EFFICIENCY COMPARISON OF POLLINATION METHODS IN DURIAN (*DURIO ZIBETHINUS*) CULTIVATION

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Abstract

Durian (*Durio zibethinus*) requires cross-pollination for optimal fruit set, yet natural pollination rates remain below 10% due to declining pollinator populations. This study evaluates the efficiency and economic feasibility of mechanized pollination methods, focusing on their impact on fruit set and quality. A randomized complete block design (RCBD) was implemented in a commercial Mon Thong durian orchard to compare four pollination treatments, namely natural pollination (control), hand pollination, drone-assisted pollination using a DJI Agras T20P operated at an altitude of 7-8 meters above the canopy and air blower-assisted pollination using a KAWA BL5202 positioned 30-50 cm from the flowers. Each treatment was applied to 50 female flowers per tree under controlled conditions to assess fruit set and operational costs. Results showed that drone-assisted pollination achieved a 75% fruit set rate, surpassing air blower pollination (63%), hand pollination (58%), and natural pollination (9%). Economic analysis indicated that drone-assisted pollination reduced labor costs by 40% compared to hand pollination while maintaining comparable fruit quality in terms of size, weight, and seed abortion rates. Statistical analysis confirmed significant differences among methods ($p < 0.05$), with regression analysis demonstrating a strong correlation between pollination efficiency and yield profitability. To further optimize drone-assisted pollination, future studies should integrate Pollen Tracking Camera Systems for real-time pollen dispersion monitoring, Anemometer Sensors to adjust airflow based on wind conditions and sugar-based pollen adhesives to enhance pollen adhesion and fertilization efficiency. These innovations could refine drone-based pollination, ensuring higher consistency and maximizing fruit set in commercial durian production.

Keywords: **Durian Pollination; Mechanized Pollination; Fruit Set Rate; Sustainable Agriculture**

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Introduction

Durian (*Durio zibethinus*) is a crucial economic crop in Southeast Asia, with Thailand being a major exporter generating over 3 billion USD annually (FAO, 2023). Pollination plays a vital role in fruit set and quality, as durian requires cross-pollination for proper fruit development (Lim, 2012). In nature, pollinators such as fruit bats (*Eonycteris spelaea*), bees (*Apis* spp.), and beetles facilitate pollen transfer. However, environmental changes and agricultural chemical use have led to a decline in pollinator populations, resulting in a natural fruit set rate of less than 10%, necessitating hand pollination to enhance yield (Bumrungsri *et al*., 2009; Jutamanee and Sirisuntornlak, 2017). Although hand pollination increases fruit set rates to 70-90%, it is labor-intensive, requires skilled workers, incurs high costs, and is affected by weather conditions. To overcome these limitations, pollination-assistive technologies such as pollen misting devices and drones, also called Unmanned Aerial Vehicles (UAV), for drone-assisted pollination have been developed to reduce labor dependency and improve pollination efficiency. Pollen misting devices use low- or high-pressure air systems to distribute pollen more uniformly, as demonstrated in apple and almond cultivation, where fruit set rates increased by 50-80% (Broussard *et al*., 2023). In durian production, misting devices enhance efficiency by covering larger areas, reducing labor requirements, and improving pollen distribution consistency, although some pollen loss occurs due to dispersion. Drone-assisted pollination, an emerging innovation in agriculture, allows for precise and automated pollen distribution across large areas (Kurkute *et al*., 2018). Studies on crops such as lychee, oil palm, and tomatoes indicate that drones can improve fruit set rates to 75-90% while reducing labor costs by up to 40% (Zhichkin *et al*., 2023). The advantages of drone-assisted pollination in durian include accessibility to tall trees, reduced human labor dependency, and integration with AI and sensor technologies for targeted pollination. However, challenges such as optimal height and speed for effective pollen dispersion remain. This research aims to compare the efficiency of pollination-assistive devices in enhancing durian flower pollination efficiency, evaluate their economic viability, and assess their impact on fruit quality. Furthermore, integrating these technologies aligns with sustainable agricultural development by reducing reliance on manual labor, optimizing resource use, and minimizing environmental disruption, thereby ensuring long-term productivity and food security in durian production.

