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Drone-assisted augmentation of the parasitoid *Anagyrus lopezi* for cassava mealybug control in Indonesia

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Abstract. *Wasik MA, Sartiami D, Nurmansyah A. 2025. Drone-assisted augmentation of the parasitoid* Anagyrus lopezi *for cassava mealybug control in Indonesia. Biodiversitas 26: 6437-6446.* The cassava mealybug, *Phenacoccus manihoti*, is an invasive pest that causes severe damage and economic loss in cassava production in Indonesia. Biological control using the parasitoid *Anagyrus lopezi* to manage *P. manihoti* has proven effective; however, its manual releases remain constrained by time, labor, and cost. This study evaluated the effectiveness and operational efficiency of *A. lopezi* augmentation using drone-assisted and manual release techniques in cassava fields. Effectiveness was measured by the parasitism rate of *A. lopezi* on *P. manihoti*, while efficiency was assessed through cost and time analyses. The augmentation treatment significantly increased the parasitism rate (F = 1955.78; df = 2,11; p<0.001). Parasitism rates under both release techniques were 47.18±0.92% for drones and 46.87±1.04% for manual release, compared with 16.11±0.59% in the control plots. The comparable parasitism rates achieved by drone-assisted and manual releases indicate that drone deployment maintains comparable biological effectiveness to manual augmentation. Moreover, drone application requires only 25 minutes per hectare, compared to 200 minutes per hectare manually. Although the initial cost of drone use was higher at small operational scales, economic analysis indicated a break-even point at approximately 25 ha. These findings demonstrate the feasibility of drone-assisted parasitoid deployment as an operationally efficient approach for large-scale biological control of *P. manihoti*. This contribution strengthens area-wide Integrated Pest Management (IPM) programs by enabling synchronized parasitoid augmentation while also supporting the broader development of smart-agriculture technologies for cassava-based farming systems.

Keywords: Agricultural technology, Integrated Pest Management, mass release, parasitoid capsule, *Phenacoccus manihoti*

INTRODUCTION

The cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae), is a major pest that damages cassava crops in various countries (Parsa et al. 2012). This pest can cause significant yield loss and seriously threaten food security (Yonow et al. 2017). Originally from South America, this invasive pest was first reported to damage cassava crops in Asia, especially in Thailand in 2008 (Winotai et al. 2010), and has since spread rapidly across Asia (Muniappan et al. 2011; Parsa et al. 2012; Sartiami et al. 2015; Joshi et al. 2020). In Indonesia, *P. manihoti* was first detected infesting cassava fields in Bogor in 2010 (Muniappan et al. 2011) and has since expanded to major cassava-producing regions (Abduchalek et al. 2017; Nopriawansyah et al. 2019; Fanani et al. 2019; Pu'u 2019; Supartha et al. 2020). This rapid and widespread distribution indicates that the presence of *P. manihoti* has become a serious threat to the sustainability of cassava production in Indonesia.

Mealybug management is crucial due to the significant damage it can cause to cassava crops. As *P. manihoti* infestations increased, the availability of effective insecticides for their control was very limited (Mani and Shivaraju 2016). Biological control using the specific parasitoid *Anagyrus lopezi* (De Santis, 1964) (Hymenoptera: Encyrtidae) has proven highly successful in suppressing *P. manihoti* populations (Thancharoen et al. 2018). Various countries have introduced this parasitoid as a key natural enemy in biological control programs against *P. manihoti*. In Asia, *A. lopezi* was first introduced from Benin, Africa, to Thailand in 2009, leading to substantial reductions in mealybug infestations (Winotai et al. 2010; Thancharoen et al. 2018). In Indonesia, *A. lopezi* was introduced in 2014 in the Bogor area (Wyckhuys et al. 2014) and has since established populations in various cassava-producing regions (Fanani et al. 2019). This success highlights the potential of larger area biological control programs using *A. lopezi* for sustainable cassava protection. However, the implementation of this biological control program still relies heavily on manual release techniques, which are labor-intensive, time-consuming, and costly, particularly when conducted over large areas or inundatively (Dionne et al. 2018; Cluever et al. 2023). These operational limitations restrict the scalability of augmentative releases and highlight the need for more efficient, technology-based delivery systems. Although drones have recently been explored for biological control applications, their use for parasitoid deployment remains largely untested at operational field scales, with no empirical evaluations reported.

