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Original Article

Evaluation of UAV Flight Speed for Effective Pineapple Plantation Spraying

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Abstract - *A Crewless Aerial Vehicle (UAV) is a flexible flying platform suitable for fertilizing operations, regardless of the geographical factor, without the need for dedicated landing sites. The application of Precision Agriculture (PA) is tested in the pineapple plantation as a solution through UAV spraying. Proper application of agricultural products in the field is critical to plant growth and sustainability. The lack of product results in insufficient growth or deficiency, and too much will lead to runoffs. The study aims to evaluate the spraying performance through droplet deposition density and spray coverage rate on pineapple. A low flight altitude of 2 m from the ground with varying flight speeds (1.00, 1.50, and 2.00 m/s) and a 2 m spraying boom with a hollow cone nozzle was used with a straight flight pattern through the field. The pineapple leaves are lined with two layers of Water-Sensitive Papers (WSP) and a fixed spraying rate of 7.65 L/min through a pineapple field following the Malaysian Pineapple Industrial Board (MPIB) standard. Results showed a decrease in the mean droplet density deposition with an increment in flight speed from 1 to 2 m/s. Exhibiting a drop from 60 to 35 $\mu L/cm^2$ at the upper layer and 28 to 19 $\mu L/cm^2$ for the lower layer. The mean spray coverage had a similar pattern observed relative to flight speeds of 75 to 65% at the upper layer and 55 to 40% at the lower layer. Concluding a poor performance in droplet density and spray coverage if the drone speed exceeds 1.5 m/s.*

Keywords - *Agriculture Drone, Droplet Distribution Flight Speed Optimization, Aerial Spraying System*.

1. Introduction

Pineapple (Ananas comosus) is one of the main products in Malaysia, with an output of 586,133 metric tons, on 18,135 hectares of planted areas, according to the Interim Report of the 2024 Agricultural Census. Johor, located to the south of Malaysia, a state neighboring Singapore, held the highest production output accounting 59.9% (351,172 metric tons) of the total national output [1]. Uncrewed Aerial Vehicles (UAVs), or drones as they are commonly known, are rapidly developing in various fields, including for monitoring and agricultural purposes. UAVs are used to dust crops, monitor plants, spray, etc., and replace the slow-paced human workforce. Malaysian farmers use traditional methods for fertilizing tasks, such as manual application, knapsack sprayers, and tractor-mounted high-pressure sprayers [2]. The drone can apply the plantation-aiding liquid more economically than traditional ways, saving time [3]. It is also noted that better mobility and application efficiency of pesticides is achieved by aerial spray compared to a ground mechanical spray [4]. Studies on agriculture recently focus on crop production and protection material (fertilizer and pesticides) efficiency, and their impact on soil and the surrounding environment. There are practical issues in UAV spraying, such as UAV operating parameters ambiguity, poor penetration, and low percentage of area coverage [4]. An extensive study of spraying parameters on agriculture drones, such as sprayer flow rate, flight altitude, and speed on certain types of plantations, which have critical roles in crop-dusting efficiency [4, 5]. The movement of pesticide particles or droplets toward areas designated as non-target areas is driven by airflow during aerial spraying and is known as drift [4]. Spray drift and safety during application have always been critical issues in UAV spraying. It wastes pesticides, exposes operators to chemicals, and pollutes the environment via runoffs.

Therefore, recent studies have shown that improper spraying parameters impair the control effect against insects and induce the drift of pesticides [3, 4, 5]. In addition, it is found that aircraft altitude and speed influence the droplet drift, and droplet size is heavily influenced by spray flux [4]. Suggestions made through observing airflow behavior on design and operating specifications, such as sprayer nozzle, flight speed, and hovering altitude, are also given in several studies [3, 4, 6]. A study on the droplet deposition density in various crops using a quadcopter UAV with four nozzles attached was conducted, with the exception of pineapple cultivation [4]. The UAV should fly at a low altitude ranging between 2.0 and 5.0 m over the crops since the aerial spraying only produces tiny droplets due to low-volume capacity [4, 7]. The evaluation shows that the spray drift increases as the spray height increases. However, spray drift produced at 1.0 m and 1.5 m was 4.1% and 4.5%, respectively. [4, 5, 7] had effectively reduced the droplet drift of the UAV with the lower flight altitude.

