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Mechanical Pollination of Strawberry Plants

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Abstract—The purpose of this study is to investigate and evaluate multiple mechanical pollination technologies to replace insect pollination for use in indoor farming of strawberries. Four strawberry planters containing ten strawberry plants each with automated watering and lighting systems were used for testing. Data on flower appearance, flower duration, berry growth, berry appearance and berry weight were collected over the course of the five-month study. The data was used to analyze pollination effectiveness, showcased as the efficacy of the pollination process. Two hand-pollinated plants grown in the same conditions as the testing plants were used as a control group to compare the mechanical pollination solutions to the other most common non-insect pollination method. Using the collected data, the different pollination methods were compared. Vibration of plant stock and eddy inducing air circulation were found to be the most effective methods of pollination but were not found to be as cost effective as bee pollination, even for indoor use. Other factors may take precedence in deciding to use mechanical pollination strategies.

Keywords-mechanical pollination; artificial pollination; indoor agriculture; strawberries; vibration; air circulation;

I. INTRODUCTION

Flower pollination is one of the most important cornerstones of agriculture. All fruiting plants require pollination to occur so that consumable flesh can develop. Even when the development of consumable fruit is not a requirement, seeds produced from the pollination process are required for the propagation of plants. In nature and in most outdoor agriculture, the main sources of pollination for fruit-bearing crops are insects and wind, with insect sources consisting primarily of bumblebees and honeybees in commercial settings. Insect pollination is the most important form of pollination for crops used for human consumption [1] [2] [3], a dependence that continues to increase as more and more agriculture shifts to monoculture models and becomes increasingly industrialized. Cost to hire a hive for pollination depend on the specific crop needing pollination, but typically ranges from $90 for berries and small fruits to $180 for apples and cherries [4] [5]. The number of hives also depends on the plant species, with one hive per acre required for easy to pollinate or sensitive flowers like strawberries and plums or up to three per acre for apples and blueberries [6].

However, bee pollination faces a variety of challenges that continues to worsen. High-intensity agriculture negatively affects local bee populations as industrialized processes required for large scale monocultural farming contribute to soil erosion and natural habitat loss. The increased risk of diseases spreading necessitates higher herbicide and pesticide use. Changing weather patterns have also increased the pressures faced by honeybee populations, including earlier and larger parasitic mite and fungal infestations [7]. This leads to higher mortality rates during wintering of up to 45% of the entire colony [8]. These trends have led to steep declines in bee populations worldwide [9] [10] [11], as shown in Figure 1.

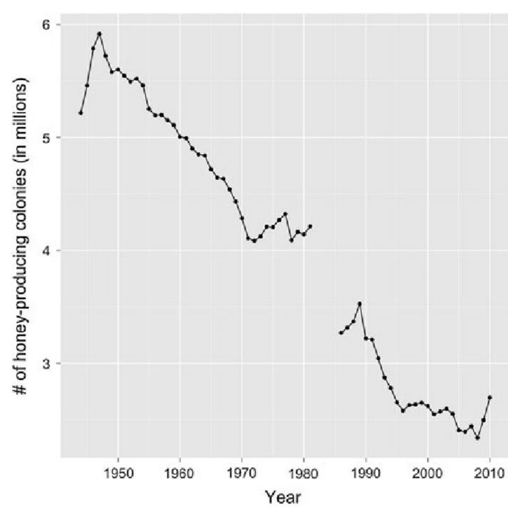

Figure 1. Honeybee colony decline over 70 years [11]

Indoor agriculture has also grown as an industry. This rapid shift to indoor agriculture is due to increasing climate instability and rapid urbanisation. With an estimated 80% of total arable land currently being used, innovations are needed to meet growing food demands [12]. Indoor farming, specifically vertical farms where plants are laid out vertically on top of each other to maximizes space, hold promising future potential, especially in energy, water usage, and land use efficiency [13].

Most intensive indoor agriculture focuses on leafy greens like lettuce, which don't require pollination [14]. Pollination-dependent crops, such as fruits and certain vegetables, are less common due to the challenges of indoor beekeeping, including high climate control costs and disease spread. The close proximity of plants also increases the risk of pests and infections, affecting both crops and beneficial organisms like bees [15] [16]. Even for indoor agriculture, bees face challenges including increased disease risk, limited food diversity, and potential crop damage from over-pollination [17] [18]. Additionally, growth-optimized light spectrums may harm bee health and navigation.