In response to these challenges, drone or Unmanned Aerial Vehicle (UAV) technology has emerged as a promising tool for augmentative biological control. Drone-based releases have been successfully implemented in several countries for different biological control agents such as *Trichogramma ostriniae* and *Trichogramma minutum*

(Hymenoptera: Trichogrammatidae) (Martel et al. 2021), *Anastrepha ludens* (Diptera: Tephritidae) (Moses-Gonzales et al. 2021), *Rhinoncomimus latipes* (Coleoptera: Curculionidae) (Kim et al. 2021), *Chrysoperla rufilabris* (Neuroptera: Chrysopidae) (Pozo-Valdivia et al. 2021), and *Cryptolaemus montrouzieri* (Coleoptera: Coccinellidae) (Moretti and Schmidt-Jeffris 2025). However, to date, there has been no report on the use of drone technology for the augmentative release of *A. lopezi*, either in Indonesia or globally. To our knowledge, this study represents the first application of drone-assisted augmentation of *A. lopezi* for cassava mealybug control, providing a novel and scalable approach for improving the efficiency and sustainability of parasitoid-based biological control within smart-agriculture frameworks. Therefore, this study aimed to evaluate the effectiveness of *A. lopezi* parasitism on *P. manihoti* using drone-assisted versus manual release techniques. Furthermore, it aimed to analyze these techniques' cost and time efficiency as a foundation for advancing smart and large-scale integrated pest management strategies. We hypothesized that drone-assisted releases would achieve comparable parasitism rates to manual releases while offering greater operational efficiency in time and cost.

MATERIALS AND METHODS

Time and study area

The study was conducted from May to September 2025. Mass rearing of the parasitoid *Anagyrus lopezi* was performed at the Insect Biosystematics Laboratory, Department of Plant Protection, Faculty of Agriculture, Institut Pertanian Bogor, Indonesia. Field experiments on parasitoid augmentation were conducted in cassava fields in Sukaraja Subdistrict, Bogor Regency, West Java, Indonesia. Mealybug and parasitoid samples were collected from the same cassava fields to ensure that laboratory rearing and field evaluations originated from populations exposed to comparable environmental conditions. All sampling plots were located within the same contiguous cassava cultivation area and exhibited similar microclimatic conditions, ensuring that treatment differences were not confounded by climatic variation among fields.

Procedures

Rearing procedures

The experimental preparation involved mass rearing of three main components: cassava host plants, the cassava mealybug *Phenacoccus manihoti*, and the parasitoid *A. lopezi*. Rearing procedures followed Wasik et al. (2025), with controlled laboratory conditions maintained at 27-30°C and 65-70% relative humidity throughout all rearing stages to ensure optimal parasitoid development and consistent rearing quality prior to field release. Cassava cuttings of the Manggu variety were grown and maintained for two weeks until new leaves developed, then infested with *P. manihoti* ovisacs and placed in insect cages measuring 75×50×50 cm for colony establishment. After three weeks, the mealybugs developed into third-instar nymphs, which were used as hosts for *A. lopezi* rearing. To ensure host-age uniformity across cages, only third-instar nymphs of similar size were selected, while individuals that developed earlier or later were excluded.

For parasitoid rearing, pairs of *A. lopezi* adults were placed in glass tubes for 24 hours to ensure mating, after which mated females were introduced into insect cages containing nine cassava cuttings infested with third-instar *P. manihoti*. After two weeks, parasitized mealybugs developed into mummies, which were collected for field augmentation.

Field assessment of Phenacoccus manihoti *population*

The population density of *P. manihoti* in the field was estimated using a diagonal sampling method. Each experimental plot of 1,000 m² was divided into 5 subplots measuring 3×2 m, arranged diagonally. Each subplot contained six cassava plants, resulting in a total of 30 plants observed per plot. The number of nymphs and adults of *P. manihoti* on all leaves of each plant within the subplot was counted visually in situ using a hand lens to ensure clear visibility. Observations were focused on the shoot tips, buds, and young leaves, which represent the preferred feeding sites of *P. manihoti*. Mealybugs were counted per plot, and the mean density per plant was calculated by dividing the total number of individuals per plot by the number of cassava plants within the plot.

Determination of parasitoid release numbers

The number of *A. lopezi* parasitoids released in the cassava field was determined based on the observed population density of *P. manihoti* at the experimental site. One female *A. lopezi* can parasitize up to 20 *P. manihoti* individuals under laboratory conditions (Fanani et al. 2020; Naimah et al. 2023); therefore, a 1:20 parasitoid-to-host release ratio was applied. Mealybug mummies obtained from laboratory rearing of *A. lopezi* were used for field releases, and parasitized individuals were identified by their hardened bodies and dark-brown coloration. Female and male parasitoids were distinguished based on body size, with females being visibly larger; size-selection was implemented consistently in all rearing batches, and only morphologically confirmed females were used for field release to ensure sex-ratio accuracy. Paper strips containing parasitized mealybugs were then inserted into biodegradable gelatin-based capsules with small perforations at both ends to facilitate adult emergence. These capsules protected the mummies during transport and deployment while allowing gradual emergence in the field and served as release units for augmentative field applications.