Another study was conducted to determine the effect of droplet deposition and control sprayed from a UAV [3, 8]. A UAV flying at low altitude was used; 28% of the average deposition from the total spraying at the upper layer was found, and deposition of 26% at the underlayer. So, about 92.8% deposition was observed from the underlayer-upper layer. Droplet drift data of 12.9% from the total spray traveled towards the non-target area. Meanwhile, within 8 m, 90% of the droplets were deposited at the target area, and recording of the drifted spray showed a close to zero value from 50 m away.

UAV spray applications frequently achieve high-efficiency area coverage at speeds exceeding 2.0 m/s in flexible crops such as rice and wheat [5, 6]. However, the high speed of flight does not translate to pineapple cultivation. The pineapple plant (Ananas comosus) is a dense, whorled rosette architecture plant with stiff, waxy leaves that interlock to form a rigid canopy shield or ‘umbrella’. The 'umbrella effect' alters the aerodynamic requirements for droplet penetration. Unlike slim stalks of wheat and rice that sway under rotor downwash to allow droplet ingress, the rigid pineapple leaves require a sustained, high-pressure downwash to force the active ingredients into the lower stem [7]. Hence, the operational flight speed optimized for grain crops invariably results in superficial top-layer deposition when applied to pineapples, requiring a dedicated re-evaluation test for the pineapple application. There is a lack of studies about the effect of operation speed on targeted points from an extended boom sprayer in pineapple cultivation. Therefore, this research was performed following the recommendation from the previous studies on the effect of operation speed on the spray quality on pineapple farms using a quadcopter UAV with the aid of WSP. Establishing and identifying if 1.0 to 2.0 m/s as the approximate flight speed limit for adequate penetration to occur is a critical step for scaling Precision Agriculture (PA) in pineapple cultivation. Defining these limitations provides the necessary information for developing the exact spray requirements or deficits caused by faster flight speeds. This study provides the mathematical justification for prioritizing biological application efficacy over arbitrary hectare-per-hour efficiency metrics in rigid-canopy crops.

2. Methodology

Approaching the problem to obtain information and data to study the effect of operation speed with WSP starts with the site. The site is emulating a pineapple cultivation field outlined in Figure 1 and Section 2.1 Experiment site. The UAV used for the spraying is shown in Figure 2, a quadrotor drone with a 2 m hollow cone nozzle equipped boom. The WSP placement strategy is mentioned in Section 2.3. The experiment flow in Section 2.4 explains the flight plan and parameters. Lastly, Section 2.5 is how to process the WSP collected into usable data, such as the droplet distribution and spray coverage.

2.1. Experiment Site

This experiment was conducted at the drone cage, Universiti Tun Hussein Onn Malaysia. A single crop was plotted according to the Malaysian Pineapple Industrial Board (MPIB) manual in Figure 1. The crop bunch consisted of two rows of two pineapple plants with a height of 0.28 m each, spaced at 60 cm from each other in the row, with a 30 cm spacing between each plant in the line. As for the distance between each plant bunch row, it is set to 90 cm according to the cultivation manual.