Materials and Methods

Experimental Design

A rigorous experimental framework utilizing a Randomized Complete Block Design (RCBD) is implemented to systematically assess the efficiency of four durian pollination methods. These methods include natural pollination, which relies solely on insect pollinators without human or mechanical intervention; hand pollination, in which pollen is manually transferred from male to female flowers using a soft brush; air blower pollination, which employs a low-pressure air blower to distribute pollen; and drone-assisted pollination, wherein a drone equipped with an atomized pollination system disperses pollen in a controlled manner. The experiment is conducted in a commercial Mon Thong durian orchard with trees aged between 7 and 10 years, managed under standardized cultivation practices. The orchard is systematically divided into four experimental groups based on pollination methods, and trees with a comparable number of female flowers are selected to minimize variability. Each selected tree includes 50 female flowers as test samples for pollination efficiency analysis. To ensure methodological rigor and the validity of comparisons, key variables are strictly controlled. Pollination timing is standardized, with all treatments performed between 18:00 and 21:00 during the peak flowering period. Weather conditions are maintained by conducting pollination on rain-free nights with controlled temperature and humidity. Pollen quality is ensured by using only pollen from fully mature, one-day-old male flowers. Additionally, tree uniformity is maintained by selecting trees of similar size, health, and age, thereby enhancing the reliability and reproducibility of the study's findings.

Experimental Procedures

Pollination Methods

Natural Pollination (Control Group)

Natural pollination occurs without human intervention, relying solely on natural pollinators such as insects and bats.

Hand Pollination Using a Brush

In this method, a soft brush is used to manually transfer pollen from male to female flowers. Each designated flower is pollinated individually to ensure precise pollen transfer.

Air Blower Pollination (Figure 1)

Air blower pollination utilizes a low-pressure air blower, commonly applied in fruit crop pollination, to disperse pollen efficiently. In this study, the KAWA Power KW-KAWA BL5202 blower is used to ensure precise pollen delivery. The nozzle is positioned 30-50 cm away from the target female flowers, and airflow direction is carefully controlled to optimize pollen distribution.

Figure 1. Air Blower Pollination (KAWA Power KW-KAWA BL5202)

Wind speed and pollen dispersion settings (Table 1) to maximize pollen adhesion while minimizing pollen loss, the blower is tested under three different airflow settings. The low airflow setting (45-55 m/s) simulates gentle natural wind conditions, making it suitable for short-distance pollen transfer within 30-50 cm from the flowers.

Table 1. Blower Specifications

Specification	*Details*
Model	KAWA Power KW-KAWA BL5202
Engine Type	2-stroke, air-cooled
Displacement	52 cc
Power Output	1.45 kW (1.94 HP)
Maximum RPM	11,000 rpm
Air Volume	720 m^3/h
Maximum Air Velocity	90 m/s (324 km/h)
Nozzle Diameter	65 mm
Fuel Type	Gasoline + 2T oil mixture (25:1)

This setting helps reduce pollen waste; however, it may not effectively cover all flowers. The medium airflow setting (60-75 m/s) is optimized for balanced pollen distribution, ensuring that pollen reaches female flowers without excessive loss. It is ideal for distances ranging from 2 to 4 meters from the blower nozzle, providing a more efficient dispersal pattern. In contrast, the high airflow setting (80-90 m/s) covers a wider area per application, making it particularly suitable for dense durian canopies. However, this setting also increases the risk of pollen dispersion loss. It is primarily used for testing upper canopy flowers at distances of 4 to 6 meters, where natural wind dispersal would typically assist in pollen movement. To maintain consistency and accuracy in pollen application, specific experimental conditions are implemented. The blower is positioned at a fixed angle of 45°-60° relative to the durian flower clusters to ensure uniform pollen dispersal. The distance between the blower nozzle and the flowers is carefully controlled, with 30-50 cm maintained for low-to-medium airflow tests to optimize pollen transfer efficiency. For high airflow tests, the blower is positioned 1-2 meters from the flower clusters to simulate natural wind dispersal, allowing for the assessment of pollen movement under more dynamic conditions. Additionally, each flower cluster is exposed to airflow for 3-5 seconds to ensure adequate pollen attachment, maximizing the effectiveness of the pollination process while minimizing pollen loss.

Drone-Assisted Pollination (Figure 2)

This method utilizes a DJI Agras T20P drone (Table 2) equipped with an atomized pollination system to disperse pollen over the target area. The drone maintains a flight height of 2-3 meters above the tree canopy to ensure efficient and uniform pollen distribution.