Assessment of Anagyrus lopezi *effectiveness*

Augmentation of *A. lopezi* parasitoids was conducted in cassava fields planted with the Manggu variety at 4-6 months of age, using a 100×80 cm spacing. The experiment followed a randomized complete block design (RCBD) with 3 treatments and 5 replications (blocks). Treatments consisted of (P1) control (no parasitoid release), (P2) drone-assisted release, and (P3) manual release. Each treatment was applied to plots measuring 1,000 m², with 50-70 m inter-plot distances. The drone-assisted release used a DJI Agras T50 multirotor drone equipped with a spreading system and a GPS-based autonomous navigation unit for pre-programmed flight routes. The drone evenly distributed parasitoid capsules across each plot at a flight speed of 3 m s^{-1} and a release height of 8 m above ground level (AGL) (Figure 1). A total of 200 capsules were released per plot, distributed evenly along the drone flight route to ensure homogeneous spatial coverage of parasitoids across the field area. In the manual release treatment, field personnel distributed the same capsules evenly by hand within the experimental plots.

Parasitoid effectiveness was evaluated seven days after the parasitoid augmentation in cassava fields. Sampling was conducted randomly in each experimental plot by collecting 20 cassava shoot tips per plot, 15-20 cm long, infested with *P. manihoti*. The sample size of 20 shoot tips per plot was selected based on Fanani et al. (2019), who demonstrated that this sampling intensity provides reliable estimates of *P. manihoti* density and the parasitism rate of *A. lopezi* at the plot scale. Each cassava shoot tip was examined to count the number of nymphs, adults, and mummies. Cassava shoot tips with live nymphs and adults were placed in transparent plastic cups and maintained under laboratory conditions. All samples were observed daily for two weeks to monitor signs of parasitism and the emergence of adult parasitoids, ensuring that late-stage mummification was recorded. Parasitism rate (%) was calculated as the proportion of parasitized mealybugs relative to the total mealybugs observed on each cassava shoot tip. Parasitism rates were presented as percentages to indicate the effectiveness of parasitoid augmentation in cassava fields. Data were analyzed using analysis of variance (ANOVA) based on an RCBD. Before ANOVA, the data were evaluated for statistical assumptions, including independence (Durbin-Watson test), normality (Kolmogorov-Smirnov, Cramér-von Mises, and Anderson-Darling tests), and homogeneity of variances (Levene's, Brown-Forsythe, and F tests). The results confirmed that all data met ANOVA assumptions; therefore, no data transformation was required. Following ANOVA, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at $P<0.05$. All analyses were performed using R software.

Efficiency analysis

The efficiency of *A. lopezi* augmentation was assessed based on both cost and time required for field application, referring to procedures adapted from Pozo-Valdivia et al. (2021) and Umeda et al. (2022). The analysis compared drone-assisted and manual release techniques. For drone-assisted release, the calculated costs included drone rental and parasitoid production costs, while for manual release, costs included labor wages and parasitoid production costs. Drone rental rates were calculated on a per-hectare basis and included the pilot and battery use, while labor wages were based on the average daily agricultural wage rate in West Java during the study period. Parasitoid production costs were derived from the laboratory's total rearing expenses for *A. lopezi* mummies. According to Wasik et al. (2025), these costs consisted of material and equipment components as well as labor expenses required for mass rearing. The material and equipment components included insect rearing cages, cassava stem cuttings, liquid fertilizer, plastic cups, styrofoam, cotton, wool thread, and honey. Operational efficiency was evaluated regarding the time required per hectare (min ha^{-1}) and the total operational cost per hectare (IDR ha^{-1}), measured directly under field conditions. These results served as the basis for evaluating each augmentation technique's technical and operational feasibility.