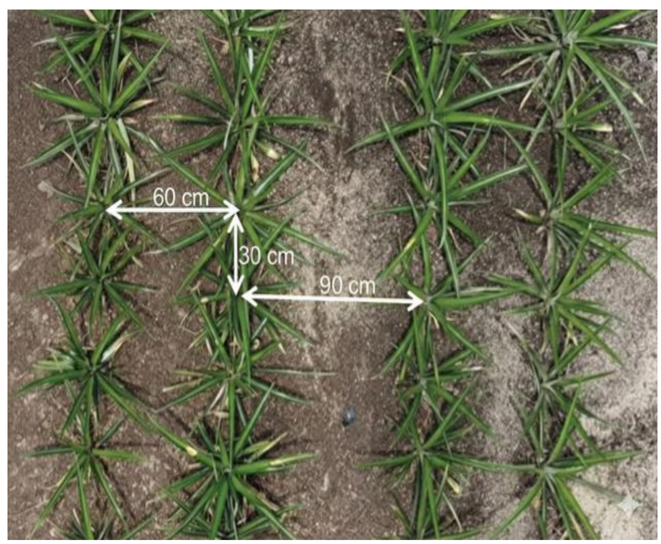


Fig. 1 Pineapple arrangement of plotted crop [4]

Table 1. SOTA UAV spraying parameter comparison

Ref.	Crop type	Canopy morphology	Evaluated flight speed (m/s)	Optimal efficacy speed (m/s)
[8]	Rice/Paddy	Flexible, vertical	3.0, 4.0, 5.0	4.0
[9]	Wheat	Semi-flexible dense	1.0, 2.0, 3.0, 4.0	2.0 – 3.0
[10]	Pineapple	Rigid, whorled rosette	Varying meteorological	Low speed / Low altitude
Current study	Pineapple	Rigid, whorled rosette	1.0, 1.5, 2.0	1.0

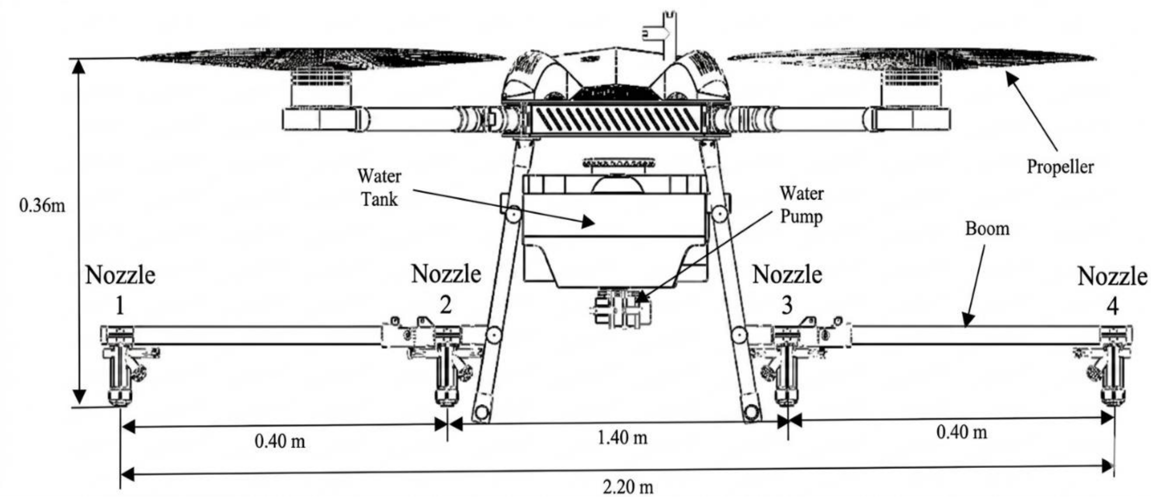


Fig. 2 Pinexri-20 used as an aerial spraying test bed

2.2. Equipment and Materials

The multi-rotor UAV with four propellers (Pinexri-20), in Figure 2, was used in this experiment to perform the spraying test.

The Research Center for Unmanned Vehicles (ReCUV) fully customized the spraying drone in the Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia. The specifications for the developed agricultural drone are shown in Table 2.