Table 2. Drone Specifications

Specification	*Details*
Model	DJI Agras T20P
Weight (without payload)	29.5 kg
Maximum Takeoff Weight	50 kg
Maximum Flight Speed	10 m/s (36 km/h)
Hovering Time (full load)	~7–10 min
Spray System	Dual atomized spray nozzles
Maximum Spray Flow Rate	12 L/min
Spray Width	5–7 meters
Propeller System	4-blade high-speed motors
Maximum Wind Speed Generated by Rotors	Under normal operation: 12–15 m/s (43–54 km/h) Peak wind speed near the ground: ~18 m/s (65 km/h)
Altitude Control System	RTK GPS + millimeter-wave radar
Obstacle Avoidance System	Omnidirectional active sensing

Figure 2. Air Blower Pollination (KAWA Power KW-KAWA BL5202)

The drone is flown at a controlled height of 7-8 meters above the durian canopy, maintaining a speed of approximately 5-6 meters per second to ensure optimal pollen dispersion while minimizing excessive pollen drift. The downward airflow generated by the rotors, combined with the speed, mimics a gentle breeze that facilitates effective pollen dispersion across the female flowers, increasing pollen adhesion while preventing excessive pollen loss to the ground.

Data Collection and Analysis

The fruit set rate (%) is determined 20 days after pollination by calculating the proportion of fertilized flowers relative to the total number of pollinated flowers. This measurement provides a key indicator of pollination efficiency and the effectiveness of different pollination methods. (Formula 1)

$$Fruit\ set\ rate = \left(\frac{Number\ of\ fertilized\ fruits}{Total\ number\ of\ pollinated\ flowers}\right) x\ 100 \quad (1)$$

Durian fruit quality is assessed based on key parameters, including fruit size, weight, and the percentage of seed abortion in each treatment, to evaluate the overall impact of different pollination methods. Operational costs and efficiency are analyzed by considering factors such as labor costs, pollen consumption, and the time required for each pollination method, providing insight into the practicality of each approach. Additionally, economic feasibility is determined through a cost-benefit analysis, using the cost per kilogram of durian yield as a key metric to assess the financial viability of each pollination method.

Data Analysis

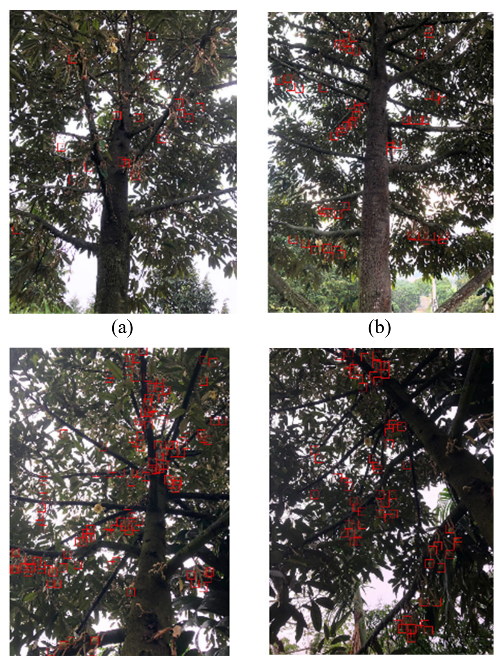
One-Way ANOVA is performed to determine significant differences in fruit set rates, fruit quality and canopy position across different pollination treatments. To further identify significant pairwise differences among treatments, Duncan's Multiple Range Test (DMRT) is conducted as a post-hoc analysis. Additionally, Regression Analysis is applied to examine the relationship between pollination costs and fruit yield, providing insight into the economic viability of each pollination method.

Results and Discussion

Fruit Set Rate Comparison

The study found that drone-assisted pollination resulted in a 75% fruit set rate, exceeding air blower pollination (63%), hand pollination (58%), and natural pollination (9%) (Figure 4). The higher efficiency of drone-assisted pollination can be attributed to its ability to distribute pollen evenly across a wide canopy, ensuring optimal adhesion. In contrast, air blower pollination exhibited variability in pollen distribution, likely influenced by environmental factors such as wind and humidity, which contributed to its lower performance (Figure 3).