Figure 1. A. DJI Agras T50 Spreading System drone used for parasitoid capsule distribution. B. Drone-assisted release of parasitoid capsules in cassava fields. C. Insertion of parasitoid capsules into the drone tank

A cost-benefit analysis was performed following the general framework of Hwang et al. (2025) and Umeda et al. (2022) to further assess economic feasibility. In this study, drone rental costs were calculated per-hectare basis and decreased with increasing operational area, reflecting a bulk-rate pricing system commonly used in drone services. The total operational cost for each technique was obtained by summing all fixed and variable costs across incremental field areas. The break-even point (BEP) was empirically determined as the minimum operational area at which the cumulative total cost of drone application became equal to that of manual release. This empirical BEP represented the threshold where drone deployment achieved cost equivalence with manual release, and was used to evaluate the economic feasibility and scalability of drone-assisted augmentation under field conditions.

RESULTS AND DISCUSSION

Population of *Phenacoccus manihoti* in cassava fields

Observations revealed that the population of *Phenacoccus manihoti* ranged from 19,792 to 20,150 individuals per plot (Figure 2). All developmental stages, first-instar, second-instar, and third-instar nymphs and adults, were present across the observation plots, with early instars, particularly first-instar individuals, predominating in the population structure. The average abundance of *P. manihoti* was approximately 16 individuals per plant. The relatively uniform distribution of developmental stages among plots indicates that initial infestation levels were comparable across treatments, providing a consistent baseline before parasitoid augmentation. The dominance of early instars also suggests that the population was in an active expansion phase, which is ecologically relevant for determining the optimal timing of parasitoid release.

First-instar nymphs, or crawlers, are more mobile than other developmental stages and thus play a key role in the spread of *P. manihoti* populations between plants (Parsa et al. 2012). The dominance of this stage indicates that the population is in an active growth phase, with potential for outbreaks if not controlled promptly. Early instar nymphs are considered more favorable hosts for *A. lopezi* because of their relatively thinner cuticle and less-developed defensive mechanisms, which may facilitate oviposition and parasitoid development. Moreover, their high mobility and feeding activity increase the likelihood of parasitoid-host encounters, making the prevalence of early instars an important ecological indicator for determining the optimal timing of parasitoid release to achieve maximum control efficiency (Adriani et al. 2020; Naimah et al. 2023; Salerno et al. 2024). The average abundance of 16 individuals per plant across all plots suggests that field conditions were favorable for *P. manihoti* survival and reproduction. This observation aligns with reports from other cassava-producing regions, such as Bali Island (Supartha et al. 2022), Lampung, and East Nusa Tenggara (Fanani et al. 2019), indicating that *P. manihoti* exhibits high adaptability to diverse environments. High population densities in the present study site were influenced by limited pest management interventions. This pattern aligns with reports from other cassava-growing regions where inadequate control efforts contribute to sustained *P. manihoti* populations (Fanani et al. 2019; Supartha et al. 2022). Therefore, the dominance of early instars, high population density, and favorable cultivation practices highlight the importance of timely, integrated biological control strategies, particularly through synchronized parasitoid releases that match the developmental phase of *P. manihoti* populations in the field.

Number of parasitoids for field augmentation

Based on the observed field population of *P. manihoti* and the established parasitism capacity of *A. lopezi*, a functional release ratio of 1:20 (parasitoid: host) was applied to determine the number of individuals required for effective augmentation. This ratio, supported by previous studies demonstrating that a single female *A. lopezi* can parasitize approximately 20 mealybugs (Fanani et al. 2020; Naimah et al. 2023), resulted in the deployment of 1,000 mummies per plot. Parasitoids were released in the mummy stage to preserve viability during field distribution and to ensure a gradual emergence of adults under field conditions. To maximize the functional contribution of released parasitoids, mummies were selected to favor a female-biased emergence pattern, as females are solely responsible for host parasitism (Wang et al. 2021; Borase et al. 2024). Female emergence is typically associated with larger mummies originating from later host instars (Naimah et al. 2023), and prioritizing such mummies helps ensure that the released population has strong biological activity in the field. Female-biased mummies were prioritized during preparation to enhance functional potential; however, the sex ratio was not quantified for the released batches. Thus, any discussion on the influence of sex ratio on field performance is based on established literature. This biologically optimized release composition emphasizes that successful augmentation relies not only on adequate release numbers but also on the biological quality and sex composition of the parasitoids. The standardized release density and female-biased functional profile provided a robust and comparable baseline for evaluating the performance of drone-assisted and manual release techniques.

