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Weed control efficiency of unmanned aerial vehicle spray in replanting oil palm plantation areas

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Abstract

Efficient chemical weed management considers precise application of herbicides, maximizing herbicide retention and absorption, reducing the impact of abiotic factors, and mitigating off-target movement in order to optimize herbicide efficacy. Hence, this study assessed the employability and cost-efficiency of an unmanned aerial vehicle (UAV) for preplanting application and postemergence selective weed control of grasses infesting legume cover crops (LCCs) in an immature oil palm (*Elaeis guineensis* Jacq.) plantation. Field experiments were conducted in 2020 and 2021 at a research center and an oil palm replanting area in Jerantut, Pahang, Malaysia. Droplet deposition and distribution analyses revealed that the pressure at 0.25 MPa yielded better spray coverage and increased droplet counts compared with 0.15 MPa. For preplanting application, both the UAV and mist blower resulted in total weed control. Meanwhile for selective grass control in the LCCs, conventional knapsack sprayer (CKS) application provided slightly better weed control than the UAV over the 12-wk observation. However, a cost-efficiency analysis revealed that UAV spraying yielded economically favorable results for areas greater than 3,000 ha, with potential savings ranging from 4% to 28%. Furthermore, UAV spraying demonstrated superior operational efficiency and reduced working hours by 37%, water consumption by 91%, and human labor expenses by 81% compared with both conventional methods. These findings underscore the potential of UAV-based spraying for large-scale weed control in oil palm plantations and highlight its efficiency, comparable effectiveness, and cost-saving benefits.

Introduction

Weed control is economically critical during the oil palm (*Elaeis guineensis* Jacq.) replanting phase to ensure uninterrupted growth of both oil palm seedlings and cover crops (Goh et al. 2015). Current practice relies on conventional methods, particularly mechanical removal and chemical control using herbicides through various spraying techniques, including knapsack sprayers, mist blowers, boom sprayers, and motorized power sprayers. However, spraying with ground-based equipment is often laborious and time-consuming (Matthews et al. 2014; Oerke 2006). Given the persistent labor shortage in oil palm plantations, there is an urgent need to automate labor-intensive tasks like harvesting and pesticide application. Spray operators also face challenges in achieving uniform herbicide distribution across certain areas (Chavan 2019), due to limited ground accessibility caused by irregular terrain such as steep slopes, undulating landscapes, and water-saturated soils. Thus, deployment of an aerial sprayer is ideal for targeting isolated patches of weeds, especially in relatively small fields or areas with uneven distribution and varying elevations that are challenging to access without causing damage to the crops (Wang et al. 2020).

The use of an unmanned aerial vehicle (UAV) for aerial spraying is an effective technique for reducing tedious and time-consuming operations (Chen et al. 2019; Sun et al. 2020; Wang et al. 2022) by at least 33% compared with conventional approaches (Su et al. 2018). For instance, Qin et al. (2016) successfully demonstrated the spray efficiency and minimal damage of miniaturized UAVs over the conventional stretcher sprayer for pesticide spraying in hilly areas of China. Castaldi et al. (2017) also highlighted a precision weed control system incorporating weed maps and an aerial spray system, which substantially reduced herbicide use by 39% compared with a traditional blanket application. A key advantage of aerial application is its speed and capacity for covering large areas quickly, making it ideal for accessing crops in remote or inaccessible locations, while minimizing potential crop damage and soil compaction associated with ground machinery (Cerro et al. 2021). Furthermore, aerial application reduces the risk of herbicide exposure for applicators by minimizing ground contact during spraying (Berner and Chojnacki 2017).

Effective preplanting weed control is crucial to ensure optimum growth of young palms in the replanting areas and involves two strategies: the broadcast application of preplant herbicides and application of grass-selective postemergence herbicides within the legume cover crops (Felda Global Ventures 2018). Given the pressing labor issues and the drive for improved efficiency, researchers are exploring alternative methods for a more cost-efficient weed control in oil palm plantations. One promising approach is the use of UAV for herbicide applications. Preliminary findings by Felda Global Ventures Research and Development (FGV R&D) observed that UAV spraying at the replanting stage can boost operational productivity from 3 to 4 ha man-day^{-1} to 10 to 12 ha man-day^{-1}. The adoption of UAV technology not only yields substantial labor savings but also demonstrates increased efficiency (Zhang et al. 2019). Furthermore, remotely operating the aerial sprayer and tank filler minimizes direct contact with chemicals during spraying operations, thereby reducing long-term chemical exposure (Reddy et al. 2020). Nonetheless, there is a lack of documentation on using aerial sprayers in oil palm plantations, particularly for broadcast spraying in replanting areas and targeted selective herbicide application in cover crops. Therefore, this study evaluated the weed control efficiency, crop phytotoxicity, and productivity of UAV spraying in the replanting areas of oil palm plantations.

Material and Methods

UAV Specification

A custom-made electrical-powered UAV (Figure 1A) sprayer was obtained from VTS Universe Sdn. Bhd., Selangor, Malaysia. The UAV had dimensions of 110-cm length/width and 65-cm height and was equipped with a 120-cm boom length with six rotors, six flat-fan nozzles, and six sets of propellers. The six downward-oriented nozzles with a spray angle of 80° delivered a spray width measuring from 27 to 33 cm per nozzle and produced droplets sized 225- to 325-μm volume median diameter (VMD). The droplet intensity produced was a minimum of 40 droplets cm^{-2}. The UAV spray system had a 16-L capacity tank and a 15-kg payload.

Characterization of Droplet Deposition

The research was conducted in an open field at Tun Razak Agricultural Research Centre, FGV Agri Services Sdn. Bhd. (3.8828°N, 102.5210°E), a scientific research base in Jerantut District, Pahang, Malaysia. Spray deposition was determined using two pressures, 0.15 and 0.25 MPa, with a pressure gauge mounted on the aerial sprayer to ensure accurate measurements (Figure 1B). The operation height was maintained 3 m above the soil surface, and the flight speed was 4 m s^{-1}.

Water-sensitive paper (WSP; SpotOn® Paper, Washington, NJ, USA) was used to examine the coverage and distribution of droplets falling onto the ground. Briefly, the WSP was cut into small rectangular pieces (2 cm by 2 cm) and then placed in a straight, central line, 1 m apart on a rubber wooden block spanning 10 m in total (Figure 2). The placement of WSP on the ground in a straight line served as qualitative and quantitative markers of the operations performed (Berner and Chojnacki 2017; Wang et al. 2020). The sample positions were replicated three times in the direction of the spray, with an interval of 10 m between each repeat. At 30 s after spraying, samples were photographed, and all WSP was collected and placed in plastic bags labeled with site information.

Sampling was only carried out at the center of each plot to prevent cross-contamination between fields. Number of droplets, density of droplets, and percentage of droplet coverage of the WSP were assessed using the SnapCard application (Android app developed by the University of Western Australia, Perth, Australia) and ImageJ software v. 1.53t (an open-source Java-based image software developed by the University of Wisconsin–Madison, WI, USA). The coverage was calculated as the percentage of the WSP surface area covered by blue-dyed droplets (Ferguson et al. 2016; Lou et al. 2018).