Table 2. Specification of agricultural UAV

Detail	Specification	Detail	Specification
UAV platform		**Sprayer system**	
Drone type	Quadrotor	Tank capacity	10 liters (9.9 kg)
Dimensions	1.50 x 1.50 x 0.44 m	Pump type	Diaphragm
Drone weight	14.87 kg (without payload)	Pump voltage	12 V
Payload capacity	10 kg	Pump battery configuration	1 x Li-Po 3S
Operating voltage	44 V (12S)	Pump flow rate	8 L/min
Battery configuration	2 x Li-Po 6S		
Navigation system	RTK-GPS	**Nozzle specifications**	
Transmitter range	800 m	Nozzle type	Hollow cone
Flight controller	Holybro Pixhawk 4	Nozzle model	VP110-02 (yellow)
Motor	T-Motor P80 III KV100	Outlet diameter	0.8 mm
Electronic speed controller	T-Motor Flame 80A	Angle	80°
Propeller	29 inch	Nozzle distribution	Dynamic boom sprayer
Rangefinder	Lidar Lite V3		

A payload capacity of 10 L and a flight duration of 8 minutes with a full payload. Powered by a 12S Li-Po battery driving the 29-inch rotor with a 100KV motor by T-Motor, controlled by a Holybro Pixhawk 4 flight controller. The UAV is also aided with an RTK-GPS and a lidar range finder to ensure positional accuracy during spraying.

2.3. Droplet Collection

Various researchers use Water-Sensitive Paper (WSP) to evaluate the droplet pattern and count after spraying on the experiment site [11].

WSP was placed in two orientations: a vertical layout and a linear layout. Vertical has two layers on the top of the leaf and in the middle of the plant, at the lower layer of leaves, as shown in Figure 3 (a).

The WSP, 1.8 x 3.7 cm collection card, was used to collect the droplets. The WSP's original color is yellow and changes to a dark blue once the paper meets liquid, as observed in Figure 3 (b). WSP with droplets must be sealed immediately to prevent any other exposure to droplets or humidity.

As for the horizontal layout, Figure 4 illustrates the WSP placement in the vertical yellow box in the middle with P1 to P4 marked from top to bottom, and the orientation of the flight is facing the Northeast (NE) direction.

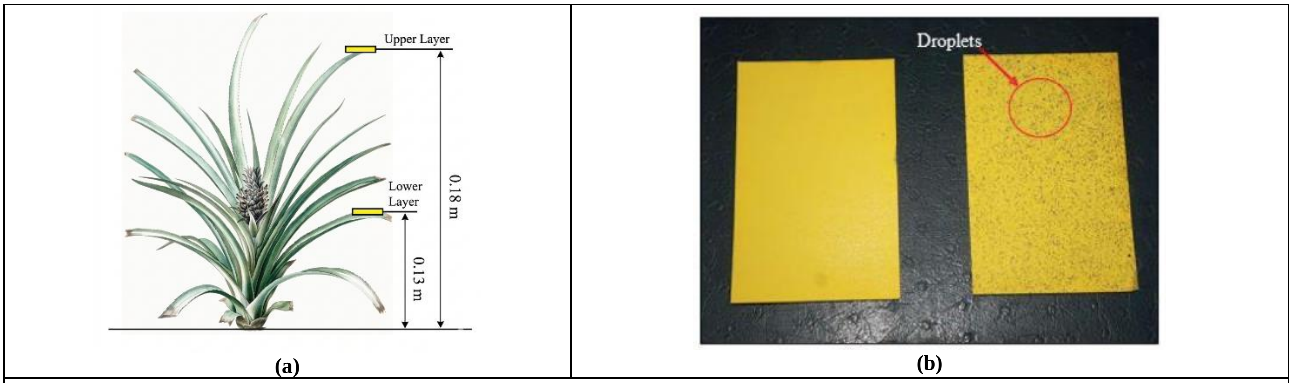


Fig. 3 (a) WSP arrangement on pineapple leaves (b) blank WSP versus containing

2.4. Experiment Method

This study used the UAV with sprayer functionality to evaluate the droplet size and coverage on the pineapple crop with different operation speeds selected at a fixed altitude mentioned by [5, 8, 12, 13]; a lower altitude produced better coverage and lower drift. The UAV was set to operate automatically as the Flight Controller (FC) was programmed to fly according to the flight path, as shown in Figures 4 and 5.