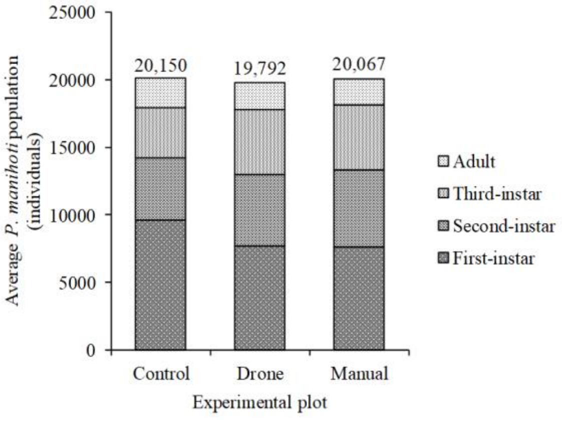

Figure 2. Population of different stages of *Phenacoccus manihoti* at three different treatments (individuals per plot)

Effectiveness of *Anagyrus lopezi* augmentation in cassava fields

Parasitism rates increased markedly following both drone-assisted and manual releases, indicating successful establishment and activity of the introduced parasitoids. Statistical analysis confirmed that augmentation treatments significantly affected parasitism levels (F = 1955.78; df = 2,11; $p<0.001$). Both drone-assisted and manual releases resulted in a comparable level of parasitism, approximately threefold higher than that observed in the control plots without augmentation (Figure 3). This result demonstrates that drone-assisted augmentation performs as effectively as manual release in suppressing *P. manihoti* populations under field conditions. The comparable performance between the two release techniques suggests that the mode of parasitoid deployment does not compromise biological efficacy, supporting the feasibility of drones as an operational tool for large-scale parasitoid distribution. From an operational perspective, this comparable effectiveness indicates that drone-assisted release can be directly adopted in field-scale parasitoid programs without compromising biological outcomes, thereby facilitating faster and more uniform implementation of augmentative control strategies.

The significant increase in parasitism observed under augmentative treatments indicates that inundative release of *A. lopezi* is effective in enhancing parasitism of *P. manihoti* in cassava fields. The natural parasitism rate in control plots was only 16.11%, consistent with reports stating that field parasitism by *A. lopezi* typically does not exceed 30% (Lema and Herren 1985). Low levels of natural parasitism may result from several factors, including low parasitoid density in the field, competition with other natural enemies such as predators or hyperparasitoids, and unfavorable environmental conditions that hinder parasitoid activity and survival, such as fluctuations in temperature and humidity or limited availability of susceptible hosts (Xia et al. 2025). Conversely, inundative augmentation rapidly increases parasitoid populations in large numbers, enabling effective suppression of pest populations regardless of natural dynamics. These findings confirm that *A. lopezi* augmentation is an effective and practical biological control strategy. Previous studies have also supported the effectiveness of parasitoid augmentation for controlling agricultural pests (Sigsgaard et al. 2017; Baoua et al. 2018; Sandanayaka et al. 2018; Salazar-Mendoza et al. 2020; Yuan et al. 2024; Burgio et al. 2025).

While the biological effectiveness of augmentation was evident, the success of field implementation can also be influenced by short-term environmental factors that affect parasitoid distribution and activity. Field implementation of *A. lopezi* augmentation is influenced by environmental conditions, particularly wind and rainfall, which affect the spatial distribution and survival of released parasitoids. Wind speed and direction can alter the trajectory of capsules during drone releases; under strong winds, capsules may drift beyond target plots, whereas calm conditions support more stable deposition. In this study, measured wind speeds during release ranged from 0.8 to 2.1 $m\ s^{-1}$, conditions that supported stable capsule trajectories and deposition within plot boundaries. Although no formal spatial analysis of capsule distribution was conducted, field observations indicated that capsules were consistently deposited inside the plots without noticeable drift or clustering. Releases were conducted in the early morning under these stable conditions to minimize environmental constraints and facilitate reliable field implementation of drone-assisted augmentation. Therefore, optimizing release timing according to local weather patterns is a key factor for maximizing the field success of drone-assisted biological control. Similar weather-related effects on drone-based releases of other biological control agents have been documented in recent studies (Lake et al. 2020; Pozo-Valdivia et al. 2021; Naharki et al. 2024; Gundreddy et al. 2024).

The findings also showed no significant difference between drone-assisted and manual release techniques, indicating that both approaches were equally effective in increasing the parasitism rate of *A. lopezi* on *P. manihoti*, consistent with previous reports that drone-based releases can achieve biological performance comparable to manual techniques (Martel et al. 2021; Pozo-Valdivia et al. 2021; Moretti and Schmidt-Jeffris 2025). This finding demonstrates that drone technology, although relatively new in applied biological control, can achieve effectiveness comparable to conventional manual release techniques. Similar findings were reported by Martel et al. (2021), who showed that drone releases of *T. minutum* were as effective as manual trichocard placement. Technically, manual release enables more precise placement of parasitoids at infestation sites; however, it requires greater time and labor input (Dionne et al. 2018). In contrast, drone releases can cover larger areas in less time with minimal labor, making them highly suitable for larger area applications. Various studies have reported the successful use of drone technology for releasing biological control agents, including parasitoids and predators (Kim et al. 2021; Moses-Gonzales et al. 2021; Pozo-Valdivia et al. 2021; Moretti and Schmidt-Jeffris 2025). The comparable effectiveness of drone releases supports the integration of technology-based approaches into parasitoid augmentation strategies.