Spray Setting

The aerial spray operation (UAV) flow rate was set up between 2.1 and 2.7 L min^{-1}, delivering 40 L ha^{-1} over the target area. The spray was delivered through six flat-fan nozzles mounted on a boom at a pressure of 0.25 MPa. The target application zone covered a 3-m-wide swath at a height of 3 m. The UAV sprayer was flown at a speed of 4 m s^{-1}, aiming for a medium droplet size of 225 to 325 μm with a minimum density of 40 droplets cm^{-2}. Table 1 summarizes the spray parameter settings. Meteorological conditions before UAV spraying were recorded using a weather meter (Kestrel 5500AG, Nielsen-Kellerman Company, Boothwyn, PA, USA). Spraying was conducted when wind speeds were below 4 m s^{-1}, with temperatures between 30 and 40 C and a relative humidity below 60%. The application rate, flow rate, spray width, and forward speed were calibrated before herbicide treatment, in accordance with a protocol described by Matthews et al., (2014) as follows:

Calculation of spray volume:

$$\text{Liter/hectare} = \frac{\text{Flow rate (Lmin}^{-1}) \times 10,000\ \text{m}^2}{\text{Swath (m)} \times \text{travel speed (mmin} - 1)} \quad [1]$$

$$\text{Flow rate} = \frac{\text{Nozzle output}}{10,000 \times \text{swath} \times 60\ \text{s}} \quad [2]$$

Chemical used per pump:

$$\text{Rate per pump} = \frac{\text{Herbicide recommended rate (Lha}^{-1}) \times \text{pump capacity}}{\text{Spray volume (Lha}^{-1})} \quad [3]$$

Broadcast Spraying at the Replanting Stage

The efficacy of a UAV for a broadcast preplanting application was assessed by comparing weed control efficiency between two application methods: a mist-blower application at 50 L ha^{-1} and UAV application at 40 L ha^{-1}. The mist blower (SR430, Stihl, Andreas Stihl AG & Co. KG, Waiblingen, Germany) was equipped

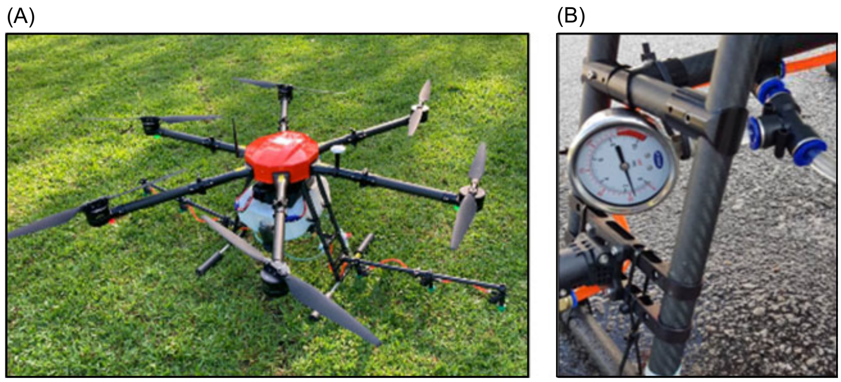

Figure 1. (A) Customized electric-powered unmanned aerial vehicle (UAV) and (B) a pressure gauge mounted on the UAV.

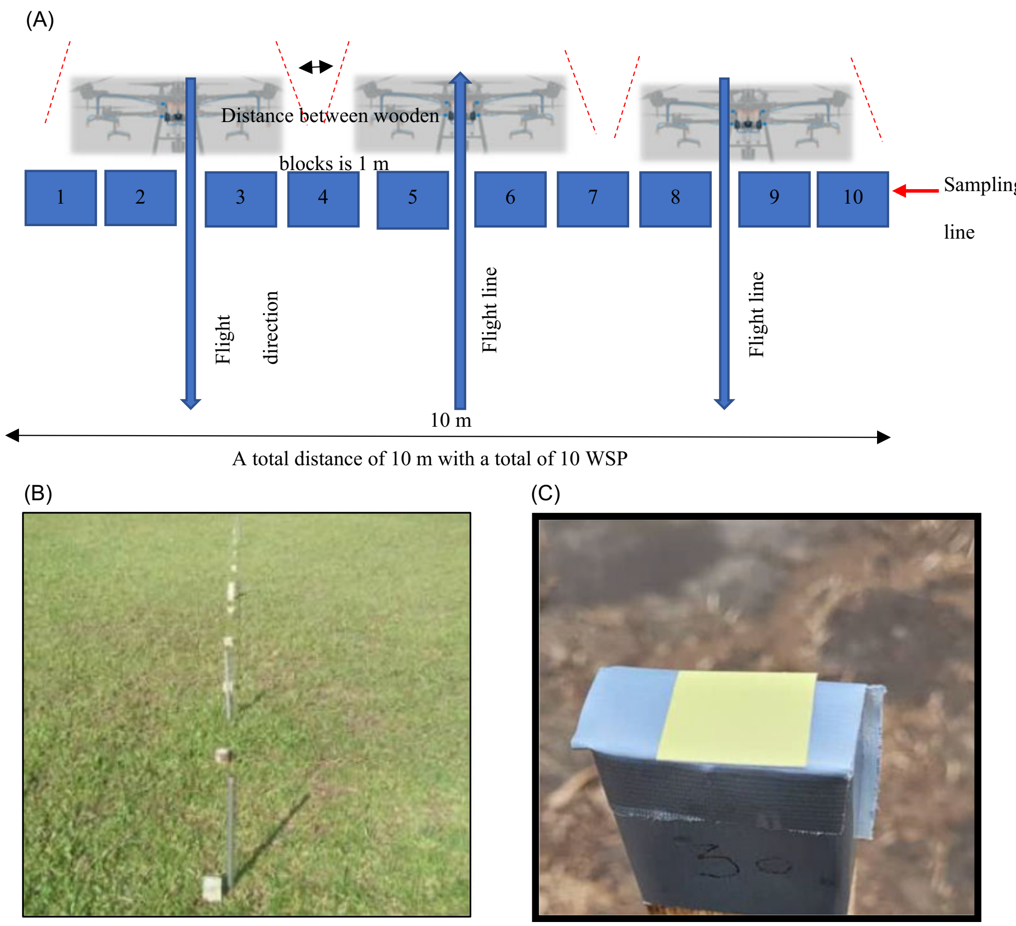

Figure 2. (A) Back-and-forth unmanned aerial vehicle (UAV) operating procedure in which deposition of the left wing overlaps with that sprayed by the right wing. (B) Water-sensitive paper (WSP) positioning in the open field and on the (C) wooden block.

with a 14-L tank, cone nozzle, deflection, and double-deflection mesh for uniform dispersion. Its specifications included a two-stroke engine, a spray swath of 10 m, and an adjustable pressure range from 0 to 3 MPa.