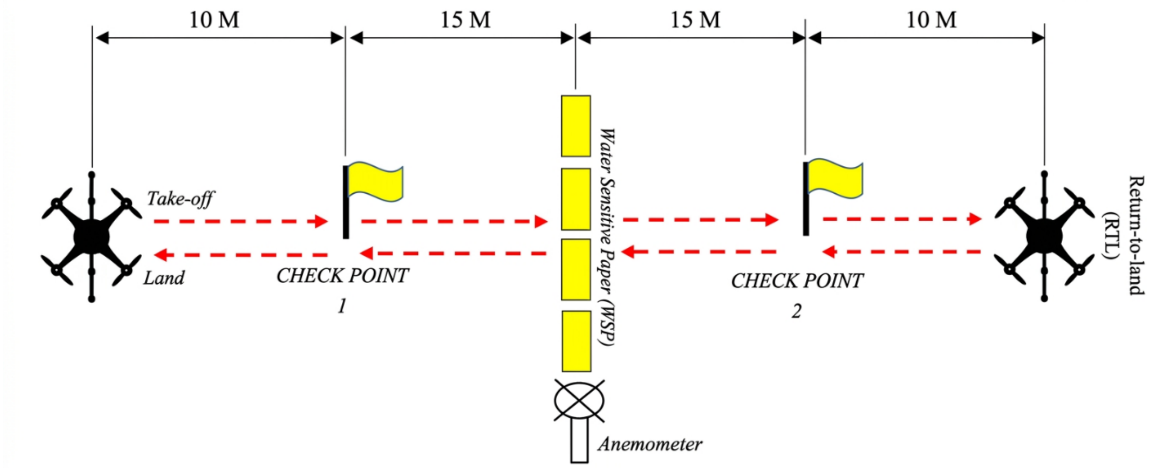


Fig. 4 Test site layout and WSP locations

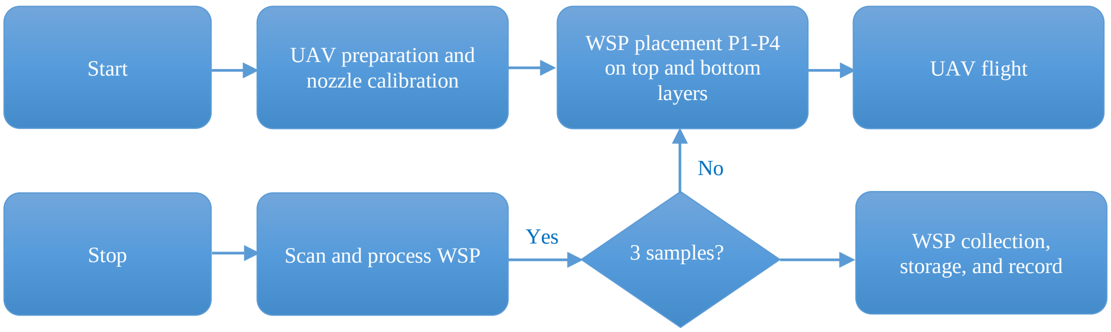


Fig. 5 Flowchart of the experiment flow

Prior to the flights, the 2 m boom sprayer underwent physical calibration to ensure application uniformity. While the onboard diaphragm pump and the four VP110-02 hollow cone nozzles possess a combined maximum mechanical rating of 8.0 L/min in Table 2, static calibration was executed to verify the actual output. The pump was operated at a 100%, and the volumetric output was captured in a measuring cylinder over a designated time interval. During the flight tests, the pesticide was deployed at a 100 % of 7.65 L/min. This static flow rate, paired with the varying flight speeds, allowed the experiment to isolate the rotor downwash as the primary independent variable affecting droplet penetration. Environmental variables were monitored and logged before the flight phase to note the impact of flight speed on spray drift. An anemometer was positioned at the experiment site, Figure 4, to continuously sample localized wind speed and direction as recorded in Table 3. Prevailing crosswind was consistently recorded from the South-East (SE) across all speeds; the resulting horizontal spray drift was treated as a constant environmental variable. This permitted an accurate analysis of the windward (P1) versus leeward (P4) deposition gradient across the swath. WSPs are placed at the designated location outlined in Figures 3 and 4 before the UAV takes flight and initiates the spraying process for the DAQ phase. The UAV automatically takes off to an altitude of 2.0 m and flies towards the designated route. This method allows the UAV to readjust its position before it flies through the designated flight path. When the UAV reaches the first checkpoint, the pilot signals the pre-deployment of pesticide 15 m before flying through the WSP.

Table 3. Operation parameters during the experiment

Flight speed (m/s)	Flight altitude (m)	Spray rate (L/min)	Wind speed (m/s)	Wind direction (NESW)
1.00	2.00	7.65	0.56	SE
1.50	2.00	7.65	0.45	SE
2.00	2.00	7.65	0.62	SE

Table 4. Data table based on position and speed for droplet density and spray coverage, upper and lower layer

Position	P1			P2			P3			P4		
Speed (m/s)	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0
Droplet density (μL/cm²)												
Upper layer	62.27	56.35	39.74	58.61	44.71	42.27	50.84	49.52	31.43	43.59	38.97	26.19
Lower layer	32.86	36.25	20.57	28.52	26.90	24.3	22.37	29.43	18.94	20.26	22.69	15.11