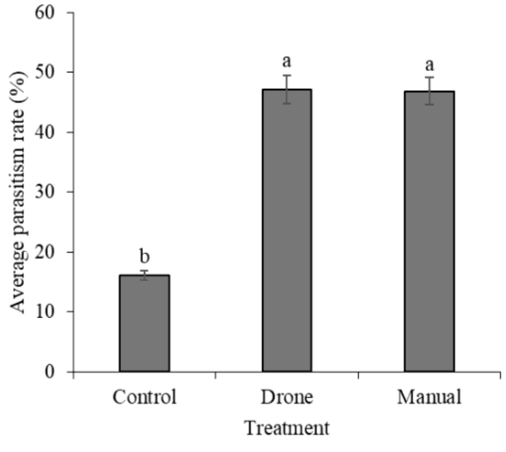

Figure 3. Parasitism rate (x ± SD) of *Anagyrus lopezi* parasitoid in each treatment. Bars with different letters indicate significant differences (Tukey test, α = 5%)

This study also highlights the technological innovation underlying the use of drones for augmentative biological control. The application of a drone-assisted release system represents the first operational use of UAVs for the augmentation of *A. lopezi* in cassava fields. Compared with conventional manual techniques, drone deployment offers several practical advantages, including higher release uniformity, reduced labor dependence, and substantial time savings. Such advantages are increasingly recognised in precision agriculture and pest-management research: drones have now been reviewed as key tools for high-efficiency agricultural operations (Junior and Nunez 2024; Guebsi et al. 2024) and specifically for biological-control applications (Martel et al. 2021; Song et al. 2023; Gundreddy et al. 2024). Moreover, the integration of drone technology into parasitoid-release programmes demonstrates its potential for area-wide implementation, especially in regions where labour availability and terrain accessibility limit manual applications.

In addition to their operational advantages, several studies have highlighted technical limitations of UAVs and agricultural drones that must be considered when applied to biological control agent releases, including payload constraints, battery endurance, and wind-induced variation in dispersal patterns (Lake et al. 2020; Agrawal and Arafat 2024; Guebsi et al. 2024; Naharki et al. 2024). Payload capacity and flight duration decrease as the load increases, which can restrict per-battery operational time and reduce field productivity (Agrawal and Arafat 2024; Guebsi et al. 2024). Wind conditions may also alter the distribution pattern of released materials, as capsule or particle trajectories can shift under moderate winds, reducing release precision unless compensated with appropriate software or mechanical adjustments (Lake et al. 2020; Naharki et al. 2024). Pre-flight calibration and adaptive route planning can help mitigate these constraints by ensuring consistent parasitoid coverage under variable environmental conditions. Continued advances in automated release modules that regulate release rates and incorporate real-time monitoring are expected to enhance system reliability for large-scale biological control programs. Overall, drone-assisted deployment of *A. lopezi* remains a feasible, environmentally friendly, and operationally effective strategy that can strengthen national cassava Integrated Pest Management (IPM) programs and support sustainable agricultural ecosystems.

Efficiency of *Anagyrus lopezi* augmentation in cassava fields

The economic evaluation was based on operational costs, including drone rental, battery use, labor wages, and parasitoid production costs. Drone rental rates were calculated on an area basis (per ha) and included the pilot and battery operation. The efficiency of *A. lopezi* augmentation was evaluated based on operational cost and time requirements in cassava fields. A cost analysis revealed that drone-assisted releases incurred higher expenses (IDR ha^{-1}) than manual techniques due to the inclusion of drone rental fees. The estimated total cost of drone-assisted releases was IDR 1,200,000 ha^{-1}, while manual releases required IDR 1,000,000 ha^{-1} (Table 1). The cost disparity was primarily attributed to the higher drone rental fee of IDR 300,000 ha^{-1}, whereas labor costs for manual release were only IDR 100,000 per ha. The cost of parasitoid materials remained identical between techniques, amounting to IDR 900,000 ha^{-1}, indicating that cost variation mainly resulted from technological rather than biological inputs.