The spraying activities were conducted at the FGV Plantation Malaysia (FGVPM), Mengkarak 2 (3.2986°N, 102.3338°E), Bera, Pahang, Malaysia. The study area covered a total of 10 ha, with each hectare divided into 10 plots. The terrain was relatively flat, and the replanting area had a high weed density. Each experimental plot was subjected to a specific treatment with an application method. To mitigate border effects, 1.0-m-wide strips were excluded from each edge of a plot. The working width for spraying operations was set at 100 m to maintain a consistent spraying speed across the area analyzed. Buffer zones separated the plots, with each plot spaced 50 m apart to ensure sufficient separation between treatments and minimize potential cross-contamination or interference between adjacent plots. The herbicides used in the study were a tank mix of glyphosate isopropylamine (Roundup® Bayer Crop Science, St Louis, MO, USA), at 608 g ai ha^{-1} and metsulfuron-methyl (Ally®, Corteva Agriscience, Wilmington, DE, USA) at 30 g ai ha^{-1}. The application

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Table 1. Spray parameter settings.

Parameter	Unit	Setting
Flow rate	L min^{-1}	2.1-2.7
Spray volume	L ha^{-1}	40
Number of nozzles and type	—	Six flat-fan nozzles
Nozzle spray system	—	Boom spray at 1.2 m
Spray pressure	MPa	0.25
Spray height and spray width	m × m	3 × 3
Flying speed	m s^{-1}	4
Droplet size in volume median diameter (VMD)	µm	Medium: 225–325
Droplet intensity	cm^{-2}	Min. 40
Aerial spray productivity	ha d^{-1}	10–15
Wind speed	m s^{-1}	< 4
Temperature	C	30–40
Relative humidity (RH)	%	<60
Delta T (evaporation rate and droplet survival)	—	2–8
Wind speed	km h^{-1}	5 ± 1
Time of day	—	0800–1100 hours
Cloud cover	—	Partly cloudy

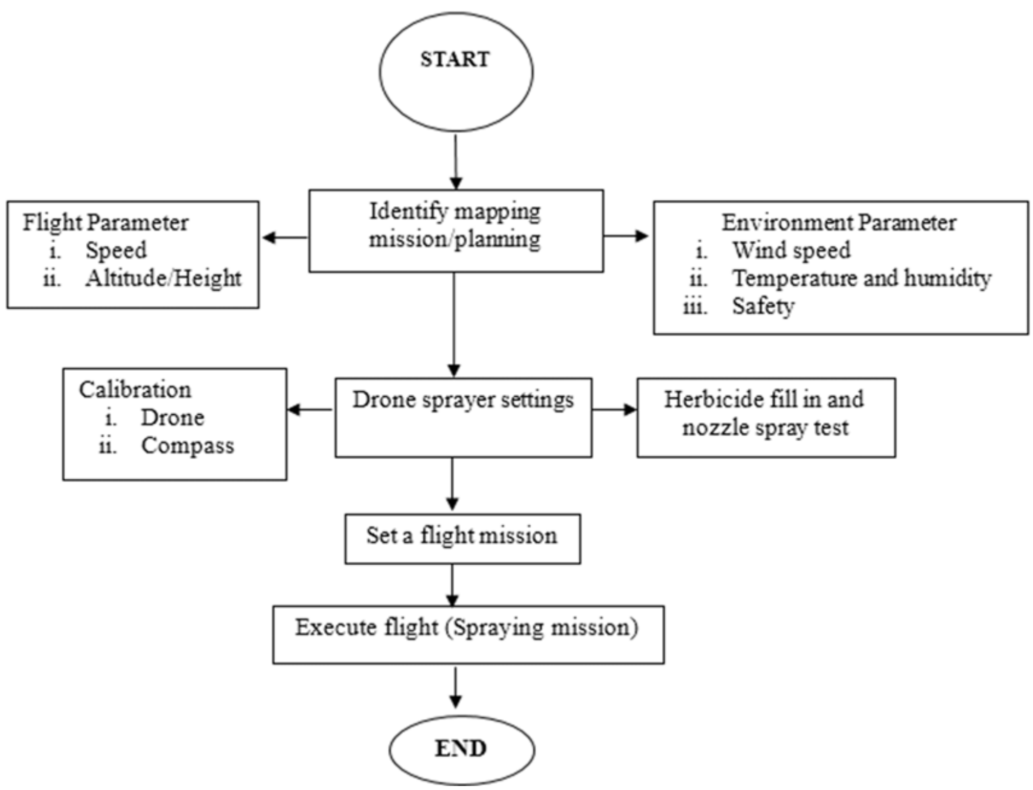

Figure 3. Unmanned aerial vehicle (UAV) spraying operation flowchart including preflight preparations, mission planning, calibration, flight execution, and postflight procedures.

rate was 50 L ha^{-1} and 40 L ha^{-1} for the mist blower and the UAV, respectively. Polyether-modified siloxane (Miracle® S240, G-Planter Sdn. Bhd., Selangor, Malaysia) at 1 ml L^{-1} was used as the adjuvant to enhance spraying effectiveness, and a colorant (Clear View, G-Planter) at 1 ml L^{-1} was added for monitoring purposes. The entire operation flowchart is depicted in Figure 3.

Selective Postemergence Herbicides within Cover Crops

To evaluate the efficacy of a UAV for selective spraying of legume cover crops, the productivities of a conventional knapsack sprayer (CKS) at 450 L ha^{-1} and a UAV application at 40 L ha^{-1} were compared. Spraying operations were conducted at Tun Razak Agricultural Research Centre, Jengka, Pahang (3.7687°N, 102.5454°E), covering a total area of 2 ha. In this study, an undulating replanting area consisting of immature (15- to 16-mo) oil palm trees was chosen, where the legume cover crops (LCCs) sinhala (*Mucuna bracteata* DC) (50%), tropical kudzu [*Pueraria javanica* (Benth.) Benth.] (30%), and calopo (*Calopogonium mucunoides* Desv.) (20%) had been established 6 mo prior.

A CKS (PB16, Jun Chong Sdn. Bhd., Kluang, Johor, Malaysia) with 16-L tank capacity was equipped with a flat-fan nozzle for

Table 2. Linear rating scale for weed efficacy assessment.[a]

Code	Effect	Rating	Level of control	Description
1	Complete	100	Complete control	Destruction of weeds
2	Severe	90	Excellent control	Very few weeds alive
		80	Good control	Stunted new weed seedlings
		70	Satisfactory	Severe injury stand loss, almost destroyed
3	Moderate	60	Moderate control	Near severe injury to weed; no recovery possible
		50	Deficient or moderate control	Persistent recovery doubtful
		40	Deficient control	Moderate injury recovery possible
4	Slight	30	Poor to deficient	Injury more pronounced but not persistent
		20	Poor control	Some stand loss stunting or discoloration
		10	Inferior control	Slight stunting, injury, or disorders
5	None	0	No control	No injury due to herbicide application/normal

[a]Source: Vanhala et al. (2004).