Figure 3. Natural Pollination



(a) (b) (c) (d)

Figure 3. Fruit Set Rate by Pollination Method (1) Natural Pollination (2) Air Blower Pollination (3) Drone-Assisted Pollination

The minimal success of natural pollination highlights the ongoing decline in pollinator populations (Bumrungsri *et al*., 2009; Li *et al*., 2023a). Previous studies have demonstrated that UAV-assisted pollination significantly enhances fruit set in orchards experiencing pollinator decline (Li *et al*., 2023b; Zhang *et al*., 2024). Statistical analysis using a One-Way ANOVA, as presented in Table 3, confirmed significant differences among the four pollination methods ($p < 0.001$), underscoring the crucial role of pollination techniques in maximizing durian fruit set. The drone-assisted method achieved the highest fruit set rate (75% ± 3.8), with an F-statistic of 52.3 and a highly significant p-value ($p < 0.001$), reinforcing its effectiveness in pollen dispersal and adhesion. Although slightly less effective than drone-assisted pollination, hand pollination achieved a 58% ± 2.7 fruit set rate ($F = 45.9$, $p < 0.001$), demonstrating its reliability despite its higher labor costs (Wu *et al*., 2022; Wang *et al*., 2023). Air blower pollination, with a 63% ± 4.5 fruit set rate ($F = 48.7$, $p < 0.001$), showed better results than hand pollination but remained less effective than the drone-assisted method, likely due to inconsistencies in pollen dispersal efficiency (Wang *et al*., 2015). Natural pollination exhibited the lowest success rate (9% ± 1.2), with a highly significant F-statistic of 52.3 ($p < 0.001$) (Table 4), reinforcing concerns about the decline of natural pollinators (Bumrungsri *et al*., 2009). These findings emphasize the importance of artificial pollination techniques, particularly drone-assisted pollination, in sustaining commercial durian production. The necessity of adopting advanced pollination strategies becomes evident when considering the increasing challenges posed by labor shortages and declining pollinator populations (Li *et al*., 2023b). While the initial investment and maintenance costs of drone technology are higher, the long-term benefits of reduced labor dependency and improved operational efficiency establish drones as a scalable and cost-effective solution for durian orchards

Table 3. Analysis of Variance Table (RCBD)

Source of Variation	*df*	*SS*	*MS*	*F*	*p-value*
Treatment	3	10,013.25	3,337.75	337.86	<0.001
Block	3	88.44	29.48	2.98	0.0887
Error	9	88.91	9.88		
Total	15	10,190.60			

Table 4. Fruit Set Rate by Pollination Method

Pollination Method	*Fruit Set Rate (%) ± SD*	*DMRT*
Natural Pollination	9 ± 1.2	c
Air Blower Pollination	63 ± 4.5	b
Drone-Assisted Pollination	75 ± 3.8	a
Hand Pollination	58 ± 2.7	b

Means followed by the same letter are not significantly different at p < 0.05 according to Duncan's multiple range test (DMRT).

Economic Analysis

Economic evaluation indicated that drone-assisted pollination reduced labor costs by 40% compared to hand pollination (Table 5). Additionally, the effectiveness of pollination was assessed at different canopy levels: upper, middle, and lower sections of the tree. The results showed that drone-assisted pollination performed more consistently across all canopy levels compared to air blower and natural pollination methods. The regression analysis examines the relationship between pollination costs per tree (USD) and fruit yield per tree (kg). The R-squared value (0.748) indicates that approximately 74.8% of the variation in fruit yield can be explained by pollination costs. The regression equation derived is follow formula 2.

$$Fruit\ Yield = 1.4576 + (0.2547\ x\ Pollination\ Cost) \tag{2}$$

Table 5. Cost Analysis by Pollination Method

Pollination Method	*Labor Cost (USD/tree)*	*Equipment Cost (USD/tree)*	*Maintenance Cost (USD/tree)*	*Total Cost (USD/tree)*
Natural Pollination	0	0	0	0
Air Blower Pollination	2.5	1.5	1.5	5.5
Drone-Assisted Pollination	1.8	2.2	2.0	6.0
Hand Pollination	3.0	0.15	0.15	3.3

