-autonomous-pollination-with-siddharth-jadhav-5ad5e
Article	Media feature by ABC Landline (Article and Short Documentary), Hort Innovation's internal newsletter and demonstration to Hort Innovation stakeholders on 10th August Article written and published on PCA publication.	1. Buzz without bees for glasshouse pollination - ABC News 2. Sunday 4/9/2022 : ABC iview 3. Hort Innovation | Micro-drones could help solve Australia's glasshouse pollination problem (horticulture.com.au) Polybee: Revolutionizing Pollination with Drones was made available on Protected Cropping's website in the following link. https://protectedcropping.net.au/polybee-revolutionizing-pollination-with-drones/ The article is intended for growers and early adopters of Polybee's technology.

Outcomes

Table 6. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Passing on knowledge and skills to operate drone technology to growers to continue pollination trials.	Training opportunities for workers and skill set improvements provided from shifting to technology providers.	Training provided to users and workers will allow them to shift from manual pollination operations to simple autonomous drone operations in the future. Their man hour time good be better allocated to other resources. Operations and Training Manual will be provided to involved stakeholders and new users in the future. Case study for troubleshooting.	Video of user taking the drone off from the phone application and allowing the operations to run autonomously.
Successful demonstration of using alternative pollination methods for tomato pollination.	Optimizing crop pollination efficiency and identifying alternative crop pollinators.	The Growers' demonstration was held at Flavorite's facility in Warragul where Polybee showcased its autonomous drone pollination technology to 30 growers and managers and explaining to them the future of this new alternative pollination method.	Growers' demonstration summary report.

Monitoring and evaluation

Table 8. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
Are growers/users well versed in operating Polybee's stack and drone technology	Polybee's deployment engineer was deployed to set up technology for the initial weeks and training was provided to users for them to continue the pollination operations in the deployment engineer's absence. Communications line was well kept between deployment engineer and user for day-to-day operations and troubleshooting when required. The technology stack is simple and easy to use based on user feedback received.	Training and technology improvements in the future when operations are on a larger scale. Better computers with higher capabilities will be required and further upgraded. This provides training opportunities for user and relevant stakeholders.
Is the technology safe and user friendly	Polybee has integrated our technology with commercial off-the-shelf drones like DJI, known for their reliability and safety features. This ensures a dependable and secure platform for our operations. We have developed our own application interface, making it intuitive and easy to understand for users of all levels. Additionally, we provide a comprehensive operation manual to guide new users through the process, ensuring a smooth and safe experience.	In addition to the current safety and user-friendly features, we are committed to continuous improvements and exploring further opportunities in this regard. Our dedication to enhancing user experience includes regular updates to our application interface, incorporating user feedback, and staying at the forefront of technological advancements. As we move forward, we aim to not only maintain but elevate the safety and user-friendliness of our technology, providing our users with the best possible experience.
Are there early adopters to the new autonomous drone pollination technology	Besides working with WSU and Perfection Fresh on pollination trials, Polybee has extended its trials to other tomato growers in Victoria and South Australia. The company is now deploying over 40 rows in total at Flavorite and Sundrop Farms.	With trial extensions over different customers and farms, Polybee can gather the different standard operating procedures in different farms and build our database to cater our technology to different types of customers in the future.

Recommendations

The key takeaway from the trial at WSU is that aerodynamically controlled pollination (ACP) using drones shows significant improvement in yield as opposed to not having any pollinators at all. With lower abortion rate and higher quality of those flowers that received a greater number of treatments with ACP, it is evident that there is room for optimizing the method for better performance.