Therefore, this study seeks to explore mechanical pollination techniques that can be used for indoor farming of strawberries as a potential replacement for bees. For strawberries, complete and successful pollination is important for the development of the "fruit". Strawberries are formed as aggregate fruit that develop from the merger of several ovaries contained within a single flower's pistils, as shown Figure 2. Strawberry flowers are hermaphroditic, meaning that they have both male and female components. Male anthers are found around the perimeter of the bud and the pistils are grouped in the centre.

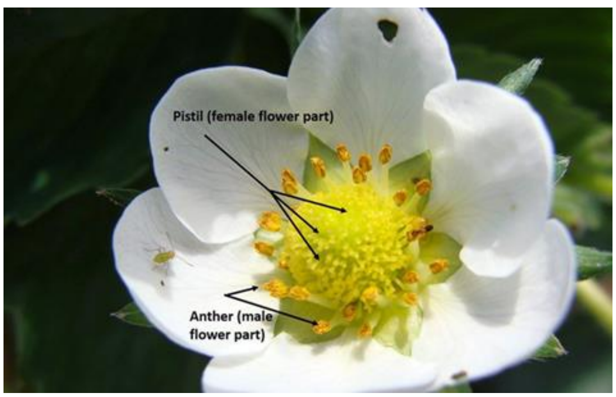

Figure 2. Reproductive organs [19] of a strawberry flower

Strawberry flowers are easily pollinated through natural motion, as their structure allows pollen to fall from the anthers onto adjacent pistils. For indoor cultivation, manual pollination with a brush was historically common but remains impractical for large-scale operations due to its labor-intensive nature. Most commercial greenhouses now employ bumblebees, though this method presents challenges: it requires suspending pesticide use, bees may exhaust their food supply after pollinating available flowers, greenhouse conditions increase disease risks, and their natural winter dormancy period limits year-round use [22].

After pollination, each pistil becomes an achene ("seed"). The strawberry's red flesh is actually an enlarged receptacle holding the achenes. While strawberries are self-fertile (wind can spread the pollen), insect pollination boosts effectiveness—without it, only 60% of flowers are typically pollinated. Wind or brushed hand-pollination results in 43% fewer pollinated ovaries versus insect pollination. Poor achene formation also reduces fruit weight (up to 25%) and quality.

II. METHOLOGY

A. Designs

This study tested three artificial pollination methods using four identical strawberry planters, each with ten plants and automated watering and lighting systems. Each planter evaluated a different mechanical pollination strategy.

The first approach used vibration alone for pollen release and distribution. In this case, an adjustable claw is used to wrap around the plant's leaf stock, as shown in Figure 3. Vibrating motors operating at 200 Hz are embedded in the claw to vibrate the entire plant. When activated, pollen is distributed from the anthers to the pistils of all flowers at the same time. With modifications to the claw size and shape this system can be easily adapted for use with different plant species with little effort. For this study, the system activated every 96 minutes during an 8-hour daily window (5 activations/day, 35 activations/week), matching optimal bee visitation rates for strawberries [23]. Each vibration lasted 64 seconds, based on average bee visit durations for similar flowers [24] [25].

Figure 3. Vibrating claw and motor

The second method combined vibration with a soft-bristled brush (Figure 4) that sweeps across plant foliage via a motorized rail system. The vibrating brush assembly dislodges and redistributes pollen while penetrating the leaf canopy.

Figure 4. Short brush pollination

This system is designed for flexible adaptation using rails of any length on vertical strawberry growing racks. While current brush speeds are limited by motor capacity, future implementations could utilize more powerful motors and advanced micro-controllers to optimize pollination for different plant species. The brush design naturally facilitates cross-pollination through pollen adhesion to the bristles. A modified version with longer bristles that demonstrated improved leaf penetration and flower pollination was also tested, as shown in Figure 5.

Figure 5. Long brush pollination

The final approach was designed to use gravity-assisted pollen deposition through controlled eddy currents. Inspired by Dr. Habiba Bougherara's research at Toronto-Metropolitan University [26], the system employs specially engineered nozzles (Figure 6) to create airflows that dislodge and distribute pollen across flowers. While operational parameters matched other methods, the control system restricted activation periods to 60-second intervals.