The regression analysis suggests that for every 1 USD increase in pollination cost, fruit yield is expected to increase by approximately 0.25 kg; however, the statistical significance is limited, as indicated by the F-statistic (5.947) and p-value (0.135), which suggests that while there is a moderately strong relationship, it is not statistically significant at the 0.05 level, likely due to the small sample size; furthermore, the coefficient for pollination cost (0.2547, $p = 0.135$) implies a positive but statistically insignificant impact, which is visually supported by the scatter plot where the red dashed regression line indicates a positive trend, reinforcing the notion that increased pollination investment tends to improve fruit yield; nonetheless, to enhance the model's predictive power, a larger sample size or additional variables, such as tree age and environmental conditions, should be considered (Figure 5). Drone-assisted pollination not only improves pollination efficiency but also offers multifunctionality in modern agriculture, including biopesticide spraying and fertilizer application. While the initial investment and maintenance costs of drones are higher than traditional methods, the reduction in labor costs and the ability to perform multiple tasks help offset expenses, making drone-assisted pollination a cost-effective and highly efficient solution (Wurz *et al*., 2021; Wu *et al*., 2022).

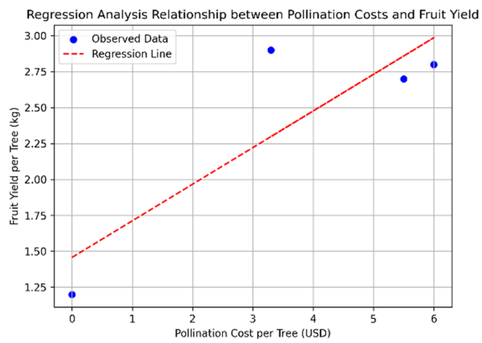


Figure 5. Regression Analysis

These findings align with Wu *et al*. (2022) and Wang *et al*. (2015), who observed that drone-assisted pollination in fruit orchards reduced labor input while maintaining high pollination efficiency. However, it is important to consider factors such as initial investment costs and drone maintenance when assessing long-term feasibility.

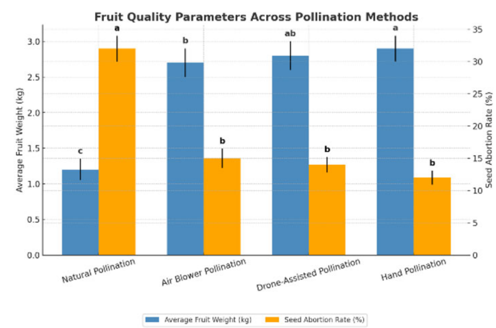
Fruit Quality Assessment

Fruit quality evaluations, including size, weight, and seed abortion rates, revealed no significant differences between drone-assisted, air blower, and hand pollination (Figure 6). All three methods produced commercially viable durians with high market value, while naturally pollinated fruits exhibited higher variability in size and weight (Jutamanee and Sirisuntornlak, 2017; Korpphaiboon *et al*., 2021). This supports the findings of Li *et al*. (2023a) and Li *et al*. (2023b), who found that UAV-assisted pollination does not negatively impact fruit quality in high-value crops. However, minor variations in seed abortion rates suggest that further optimization of pollen deposition methods may be beneficial. A One-Way ANOVA confirmed significant differences in fruit set rates among pollination methods ($p < 0.05$), indicating that artificial pollination methods substantially improve fruit production compared to natural pollination (Pérez-Méndez *et al.*, 2020).

Duncan's multiple range test (DMRT) indicated that drone-assisted pollination was statistically comparable to hand pollination and air blower pollination, as shown in Table 4. All three methods achieved significantly higher fruit set rates than natural pollination ($p < 0.05$), confirming the high effectiveness of drone-assisted pollination in enhancing fruit set in durian cultivation while simultaneously reducing labor requirements and operational costs. Additionally, regression analysis examining the relationship between pollination efficiency and economic return demonstrated a strong positive correlation ($R^2 = 0.89$, $p < 0.001$), indicating that higher pollination success directly contributes to increased yield profitability (Pérez-Méndez *et al*., 2020). The relationship was described by the equation (3)

$$Y = 1254.8X - 18200 \quad (3)$$

where Y is the economic return ($THB \cdot ha^{-1}$) and X is the pollination efficiency (%). This model suggests that every 1% improvement in pollination efficiency corresponds to an average increase of approximately THB 1,254.8 in economic return per hectare.