Moving forward, Polybee proposes the following changes to optimize the performance of ACP for strawberry pollination:

1. Hydroponic strawberry cultivation in a production greenhouse/polytunnel hosted by a grower: This allows Polybee to prove the scalability and robustness of the drone technology in actual production facilities where the length of each row could range over a longer distance.
2. Conduct trials on commercially relevant strawberry varieties that are strongly preferred by growers: This allows us to have a better, representative dataset and results for growers. Furthermore, commercial varieties tend to share certain morphological characteristics such as big flushes of flowers and longer anther length. ACP tends to perform better on varieties with such traits compared to the Lowanna variety, which is not commercially relevant.
3. Conduct pollination across the entire crop cycle: In this trial, it was observed that strawberry flowers that were pollinated over more days had a better chance of developing into a better-quality fruit. Flowers that were opened on days 3 and 4 did not get pollinated well as anthers may not have been dehisced at the point of the treatment. Thus, it is critical to ensure each flower receives the maximum number of ACP treatment during the viable pollination period. Hence, it is recommended to measure the performance of pollination across the entire crop cycle for a fair comparison of the efficacy of ACP with other treatments on strawberry.

Considering the project's outcomes at Perfection Fresh, Polybee offers a set of recommendations aimed at optimizing the performance of ACP in tomatoes.

1. Experimental Changes
    - Experiment Variables: Variables such as daily average temperature and humidity or average temperature during the pollination period should be recorded to observe any variance in pollination performance which could be used to draw a hypothesis during periods where pollination performance decreases.
    - Scale or experiment: The experiment could be extended to include more rows in different areas of the glasshouse to draw results and account for different microclimate variances in different areas of the glasshouse.
2. Development and Adoption Activities:
    - Industry Stakeholders: Establish training programs and workshops to educate growers on the proper implementation of ACP technology. Share best practices and provide resources to facilitate its adoption.

In conclusion, the project's results pave the way for practical enhancements in pollination methods. By embracing these recommendations, stakeholders can collectively contribute to the continued growth and sustainability of the industry while harnessing the full potential of Aerodynamically Controlled Pollination (ACP) as a valuable tool in modern agriculture.

Refereed scientific publications

Howard SR, Nisal Ratnayake M, Dyer AG, Garcia JE, Dorin A (2021) Towards precision apiculture: Traditional and technological insect monitoring methods in strawberry and raspberry crop polytunnels tell different pollination stories. PLoS One. 2021 May 14;16(5):e0251572. doi: 10.1371/journal.pone.0251572.

Kelly MA, Zieba AP, Buttemer WA, Hulbert AJ (2013) Effect of Temperature on the Rate of Ageing: An Experimental Study of the Blowfly *Calliphora stygia*. PLOS ONE 8(9): e73781. https://doi.org/10.1371/journal.pone.0073781

Agrology (2019) Cost of Production Analysis: Hightech Glasshouse Production in Australia. https://www.wpca.sydney/assets/Documents/Resources/Cost+of+Production+Analysis+-+Hightech+Glasshouse+Production+in+Australia_March+2020_LR.pdf

Langenhoven, P. 2018. Hydroponic Tomato Production in soilless culture. Indiana Horticultural Congress, February 13, 2018.

Shamshiri, R.R., Kalantari, F., Ting, K.C., Thorp, K.R., Hameed, I.A., Weltzien, C., Ahmad, D. & Shad, Z.M. 2018b Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture Intl. J. Agr. Biol. Eng. 11 1 22

Intellectual property

No IP to report.

Appendices

Appendix A – Raw Data of Total Fruit Count, Developed and Aborted Fruits and, Abortion Rate