Although the drone-assisted technique required higher initial costs (IDR ha^{-1}) due to rental fees, its economic advantage became apparent as the operational area increased. Drone deployment does not require additional labor and thus benefits from economies of scale. As the field area expanded, drone costs per hectare decreased markedly—from approximately IDR 300,000 at 1 ha to IDR 100,000 at 25 ha, and IDR 50,000 at 50 ha, while manual release costs increased proportionally with the number of workers required (Table 2). Consequently, both techniques reached cost parity at around 25 ha, marking the BEP where total costs were equal (IDR 25,000,000). The identified BEP (~25 ha) thus provides a clear operational reference: drone deployment becomes economically advantageous when applied across clustered or cooperative farming schemes exceeding this scale. Beyond this scale, drone-assisted releases achieved greater cost efficiency and offered superior scalability and time savings, making them more suitable for large-scale biological control applications in cassava fields.

Table 1. Parasitoid release cost by drone and manual per hectare

	Cost (IDR ha^{-1})	**Total cost (IDR ha^{-1})**
Drone		1,200,000
2000 parasitoid capsules	900,000	
Drone rental fee	300,000	
Manual		1,000,000
2000 parasitoid capsules	900,000	
Labor cost (1 person)	100,000	

Table 2. Comparison of parasitoid release costs by drone and manual techniques across different field sizes

Field size (ha)	**Drone (total IDR)**	**Manual (total IDR)**	**Remarks**
1	2,800,000	1,000,000	Drone costs more due to the setup cost
10	11,500,000	10,000,000	Cost gap narrows
25	25,000,000	25,000,000	Break-even point (BEP)
50	47,500,000	50,000,000	Drone becomes more cost-efficient

Table 3. Parasitoid release time by drone and manual per hectare

Job	**Time (min)**	**Total time (min/ha)**
Drone		25
Carrying a drone	3	
Opening and closing wings	1	
Calibration	5	
Confirmation of release location	2	
Putting the capsule into the tank	1	
Take-off and landing	3	
Release of parasitoids in the fields	8	
Battery exchange	2	
Manual		200
Labor briefing	10	
Confirmation of release location	8	
Capsule taking	2	
Release of parasitoids in the field	180	

These results confirm that drone-assisted parasitoid release systems can improve cost efficiency with increasing operational area. Although drone rental costs are area-dependent, larger-scale applications allow better resource utilization and reduced average costs per hectare through improved operational efficiency. Conversely, manual techniques depend on variable labor inputs, showing no cost advantage at scale. Similar findings were reported by Filho et al. (2020), Mourya et al. (2024), and Hwang et al. (2025), who emphasized that mechanization and drone applications become increasingly economical in large-scale agricultural operations. Likewise, Pozo-Valdivia et al. (2021) and Umeda et al. (2022) demonstrated that drone-based biological control reduced labor dependency and operational costs compared with manual techniques. Therefore, while manual release remains practical for small- to medium-sized cassava fields, drone deployment provides a more efficient, scalable, and cost-effective alternative for large-scale augmentative biological control programs.

In addition to cost, release efficiency was also assessed in terms of time. The drone-assisted technique required only 25 min ha^{-1}, whereas manual release took 200 min (≈ 3 h 20 min) ha^{-1} (Table 3). This time difference indicates that drone-assisted releases were up to eight times faster than manual techniques. Such time efficiency is a crucial factor for larger area augmentation programs, where rapid distribution of parasitoids can significantly impact the overall effectiveness of biological control efforts.

The time efficiency of drones stems from their ability to traverse large areas rapidly and access planting zones without being hindered by terrain irregularities or limited field accessibility. This operational advantage becomes particularly critical for large or fragmented fields with complex topography. Drone-assisted releases were significantly faster than manual techniques, completing the same coverage area in only a fraction of the time (Table 4). The speed at which drones can uniformly distribute parasitoids across cassava fields makes them well-suited for rapid and large-scale augmentative release programs. In contrast, manual techniques are constrained by terrain conditions and worker speed, leading to longer operation times, especially in extensive fields. These findings are consistent with Kim et al. (2021) and Martel et al. (2021), who reported that drone-based distribution of biological control agents substantially outperformed manual techniques in time efficiency. Similarly, Mahhendra et al. (2025) observed that drone sprayers reduced operational time by up to 82% and costs by 51.6% compared to manual spraying. Syarief et al. (2024) found that drone sprayers required only 0.17 hours/ha, compared to 11.57 hours/ha for knapsack sprayers, while Lubis et al. (2024) confirmed significant reductions in labor input and operational duration. Therefore, integrating drone technology into parasitoid augmentation programs provides a strategic advantage, particularly in enhancing operational speed and efficiency. Beyond labor savings, this approach ensures timely parasitoid distribution, supporting sustainable and environmentally friendly biological control practices. Ultimately, drone-assisted augmentation aligns with the principles of smart agriculture and strengthens the long-term sustainability of IPM systems.