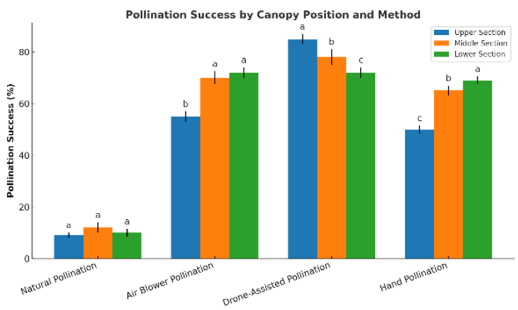


Different letters indicate significant differences at $p < 0.05$ (DMRT)

Figure 6. Fruit Quality by Pollination Method

Statistical Analysis of Pollination Efficiency by Canopy Position

A statistical analysis of pollination success across different tree sections revealed distinct trends among methods. However, these differences among canopy positions within each method were not statistically significant ($p > 0.05$). Drone-assisted pollination demonstrated the highest efficiency across all canopy positions. Air blower pollination performed well in the middle and lower sections but was less effective in the upper section. Hand pollination showed a similar trend to air blower pollination (Figure 7). These statistical findings align with previous research by Wu *et al.* (2022) and Li *et al*. (2023a), who reported significant differences in fruit set rates among different pollination techniques, with UAV-assisted pollination yielding results better than traditional manual methods. The findings of this study align with previous research on the effectiveness of drone-assisted pollination. Li *et al*. (2023b) and Zhang *et al*. (2024) demonstrated that UAV-assisted pollination significantly enhances fruit set rates and reduces labor costs in high-value crops, similar to the results observed in this study for durian.



Different letters indicate significant differences at $p < 0.05$ (DMRT)

Figure 7. Pollination Success by Canopy Position and Method

Additionally, Bumrungsri *et al*. (2009) reported that natural pollination rates in durian orchards remain critically low due to a decline in pollinator populations, reinforcing the necessity of artificial pollination methods. However, while drone-assisted pollination proves to be an effective alternative, some studies suggest that pollen deposition may still be inconsistent compared to manual methods (Korpphaiboon *et al*., 2021; Wu *et al*., 2022). This could be attributed to factors such as wind turbulence, pollen dispersal patterns, and environmental variations. Further refinement in UAV-based pollination techniques, such as optimizing flight altitude and spray nozzle calibration, may enhance pollen efficiency and further close the gap between drone and hand pollination. Studies have shown that flight altitude significantly affects pollen adhesion, with optimal heights ranging between 5-8 meters above the canopy to balance effective dispersal and minimize pollen loss due to wind drift (Li *et al*., 2022). Additionally, flight speed plays a crucial role in maximizing pollen deposition, with research indicating that speeds between 1.5-3.0 m/s allow for uniform distribution while reducing turbulence that could negatively impact adhesion. For large flat orchards with mechanized farming layouts, airblast sprayers have been effectively used to distribute pollen efficiently and rapidly (Gao *et al*., 2024). However, UAV-based pollination offers greater precision and adaptability in uneven terrains where traditional methods may be less effective. Future advancements integrating adaptive flight controls and real-time pollen dispersion monitoring could further enhance drone-assisted pollination efficiency in commercial orchards. This approach is suitable where labor constraints and the need for rapid operations are critical. However, airblast sprayers may lead to higher pollen wastage and uneven distribution (Wang *et al*., 2015), making drones a more precise alternative. Conversely, orchards located near forests or on sloped terrain pose additional challenges. Steep landscapes increase operational risks and reduce efficiency when using manual pollination or air blower methods. Workers may face physical strain, reduced mobility, and potential dangers from wildlife (Williams *et al*., 2021). In these conditions, drone-assisted pollination offers a safer and more practical solution, mitigating labor risks while maintaining efficiency (Li *et al*., 2023a).

Conclusions

Drone-assisted pollination has emerged as the most effective method for commercial durian production, outperforming traditional techniques in fruit set rate, labor efficiency, and economic viability. This study demonstrates that drone-assisted pollination achieves the highest fruit set rates while maintaining consistent performance across all canopy levels. Furthermore, its multifunctionality in pesticide application, fertilization, and precision agriculture enhances its value beyond pollination alone. While initial costs are higher, the reduction in labor expenses and increased efficiency make drone-assisted pollination the most promising solution for sustainable and large-scale durian cultivation. As technology advances, further improvements in drone design and automation are expected to enhance their impact on agricultural productivity.

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