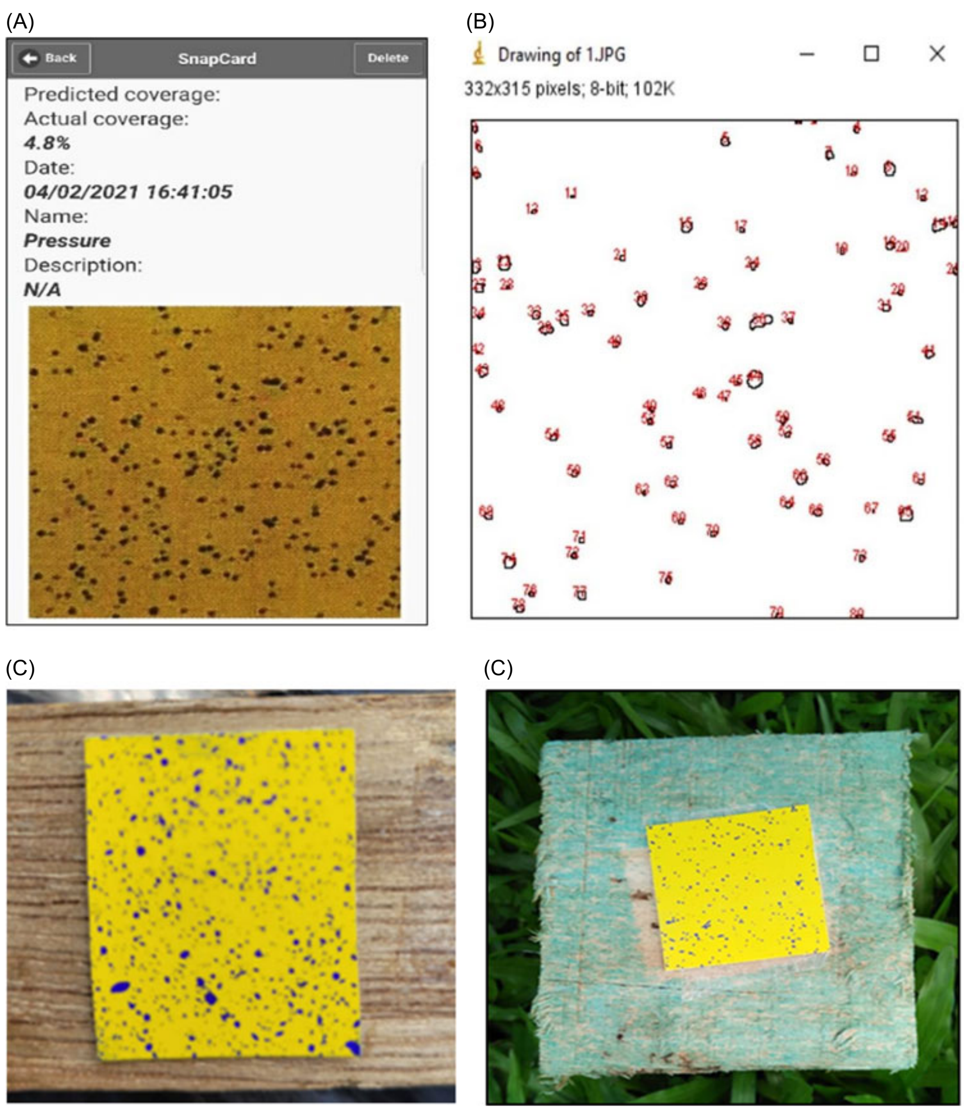

Figure 4. Droplet analysis using (A) SnapCard application and (B) ImageJ software and (C) spray deposition on water-sensitive paper (WSP).

uniform dispersion. Its specifications included a manual pump, adjustable pressure settings, and a 60-cm-long spray lance. The spray zone was 3-m wide in the area between the oil palm trees, with a row interval of 7.9 m. The selected herbicide for weed control was fluazifop-*p*-butyl (Fusilade®, Syngenta Crop Protection AG, Basel, Switzerland) at 1.98 g ai ha^{-1} with the addition of polyether-modified siloxane (Miracle® S240, G-Planter) at 1 ml L^{-1} as an adjuvant and 1 ml L^{-1} of colorant (Clear View, G-Planter, Malaysia) for monitoring purposes. The targeted weed species were hilograss (*Paspalum conjugatum* P.J. Bergius) and slender panicgrass [*Ottochloa nodosa*

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(Kunth) Dandy], and the spray method involved interrow application between the LCCs.

Weed Control Efficacy

The percentage of weed control efficacy was determined by counting the number of plants showing necrosis from the growing tips to the soil surface at 1, 2, 3, 4, 6, 8, and 12 wk after treatment (WAT). A visual scoring scale index was used to assess the impact of herbicides on target weeds, as presented in Table 2.

Spray Effectiveness

Aerial image capture was performed using a Phantom 4 Pro Multispectral multicopter (DJI, Shenzhen DJI Sciences and Technologies Ltd., Shenzhen, China) with a Sequoia Multispectral sensor before and after the spraying, with images captured 1 wk after spraying and then at 2-wk intervals in the subsequent weeks. The captured images were analyzed to determine the effectiveness of the herbicide spray. The acquisition of images in the visible, near-infrared, and short-wave infrared wavelength bands is referred to as multispectral remote sensing (Amigo 2019). Different objects reflect, absorb, and transmit certain bands of wavelength that can be captured using multispectral cameras.

The multispectral images were analyzed using an unsupervised classification technique in Earth Resources Data Analysis System (ERDAS) Imagine (Atlanta, GA, USA). Continuous raster data were classified into discrete thematic groups with similar spectral-radiometric characteristics. ERDAS Imagine utilizes the iterative self-organizing data analysis technique (ISODATA) clustering technique for unsupervised training and classification, which uses data statistics to evaluate the similarities and differences of pixel values before grouping them into distinct classes.

Cost Efficiency

The total costs per hectare and the annual cost per hectare (MYR ha^{-1} yr^{-1}) were determined by considering chemical, labor, water, maintenance, number of spraying rounds, aerial sprayer, and transportation costs. All treatments were evaluated based on their cost-efficiency. All prices corresponded to the standard prices (open market). The cost-efficiency was calculated following Turner and Gillbanks (2003):

$$\text{Cost} - \text{efficiency (\%)} = 100 - \left[\left(\frac{a}{b}\right)\times 100\right] \quad [4]$$

where *a* represents the cost per hectare per year (cost ha^{-1} $year^{-1}$) from the treated plot and *b* is the per hectare per year (cost ha^{-1} $year^{-1}$) from the untreated plot. The cost components consist of herbicide application and operational costs. The herbicide application cost considers herbicide price per liter, herbicide dosage per hectare, and the percentage of the total treated area. The operational cost component is the sum of labor, water, maintenance, transportation, and UAV aerial spraying costs per hectare multiplied by the actual number of spraying rounds conducted throughout the year.

Time-Motion Study

A time-motion study compared mist-blower and UAV-spraying weed control. The time was taken from the start of the spray and stopped at the end of the spraying mission. The working hours, operating time, and productivity (ha man-day^{-1}) to complete the task were recorded to compare the cost-efficiency between the two spray methods.

Table 3. Droplet distribution estimates on water-sensitive paper (WSP) at 0.15 and 0.25 MPa analyzed using SnapCard and ImageJ.