Figure 6. Air circulation-based pollination

The contact-free system minimizes plant disturbance and optimizes cross-pollination. However, it requires a complex setup and is less adaptable. Current airflow distribution remains uneven, with nozzles near the intake receiving the lowest flow—yet these plants paradoxically showed the best results, highlighting the need for further research on air pressure and velocity effects on the flowers.

Finally, hand pollination was also performed on two plants for comparison. Hand pollination was conducted using the AeroGarden Be the Bee Pollinator, a vibrating brushed wand primarily used for buzz pollination [27].

B. Measurements

Key developmental stages were documented for each strawberry, recording flower emergence, petal drop (typically 2 days later), flesh formation, and harvest dates (10 days for air circulation vs. 12 days for other methods). At harvest, each berry was weighed, while tracking its planter position, pollination method, and developmental sequence, to analyze growth patterns across all test conditions.

C. Berry Classification

Berry quality was evaluated according to the USDA strawberry grading standards [28] (Figure 7), with each strawberry classified as: No. 1 (highest quality), No. 2 (moderate damage), or seriously damaged. These quality classifications, along with measured berry weights at harvest, served as key metrics for assessing pollination effectiveness across all test methods.

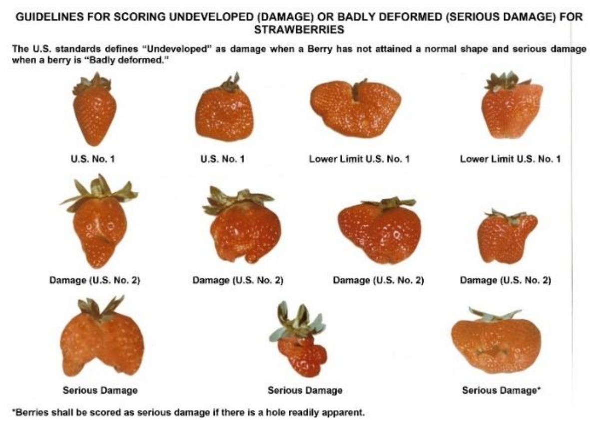

Figure 7. USDA strawberry categories [28]

These metrics effectively measure pollination success since each pollinated pistil develops into an achene ("seed"), and multiple achenes form the berry. Thus, strawberry shape and weight reliably indicate pollination quality (Figure 8).

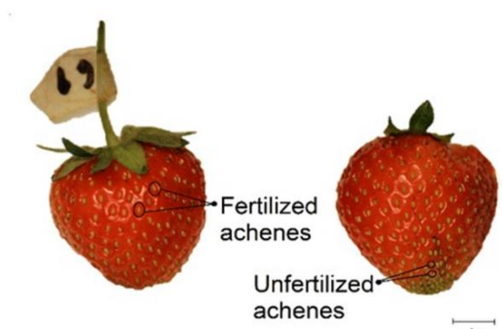

Figure 8. Strawberry fruit morphology [29]

III. RESULTS

Photographs taken at harvest (Figure 9) documented strawberry appearance for grading. All berries developed bright red coloration and sweet flavour (indicating high sugar/low acidity), regardless of physical quality variations across pollination methods.