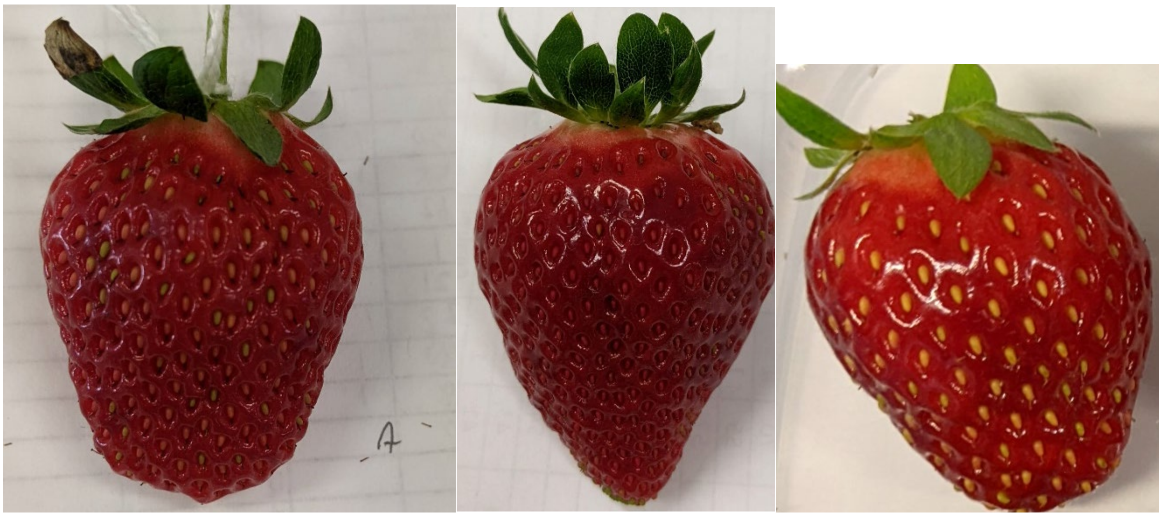
Table 1 Numbers of aborted and developed flowers in different treatment groups. Control flowers, bagged flowers, hand-pollinated flowers, fly-pollinated flowers, and flowers that open on days 1-4 of the first ACP treatment (Drone 1) and the second ACP treatment (Drone 2)

			Drones 1								Drone 2					
	Chamber	**Control 1**	1st day	2nd day	3rd day	4th day	**Total**	**Bagged**	**Hand**	**Fly**	1st day	2nd day	3rd day	4th day	**Total**	**Control 2**
Total	G7	33	18	11	16	12	57	35	29	36	15	11	13	13	52	36
	G8	36	18	14	14	12	58	28	36	36	17	16	16	17	66	26
Developed	G7	23	16	10	12	6	44	15	29	36	8	9	9	8	33	17
	G8	24	18	14	12	11	55	18	35	36	13	13	14	12	52	7
Abort	G7	10	2	1	4	6	13	20	0	0	7	2	4	6	19	19
	G8	12	0	0	2	1	3	10	1	0	4	3	2	5	14	19
Abortion rate	G7	30.3	11.1	9.1	25.0	50.0	22.8	57.1	0.0	0.0	46.7	18.2	30.8	46.2	36.5	52.8
	G8	33.3	0.0	0.0	14.3	8.3	5.2	35.7	2.8	0.0	23.5	18.8	12.5	29.4	21.2	73.1

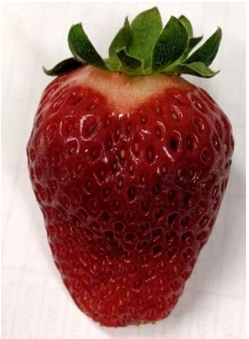
Appendix B – Guide for Grading Strawberries

It is important to keep in mind that some fruits are round, and some are rather flat. They both can be of good grades (A and B) if there are no major underdeveloped parts.

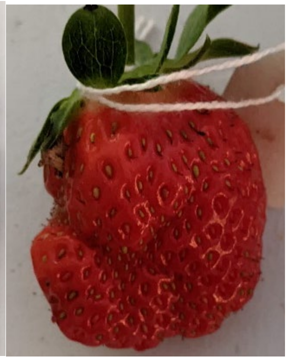
A grade: All part of the fruit is fully developed. There can be <5% achenes that look small or surrounded by underdeveloped flesh.



B grade defined by having less than 20% of the achenes surrounded by underdeveloped flesh. It generally has 1-3 groves.

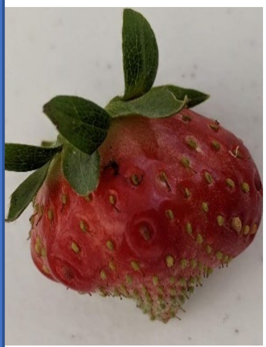


C grade defined by prominent achenes with underdeveloped flesh, but less than 50%





D grade defined by severe underdevelopment. More than 50% of the achenes/seeds are surrounded by underdeveloped flesh.




E grade fruits are distinctively small with only small portions of the receptacle developed into fruit. Sometimes there are only 3-5 developed seeds. You can easily count the number of well-developed achenes by eye.