Spray pressure	WSP card no.	Droplet coverage		Droplet count
		SnapCard	ImageJ	ImageJ
MPa		%		cm^{-2}
0.15	1	2.2	1.3	80 ± 0.18
	2	3.3	3.2	197 ± 1.53
	3	3.0	2.2	151 ± 0.67
	4	3.6	2.6	123 ± 2.45
	5	3.5	2.8	131 ± 1.96
	6	4.9	4.9	241 ± 0.34
	7	3.8	3.6	158 ± 1.74
	8	3.1	2.1	118 ± 1.85
	9	2.6	1.0	64 ± 2.53
	10	2.5	2.3	119 ± 1.26
0.25	1	5.2	4.7	272 ± 0.46
	2	4.7	2.7	183 ± 1.77
	3	4.8	4.1	218 ± 0.73
	4	5.0	4.2	226 ± 1.64
	5	4.2	2.7	135 ± 2.60
	6	4.3	2.8	168 ± 1.68
	7	4.9	4.7	282 ± 0.83
	8	5.6	8.6	424 ± 1.52
	9	3.5	2.0	104 ± 0.91
	10	2.9	1.1	69 ± 0.58

Data Analysis

The image classification was analyzed using an unsupervised classification technique in ERDAS Imagine for multispectral images. Continuous raster data were classified into discrete thematic groups with similar spectral-radiometric characteristics. ERDAS Imagine software, as previously described, employs the ISODATA clustering technique for unsupervised classification, grouping pixels into distinct classes based on statistical similarities.

Statistical Analysis

Both experiments employed a randomized complete block design with four replications. The general structure of the statistical model for the ANOVA is represented as follows:

$$Y_{\text{ijk}} = \mu + \tau_i + \beta_j + \varepsilon_{ijk} \quad [5]$$

where the ANOVA assesses whether there are significant differences in the mean response variable (*Y*) among the treatment levels (τi) after accounting for the variation due to the random effects (βj) and error term (ϵijk). Data on weed control efficacy were collected from two separate comparisons: (i) the preplanting application of mist-blower versus UAV, and (ii) selective postemergence application comparing CKS and UAV spraying in selective postemergence application were subjected to one-way ANOVA using SAS v. 9.4 (SAS Institute, Cary, NC, USA) to determine significant differences between treatments. Means comparisons were performed using the Tukey's test at a 5% significance level.

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Table 4. Wind speed (m s^{-1}) and wind direction (°) during spraying on 10 water-sensitive paper (WSP) positions.

Position of WSP		1	2	3	4	5	6	7	8	9	10
Wind speed	ms^{-1}	8.5	12.8	11.5	10.2	10.5	13.1	12.0	8.9	13.1	9.2
Wind direction	°	70	115	120	50	85	110	90	40	110	80

Table 5. Multispectral analysis of weed vegetative cover at 0, 8, 22, and 26 d after treatment (DAT).[a]

Image		1	2	3	4
		0 DAT	8 DAT	22 DAT	26 DAT
Weed vegetative cover	ha	1.65 ± 0.43	1.26 ± 1.24	1.11 ± 0.56	0.51 ± 0.29
Weed vegetative cover	%	100	76.4	67.3	31.0

[a]Data are mean ± SD.

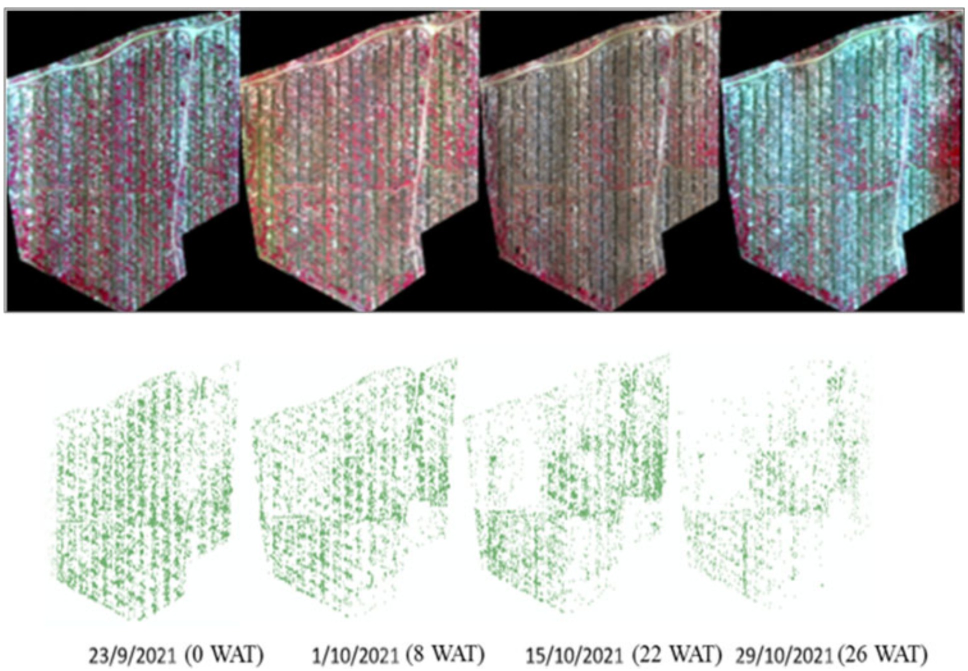

Figure 5. Monitoring weed cover at 0, 8, 22, and 26 d after treatment (DAT) using aerial imaging system equipped with multispectral sensor.

Results and Discussion

Droplet Deposition and Distribution

Droplet distribution on WSP at two different spray pressures (0.15 and 0.25 MPa) was analyzed using SnapCard and ImageJ imaging software (Figure 4). At a lower pressure of 0.15 MPa, droplet coverage, as determined by SnapCard and ImageJ analysis, ranged from 2.2% to 4.9% and 1.0% to 4.9%, respectively (Table 3). The number of droplets deposited varied between 64 to 241 droplets cm^{-2}. When the spray pressure was increased to 0.25 MPa, both imaging analyses revealed a broader spectrum of droplet counts, ranging from 69 to 424 droplets cm^{-2}, and an increase in droplet coverage. These findings show that higher pressure (0.25 MPa) resulted in a more uniform spray pattern and greater coverage compared with lower pressure (0.15 MPa). It is important to note that this study was limited by the maximum pressure capacity of the spraying equipment (0.25 MPa). Thus, further investigation at higher pressures could provide valuable insights into spray uniformity and coverage improvements.