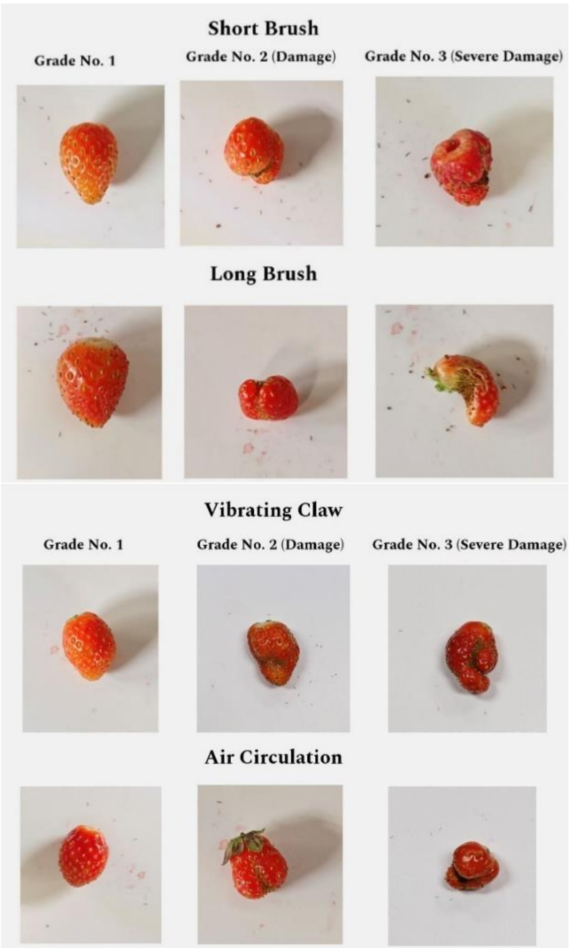

Figure 9. Pollinated strawberry exemplars

The collected data on strawberry pick dates, weights, and quality grades were analyzed by planter. Figure 10 shows the percentage of flowers that successfully developed into berries. While outdoor insect pollination achieves 94.25% success in optimal conditions [30], our mechanical methods showed promising results: both vibrating brush systems achieved approximately 80% berry formation, followed by the vibrating claw at 74%. The air circulation method yielded the lowest number of berries, while hand pollination performed moderately better at 65%, demonstrating challenges compared to mechanical approaches.

The average strawberry weight per planter, regardless of quality, is presented in Figure 11. Overall, the vibrating claw produced the highest average weight for all methods. All other methods obtained similar results, though interestingly the hand pollinated samples were lowest in terms of weight.

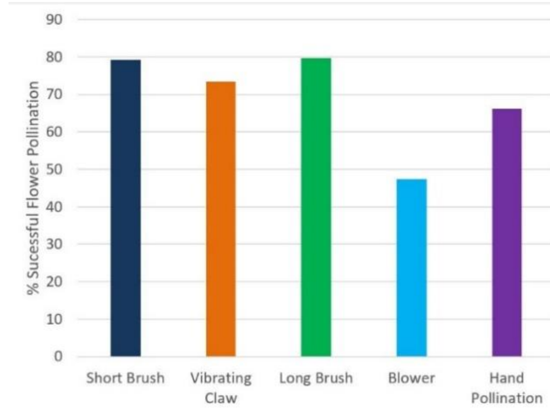

Figure 10. Percent of successful pollination by method

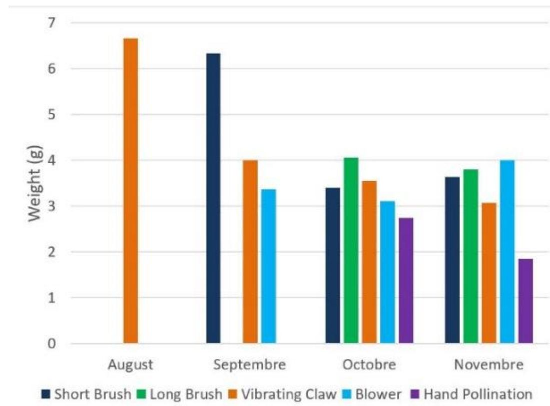

Figure 11. Average strawberry weight by month

The vibrating claw yielded the most Grade 1 berries with a detailed breakdown shown in Figures 12-13, followed by the long brush design with comparable results. Short brush and air circulation showed comparable results, though air circulation had the shortest operation time. Hand pollination performed poorly, underscoring its technical difficulty and labor-intensive nature.