Integrating drone-assisted releases offers strategic advantages for the large-scale implementation of *A. lopezi* augmentation programs. Rapid deployment enables synchronization of parasitoid releases with the early infestation phase of *P. manihoti*, thereby enhancing parasitism rates and improving biological control outcomes. Furthermore, drones help overcome operational challenges such as labor shortages and uneven terrain, allowing continuous and coordinated pest suppression across extensive cassava-growing regions. These features make drone-assisted approaches particularly suitable for area-wide management programs where timely and uniform coverage is critical. Similar benefits have been reported in other systems, where aerial release platforms significantly reduced labor inputs and improved operational efficiency compared to manual techniques (Marina et al. 2022; Gundreddy et al. 2024). Beyond direct field applications, drone technology supports broader IPM frameworks by facilitating rapid, standardized, and scalable biological control interventions.

Although drone-assisted augmentation of *A. lopezi* demonstrated high operational efficiency and economic potential in this study, its large-scale implementation in Indonesian agricultural systems may face several practical constraints. The adoption of drone-based biological control requires trained and certified operators and technical support for maintenance and calibration, which are not yet widely available in rural farming communities (Suvittawat 2024). Infrastructural limitations such as charging facilities, spare parts availability, and stable GPS or internet connectivity could also affect field operations, particularly in remote cassava-producing areas (Guebsi et al. 2024). Moreover, regulatory aspects-including flight permissions, altitude restrictions, and safety compliance under Indonesian civil aviation and agricultural regulations need to be addressed to ensure lawful and safe drone use. Therefore, the economic scalability of this technology will depend on the development of supportive infrastructure, training programs for local operators, and adaptive regulatory frameworks that facilitate the integration of drone technology into national biological control programs. Addressing these challenges through policy intervention and institutional collaboration will be crucial to translating the demonstrated efficiency of drone-assisted approaches into sustainable, large-scale applications.

To overcome these challenges and maximize the benefits of drone-assisted augmentation, supportive policies, including drone regulation, operator certification, and digital monitoring systems, are essential to ensure safe and efficient implementation. Developing regional frameworks that promote collaboration among agricultural agencies, researchers, and local stakeholders would strengthen national IPM initiatives and accelerate the transition toward sustainable, technology-driven pest management systems. Building upon these operational advantages, this study highlights several aspects that warrant further investigation to optimize drone-assisted augmentation strategies. While this study provides valuable insights into the operational and economic feasibility of drone-assisted *A. lopezi* augmentation, further research could expand its applicability under broader field conditions. The current experiment was conducted in a single location and cropping season; therefore, multi-location and multi-season evaluations would be valuable to confirm consistency under different agroecological zones and climatic conditions. Although the spatial uniformity of parasitoid capsule distribution was not quantitatively assessed, the comparable parasitism rates across treatments suggest that *A. lopezi* effectively dispersed and located its host under drone-assisted release. Future research integrating spatial mapping of capsule distribution, parasitoid dispersal dynamics modeling, and drone flight parameters refinement could further enhance precision and biological efficacy. Such advancements will enhance the scalability and reliability of drone-assisted biological control, contributing to more sustainable and technology-driven cassava pest management programs. Overall, drone-assisted augmentation represents a viable model for integrating precision technology into national IPM frameworks, bridging ecological effectiveness with operational scalability to achieve sustainable pest suppression.

In conclusion, the augmentative release of *A. lopezi*, either manually or via drone-assisted techniques, effectively increased parasitism of *P. manihoti* under field conditions. Drone-assisted releases achieved similar biological performance to manual techniques while providing greater time and labor efficiency. These findings confirm that drone technology offers a reliable and environmentally friendly alternative for large-scale parasitoid deployment in cassava fields. Drone-assisted techniques can support synchronized parasitoid releases across wide cultivation areas, enhancing the consistency and spatial reach of biological control. Policy support, operator training, and standardization frameworks are essential to ensure safe and effective implementation. Future studies should optimize dispersion precision and release mechanisms to further improve operational efficacy. Drone-based augmentation represents a practical step toward sustainable, technology-driven pest management systems in Indonesia and other cassava-growing regions.

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