The quality of spray coverage is influenced by droplet size, the number of deposits, and the coverage extent on target leaves (Zhu et al. 2011). Herbicide effectiveness is determined in part by the number of spray droplets per unit area, with more droplets increasing the likelihood of reaching the critical threshold for weed control. Both SnapCard and ImageJ were used to assess droplet distribution to ensure optimal spray quality (Table 3). At a pressure of 0.25 MPa, more droplets are produced. Shan et al. (2021) asserted that a minimum rate of 40 droplets cm^{-2} is required for effective weed control. SnapCard analysis showed that a coverage rate exceeding 4.5% corresponds to more than 40 cm^{-2}, making it a reliable method for auditing spray coverage. Between the two pressures tested, 0.25 MPa proved to be the most effective for spraying. This finding is supported by Xiao et al. (2020), who suggested a pressure range of 0.25 to 0.35 MPa for optimal coverage. Spray pressure influences droplet formation, because nozzles are designed to operate within a specific pressure range (Guo et al. 2021). Droplet distribution analysis on WSP cards at two different pressures demonstrated distinct differences. At 0.15

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Table 6. Weed efficacy (%) between the use of mist blower and unmanned aerial vehicle (UAV) spray from 1 to 12 wk after treatment (WAT) in the preplanting application for general weed control in replanting area.[a]

		Weed control efficacy[b]						
Treatment	Rate	1 WAT	2 WAT	3 WAT	4 WAT	6 WAT	8 WAT	12 WAT
	L ha^{-1}	%						
Control	Untreated	0 ± 0 b	0 ± 0 b	0 ± 0 b	0 ± 0 b	0 ± 0 b	0 ± 0 b	0 ± 0 b
Mist blower	50	85.70 ± 0.20 a	100 ± 0 a	100 ± 0 a	100 ± 0 a	100 ± 0 a	100 ± 0 a	100 ± 0 a
Customized UAV spray	40	85.68 ± 0.12 a	100 ± 0 a	100 ± 0 a	100 ± 0 a	100 ± 0 a	100 ± 0 a	100 ± 0 a

[a]Data are means ± SE ($n = 8$). Means of treatments with the same letter for consecutive doses do not differ significantly at $P < 0.05$ (Tukey's test).
[b]Major weed species: *Paspalum conjugatum* (sour paspalum), *Ageratum conyzoides* L. (billygoat-weed), *Asystasia gangetica* (L.) T. Anderson (Chinese violet), *Ottochloa nodosa* (Kunth) Dandy (nodose grass), and *Borreria latifolia* (Aubl.) K. Schum. (broadleaf buttonweed). Soil type: Renggam series (Typic Paleudult — well-drained clay loam, developed from granite, characterized by moderate fertility and good drainage properties).

Table 7. Weed efficacy (%) between the use of conventional knapsack sprayer (CKS) and unmanned aerial vehicle (UAV) spray from 1 to 12 wk after treatment (WAT) for purification of legume cover crop.

		Weed control efficacy[ab]						
Treatment	Rate	1 WAT	2 WAT	3 WAT	4 WAT	6 WAT	8 WAT	12 WAT
	L ha^{-1}	%						
Control	Untreated	0 ± 0 c	0 ± 0 c	0 ± 0 c	0 ± 0 c	0 ± 0 c	0 ± 0 c	0 ± 0 c
CKS	450	23.92 ± 0.32 a	56.40 ± 0.24 a	80.24 ± 0.20 a	82.41 ± 0.10 a	(14.00 ± 0.30) a	(24.00 ± 0.18) a	(31.00 ± 0.39) a
Custom UAV spray	40	13.88 ± 0.33 b	45.82 ± 0.15 b	70.12 ± 0.31 b	71.54 ± 0.29 b	(23.94 ± 0.25) b	(34.80 ± 0.24) b	(43.88 ± 0.27) b

[a]Data are mean ± SE ($n = 8$). Means of treatments with the same letter for consecutive doses do not differ significantly at $P < 0.05$ (Tukey's test).
[b]Major weed species: *Paspalum conjugatum* and *Ottochloa nodosa.* Soil type: Katong series (Typic Hapludox—sandy clay loam).

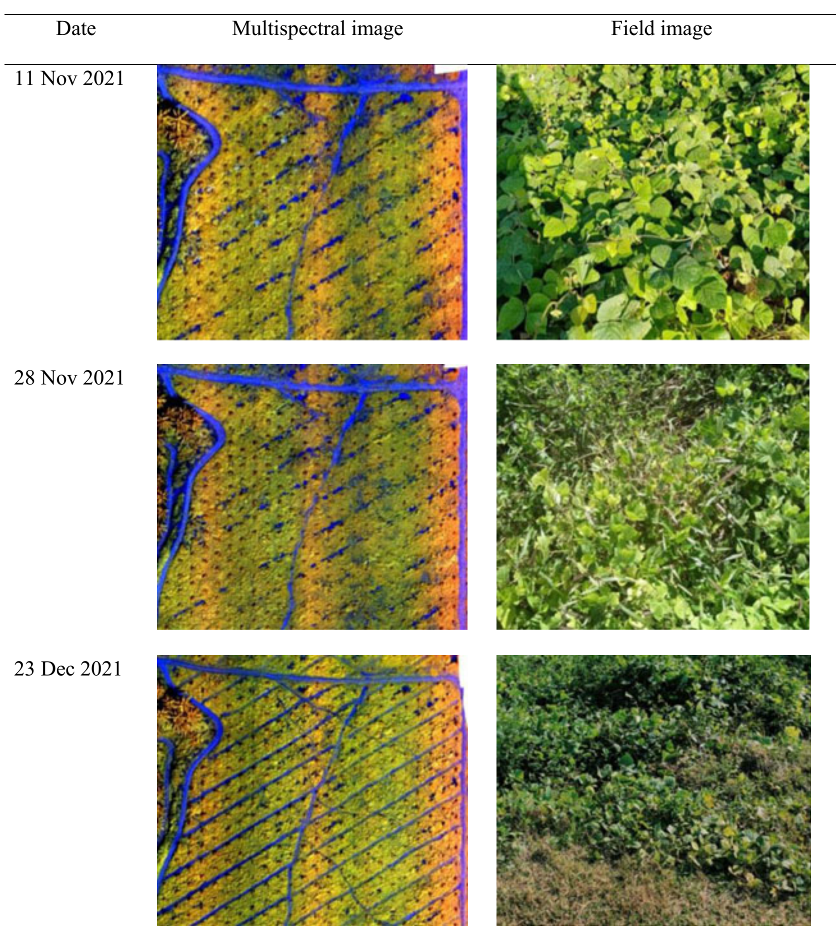

Figure 6. Visualizing the efficacy of unmanned aerial vehicle (UAV)-based multispectral imaging in weed detection and field images of legume cover crops.

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MPa, cards 4, 5, 6, and 7 had more than 3.5% coverage, with the minimum coverage being 2.2% on card 1. On the other hand, at 0.25 MPa, the maximum and minimum coverages were 5.6% and 2.9% on cards 8 and 10, respectively.

Optimal flight height during aerial spraying represents a delicate balance between minimizing herbicide drift and achieving uniform coverage across the target area. Flying too high increases the risk of spray drift, where the wind carries the droplets away and they fail to reach the intended target. On the other hand, flying too low can cause uneven distribution, resulting in insufficient coverage on the upper parts of the plants or excessive application on the lower parts. This not only leads to wastage but also risks damaging the crops. The analysis conducted using SnapCard and Image J software showed that natural wind velocity and direction influenced the position of the spray swath (Table 4). Wind speed measured at various instances during the experiment showed variability, ranging from 8.5 m s^{-1} to 13.1 m s^{-1}. These variations can significantly impact the movement and dispersion of herbicide droplets. Higher wind speeds (13.1 m s^{-1}) can potentially lead to greater horizontal movement of sprayed droplets, affecting the coverage and distribution of the herbicide. Lower wind speeds (7.8 m s^{-1}) may result in less horizontal movement, providing better control over the placement of sprayed materials. The wind speed values should be considered in herbicide application, with higher wind speed increasing the risk of drift and off-target movement. On the other hand, wind direction data represent the direction from which the wind is blowing at each measured instance.