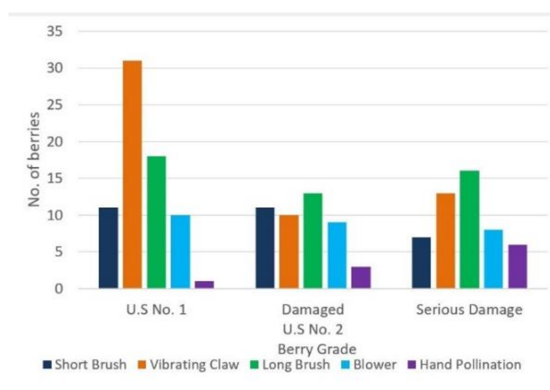

Figure 12. No. of berries by category

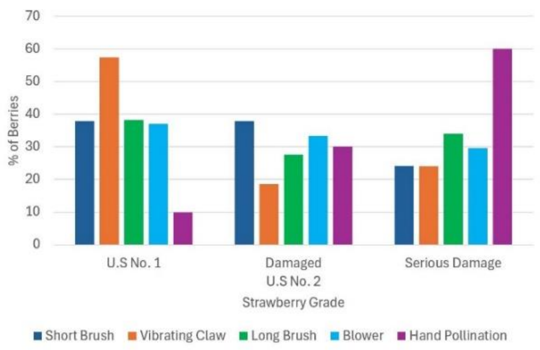

Figure 13. Berry quality per planter

Besides the vibrating claw, the long brush yielded the second highest number of berries, again indicating that the longer brushes provided superior pollination when compared to its short brush counterpart. However, the total number of berries cannot solely be attributable to successful pollination, as growing conditions also affect the number of berries and flowers a plant can sustain. Nonetheless, the results are still a reliable indicator of the design's potential success.

Moreover, it was found that as flower clusters produced strawberries, they would droop down below a height that could be contacted by the brush bristles. New flowers in these lower clusters were never successfully pollinated. Thus, these flowers were not taken into consideration when calculating successful pollination, assigned a USDA grade and so on. The percentages of flowers not pollinated by the brushes are shown in Figure 14.

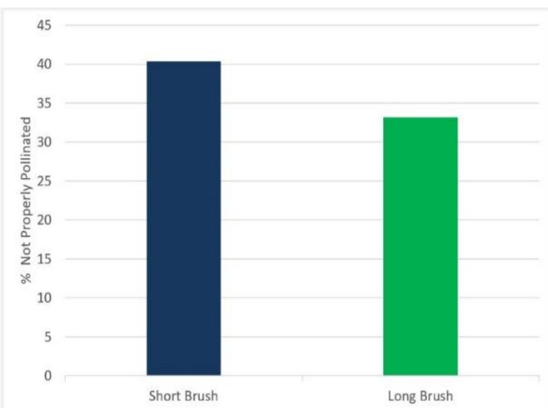

Figure 14. Percent of flowers not pollinated by brushes

Proposed design improvements include longer and stiffer brushes for better leaf penetration, contoured bristles, and adjustable heights to adapt to plant growth, along with perimeter flower supports for side-growing bundles. While brush pollination caused minimal visible flower damage, slight leaf stem bruising occurred. Notably, the long brush and hand pollination methods resulted in the highest percentage of seriously damaged strawberries (Figure 13), suggesting that repeated bristle or wand contact during fruit development may harm the berries.

Production costs were estimated for a 450-plant shipping container system. Each method has fixed (control systems, pumps) and variable (rails, pipes, clamps) costs (Table I). At this scale, vibrating claw and air circulation methods are most cost-effective, though this reverses with more plants due to higher per-unit costs. Installation and maintenance expenses remain significant. While refinements may reduce costs, mechanical systems ($2,900–$3,400) remain far more expensive than bee pollination ($90–$180 per hive). Adoption may require prioritizing non-cost factors like pollination consistency or indoor environment control.

TABLE I. ESTIMATED MECHANICAL POLLINATION PRODUCTION COSTS

Pollination method	Fixed cost	Cost per plant	Total cost (450 plants)
Vibrating claw	$275	$5.80	$2,900
Short brush	$2400	$2.30	$3,400
Long brush	$2400	$2.30	$3,400
Air circulation	$900	$4.75	$3,000

IV. CONCLUSIONS

All tested mechanical pollination methods achieved yields comparable to outdoor insect pollination, with the vibrating claw and air circulation methods showing the most promise. The claw method delivered the highest quantity and quality of strawberries, including the heaviest fruits. While vibrating brushes underperformed due to fruit contact damage, all vibration systems incurred higher labor costs for installation/cleaning than air circulation. Despite being more expensive than bee pollination, mechanical systems may be justified in certain indoor growing scenarios. Future large-scale trials with refined designs are needed to evaluate their practical viability.

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