The wind direction values varied between 40° and 120°, indicating different wind directions during the observation period. Wind direction is crucial for understanding how herbicides may drift. For instance, wind blowing parallel to the direction of herbicide application may result in less lateral movement. Variations in wind direction can influence the position and coverage of the swath region during herbicide application. Herbicide applicators should consider wind direction to minimize drift and ensure the herbicide is effectively delivered to the target area. The combination of wind speed and wind direction is essential for understanding the dynamics of herbicide application. Higher wind speeds may increase the risk of drift, and the direction of the wind plays a critical role in determining the trajectory of sprayed materials. Therefore, herbicide applicators need to carefully consider these factors to optimize efficacy while minimizing environmental impact.

Table 8. Cost-efficiency comparison between conventional knapsack sprayer (CKS) and unmanned aerial vehicle (UAV) spray for Felda Global Ventures (FGV Group).

Area	Total cost of weeding for FGV group[a]		Cost saving by using UAV spray[b]	
	CKS	UAV spray[c]		
Ha	MYR yr^{-1}		MYR yr^{-1}	%
1,000	216,020	341,620	(125,600)	−58
2,000	432,040	483,240	(51,200)	−12
3,000	648,060	624,860	23,200	4
4,000	864,080	766,480	97,600	11
5,000	1,080,100	908,100	172,000	16
15,000	3,240,300	2,324,300	916,000	28

[a]Total cost per hectare includes chemical, labor, aerial sprayer (aerial spraying, aerial photo + other equipment), maintenance, transport, and water costs. Price of herbicides according to FGV's price list in 2022. Total replanting areas: 15,000 ha^{-1} yr^{-1}; coverage area: 100% with 2 rounds per year.

[b]Values in parentheses indicate no cost saving (i.e., exceeds the total cost).

[c]UAV value: MYR100,000 (capital expenditure), with capital return in the total operating area of 3,000 ha. Value after depreciation: 1st year: MYR90,000; 2nd year: MYR80,000; 3rd year: MYR70,000; 4th year: MYR60,000; and 10th year: MYR0 (depreciated by 10% annually).

Table 9. Cost-efficiency comparison between mist blower and unmanned aerial vehicle (UAV) spray for Felda Global Ventures (FGV Group).

Area	**Total cost of weeding for FGV group[a]		Cost saving by using UAV spray[b]	
	Mist blower	UAV spray[c]		
ha	MYR yr^{-1}		MYR yr^{-1}	%
1,000	162,580	341,620	(179,040)	−110
2,000	325,160	483,240	(158,080)	−49
3,000	487,740	624,860	(137,120)	−28
4,000	650,320	766,480	(116,160)	−18
5,000	812,900	908,100	(95,200)	−12
15,000	2,438,700	2,324,300	114,400	5

[a]Total cost per hectare includes chemical, labor, aerial sprayer (aerial spraying, aerial photo + other equipment), maintenance, transport, and water costs. Price of herbicides according to FGV's price list in 2022. Total replanting areas: 15,000 ha^{-1} yr^{-1}; coverage area: 100% with 2 rounds per year.

[b]Values in parentheses indicate no cost saving (i.e., exceeds the total cost).

[c]UAV value: MYR100,000 (capital expenditure), with capital return in the total operating area of 3,000 ha. Value after depreciation: 1st year: MYR90,000; 2nd year: MYR80,000; 3rd year: MYR70,000; 4th year: MYR60,000; and 10th year: MYR0 (depreciated by 10% annually).

Weed Control Efficacy

The usage of herbicides in oil palm plantations typically falls into two categories: broad spectrum (e.g., glyphosate, glufosinate, metsulfuron methyl) and selective (e.g., fenoxaprop, fluroxypyr methyl, triclopyr). Commonly chosen formulations include aqueous concentrates, emulsifiable concentrates, and wettable powders.

The analysis of weed vegetative cover over four different dates after treatment: 0, 8, 22, and 26 d after treatment (DAT) reveal significant changes (Table 5). Initially, at 0 DAT, the weed vegetation cover was 1.65 ha, representing 100% of the area. Following the treatment, a substantial decline was observed at 8 DAT, with the weed/vegetative cover reduced to 76.4%, indicating effective weed inhibition (see Figure 5 for the corresponding multispectral monitoring of weed cover after the UAV spray). This reduction continued at 22 DAT and 26 DAT, where the weed/vegetative cover reached 67.3% and 31.0%, respectively. The decrease in weed cover over time demonstrates the efficacy of the UAV-spraying method in reducing weed growth and distribution.

The effectiveness of herbicides, crucial for weed control in agriculture, is influenced by various factors. Environmental conditions, both before and after application, significantly affect herbicide performance. Factors like light, CO_2, temperature, rainfall, and wind impact topical applications, while soil temperature and moisture affect soil-applied herbicides. These conditions influence herbicide efficacy directly by affecting penetration and translocation mechanisms and indirectly by altering plant development and physiology. Understanding these factors is essential for optimizing herbicide use in agriculture.

While the use of UAV spraying at the preplanting stage successfully eliminated weeds, its effectiveness in controlling grass weeds within the LCCs is nonetheless limited and inferior to that of CKS application. The grass weeds exhibited minimal signs of scorching or damage. Multispectral images also failed to distinguish the mixed interspersed weeds from the legumes (Figure 6). This outcome highlights the challenge of effectively

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Table 10. Comparison in operational cost-efficiency between conventional knapsack sprayer (CKS) and unmanned aerial vehicle (UAV) spraying for weed control.

Parameter	Rate	CKS	UAV
Working duration	h	8	5
Operating time	0700–1530 hours	100%	Save 37% time savings compared with conventional
Labor cost	MYR ha^{-1}	43	8.33[a] (81% labor cost reduction compared with conventional)
Labor	no. of workers	6	3
Productivity	ha $man\text{-}day^{-1}$	1.75	15 (increased 8.5-fold compared with conventional)
Area accessibility[b]	—	Limited	Flexible
Health and safety risk	—	High exposure	Low exposure
Spray volume	L ha^{-1}	450	40 (water consumption reduced 91% compared with conventional)

[a]Based on operator's salary: MYR2,500 gross mo^{-1}, 20 working days; productivity: 15 ha $man\text{-}day^{-1}$; optimum working spray time: 5 h d^{-1}.
[b]Due to uneven, steep, or inaccessible terrain or sensitive environments where ground vehicles would damage the area or crops.

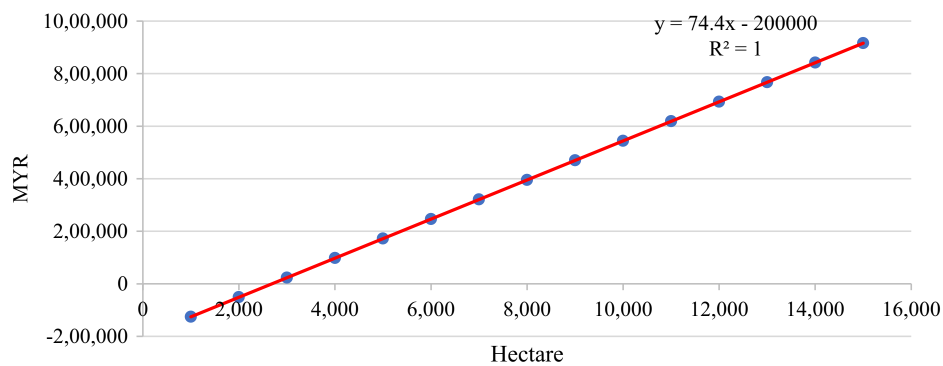

Figure 7. Linear regression of cost saving for aerial spray application using an unmanned aerial vehicle (UAV).

targeting the specific vegetation components within the densely packed legume cover crops using the UAV spray strategy.

The efficacy of UAV spraying was compared with that of a mist-blower application. No significant difference was observed between the two methods at any weeks after treatment interval (Table 6). At 1 WAT, both treatments resulted in 85% weed control efficacy, and from 2 WAT onward, a remarkable weed control efficacy of 100% was achieved, indicating that both mist-blower and UAV-spraying applications were equally effective in eradicating weeds at the preplanting stage. In contrast, in the selective postemergence herbicide application, a significant difference was observed in weed control efficacy between CKS and UAV spraying. In the early weeks after treatment (1 to 4 WAT), CKS possessed higher weed control efficacy (23.92% to 82.41%) compared with the UAV-spraying treatment, which yielded only 13.88% to 71.54% control (Table 7). As time progressed, weeds in both treatments started to regrow, although CKS still maintained its superior weed suppression as compared with UAV spray, with a slower weed regrowth of 14.00% versus 23.94% at 6 WAT, 24.00% versus 34.80% at 8 WAT, and 31.00% versus 43.88% at 12 WAT, respectively. These findings suggest that CKS was more effective in managing weeds in the immature oil palm plantations.

Cost-Effectiveness of UAV Spraying versus Conventional Sprayers

The cost-efficiency analysis shows that adoption of UAV spraying in areas less than 3,000 ha was less effective compared with conventional methods (Tables 8 and 9). However, UAV became more cost-effective in larger plantation areas. In the 3,000-ha area, a 4% cost saving was evident for UAV spraying over the CKS method, and this extended to a 28% cost saving when UAV was used in the 15,000-ha area (Table 8). However, a different trend was observed in the UAV–mist blower cost-efficiency comparison, where the mist blower was more cost-effective for sprayed areas of 1,000 to 5,000 ha. The UAV only had the upper hand when the calculated area increased to 15,000 ha, with a 5% cost saving compared with the mist blower.

The linear regression analysis (Figure 7) shows a perfect correlation (R^2 =1) and that the economies of scale are more favorable for UAV spraying when dealing with larger agricultural areas. Although the capital expenditure for the UAV is MYR100,000, the UAV's value is expected to depreciate over time at a rate of 10% annually. Given the consistent cost savings, it suggests a potentially favorable return on investment.

Operational Cost-Efficiency and Comparison between UAV Spraying and Conventional Sprayers

The operational cost-efficiency comparison between UAV spraying and the CKS highlight the advantages of UAV spraying across various operational facets (Tables 10 and 11). While both CKS and mist blower required 8 h for completion, UAV spraying significantly reduced the working period to 5 h, constituting a 37% reduction in operational time. This efficiency extended to resource consumption, with UAV sprayers resulting in 91% and 20% reduction in water consumption as compared with CKS and mist blower, respectively. This assertion is supported by Hanif et al.

Table 11. Comparison in operational cost-efficiency between mist blower and unmanned aerial vehicle (UAV) spraying for weed control

Parameter	Rate	Mist blower	UAV
Working duration	hour	8	5
Operating time	0700-1530	100%	37% time savings compared with mist blower
Labor cost	MYR ha^{-1}	18.81	8.33[a] (56% labor cost reduction compared with mist blower)
Labor	no. of workers	4	3
Productivity	ha man-day^{-1}	4	15 (increased 3.75-fold compared with mist blower)
Area accessibility[b]	—	Limited	Flexible
Health and safety risk	—	High exposure	Low exposure
Spray volume	L ha^{-1}	50	40 (water consumption reduced 20% compared with mist blower)

[a]Based on operator's salary: MYR2,500 gross mo^{-1}, 20 working days; productivity: 15 ha man-day^{-1}; optimum working spray time: 5 h d^{-1}.
[b]Due to uneven, steep, or inaccessible terrain or sensitive environments where the ground vehicles would damage the area or crops.

(2022), who highlighted that the deployment of UAVs for spraying not only results in a significant 90% reduction in water consumption and 30% to 40% reduction in pesticide usage, but also represents a significant leap in operational efficiency, with a staggering 40-fold increase in speed over the CKS method. Given that labor is a prevailing issue in the oil palm sector (Dilipkumar et al. 2020), the potential for UAV spray technology to reduce labor costs becomes even more apparent. Labor-dependent weed management methods in replanting fields are notorious for being time-consuming and labor-intensive. The Malaysian Palm Oil Association emphasizes the country's ongoing shortage of plantation labor, anticipating a loss of MYR20 billion (US$4.6 billion) in 2023 alone. This scarcity not only jeopardizes supply but also has the potential to cause global price increases.

UAV spray technology achieved a significant 81% and 56% reduction in human expenses, effectively cutting costs to MYR8.33 ha^{-1} from MYR43.00 ha^{-1} for conventional spraying (CKS) and MYR18.81 ha^{-1} for the mist blower. This shift in approach resulted in increased productivity, cheaper operational costs, shorter operating time (by 37%), lower transportation expenses (mainly water transport), and a safer working environment for operators. Despite the high initial cost of investment in equipment (aerial sprayer, mapping software, etc.), UAV has numerous advantages in the long run in terms of physical labor and time-consuming operations (Tang et al. 2021).

This study evaluated the use of UAV spraying for weed control in oil palm plantations. The investigation of droplet deposition characteristics determined that the application at 0.25 MPa pressure yielded optimal results, offering efficient coverage and distribution of droplets. The efficacy comparison between UAV and mist-blower applications revealed a comparable weed eradication rate in the preplanting application, although UAV spraying displayed a disadvantage in postemergence weed control in the LCCs. A cost-effectiveness analysis indicated that UAV spraying becomes economically viable for larger agricultural areas, with substantial savings potential. Specifically, deploying UAV for 15,000 ha in FGV plantations could result in 28% cost savings, equivalent to MYR916,000 compared with the conventional CKS approach.

Meanwhile, a 5% cost saving, which equals MYR114,400, was evident in the UAV as compared with the mist blower. The operational efficiency of UAV spraying was consistently superior, significantly reducing working hours (37% reduction in operational time), resource consumption (20% to 91% of water consumption using a mist blower and CKS), and human expenses (56% to 81% reduction from MYR18.81 and MYR43.00 ha^{-1} to MYR8.33 ha^{-1}) when compared with conventional methods. These findings collectively advocate for integrating UAV-based spraying as an effective, efficient, and economically feasible approach for weed control in oil palm plantations, especially in extensive agricultural landscapes.

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