Spray coverage (%)												
Upper layer	86.69	75.91	70.07	80.23	67.13	66.63	72.74	58.42	68.32	66.67	57.26	51.54
Lower layer	64.07	52.5	45.47	53.73	38.85	45.34	51.1	43.62	34.15	43.74	37.82	33.77

Table 5. Data table for the mean of the upper and lower layers of droplet density and spray coverage based on speed

Parameters	Droplet density (μL/cm²)			Spray coverage (%)		
Speed (m/s)	1.0	1.5	2.0	1.0	1.5	2.0
Upper layer	53.83	47.39	34.91	76.58	64.68	64.14
Lower layer	26.0	28.82	19.73	53.16	31.45	39.68

After obtaining the droplet diameters, the equation

After passing through the second checkpoint, the spray signal was stopped. Next, the UAV will hover after passing through 10 m after the second checkpoint and then return to the home location and land. A study conducted in rice paddy mentioned that at 2 m/s, a better spray quality was produced, but lacked data below 2 m/s [14]. To ensure reliability, the experiment utilized a randomized block design for the three designated flight speeds (1.0, 1.5, and 2.0 m/s). Each flight speed was replicated three times. Each plant was equipped with two WSPs at the upper leaf surface and the lower canopy layer. This configuration yielded 8 WSP samples per flight pass, resulting in a total sample size of WSPs analyzed across the entire data acquisition phase. The WSPs were collected immediately post-flight and sealed in bags to prevent humidity contamination before laboratory scanning. Means and variances were subsequently calculated across these replicates to eliminate localized anomalies.

2.5. Data Collection Method

Droplet deposition was determined using a portable computer, scanner, and computer software called 'DepositScan'. DepositScan can quantify spray deposition distribution on any surface, showing visual differences between the droplets and backgrounds [12]. The image was scanned at 600 DPI in a grayscale picture. The scanned image can be analyzed using ImageJ, a sub-software of DepositScan. ImageJ can evaluate an area in the WSP and count the number of droplets collected. ImageJ can separate the droplet spectrum ranging from 10%, 50%, and 90% of the total fluid volume represented by $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$, respectively. The D_{Va} values, where a ∗ 100% is calculated spray volume and is noted as Droplet Diameters (μm), should have values smaller than those in the ASAE Standards, 2005 parameters. Alternatively, the spot area of the spray droplets can be analyzed and converted to an actual droplet diameter (d, μm) manually via the equations below:

$$d=0.95d_s^{0.910} \quad (1)$$

$$d_s=\sqrt{(4A/\pi)} \quad (2)$$

Moreover, the spot area A (μm²) taken from the scanning resolution is calculated in terms of the number of spot image pixels. The last equation for calculation is used for the droplet size actual diameter, shown below:

$$d=1.06A^{0.455} \quad (3)$$

The following is applied to calculate each droplet volume individually, as shown below:

$$V_i=(\pi d_i^3)/6,\ i=1,\ ...,\ N \quad (4)$$

Where V_i is noted as individual droplet volume (μm^3), di is calculated from d and i as the individual droplet diameter and individual droplet order, respectively, while N is the number of droplets accumulated on the collector sample.

3. Results

The spraying performance on the pineapple was evaluated using quantified results, Droplet deposition (DD in µL/cm2) and Spray coverage (SC, in %), summarized in Tables 4 and 5, and explored in a dedicated section. Section 3.1 is specifically for DD and Section 3.2 for SC.

3.1. Spray Droplet Density (DD)

The droplet density is the coverage of the area of the WSP on the pineapple leaves. The WSP was prepared to fit the evaluation area at 6.67 cm2.

The experiment was carried out, and the results are shown in Figure 6 (a) for the upper layer and Figure 6 (b) for the lower layer. The figures note four pineapples (P1, P2, P3, and P4) with the WSP droplet deposition density plot against the UAV flight speed.

The results correlate with the experiment done by [9, 10] on the multiple-layer evaluation, as the higher layer received larger droplets than the lower layer of the plant. In addition, the upper layer of the pineapple leaves is smaller than the lower layer, so the upper layer tends to collect most of the droplets. In comparison, the remaining droplets drop down to the lower layer with support from the downwash of the UAV's rotors.

The pattern is apparent with a clear inverse relationship between the flight speed and the DD. A flight speed increase from 1.0 m/s to 2.0 m/s resulted in a decrease in the overall mean deposition by 31.6%. The faster travel speed reduces the effects of rotor downwash, preventing the downwash from assisting the droplet in penetrating the upper canopy.

A crosswind was observed in Table 2 during the DAQ. This observation correlates with the pattern observed in Figures 6 (a), (b), and 7. A gradient from left to right, a high value at P1 and a low value at P4, correlating with the crosswind. The crosswind gradient (South-east direction) recorded a high 62.27 µL/cm2 and a low 43.59 µL/cm2 at 1.0 m/s, a 42.9 % difference between P1 and P4, higher than the 2.0 m/s record. The high flow and slow flight ensured high penetration of the chemical into the lower canopy. The ‘umbrella effect’ of the rigid pineapple leaf intercepts more volume at the upper layer than the lower layer. The 1.0 m/s speed had 53.83 µL/cm2 and 26.0 µL/cm2 for the upper and lower layer, an 107% difference between them. Increasing the speed to 2.0 m/s further degrades the penetration to 19.73 µL/cm2, a 24.1% decrease.

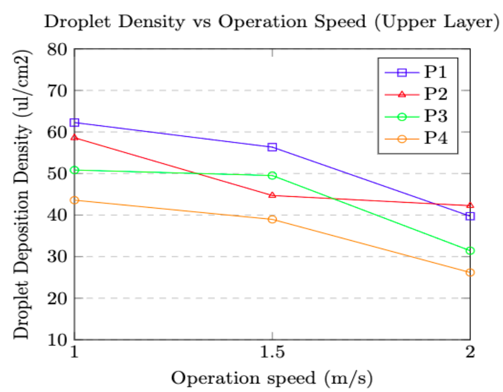
3.2. Spray Coverage (SC)

Spray coverage is the percentage of droplets covering the targeted area. The results from Figure 8 (a) and Figure 8 (b) are for the lower and upper layers, respectively.

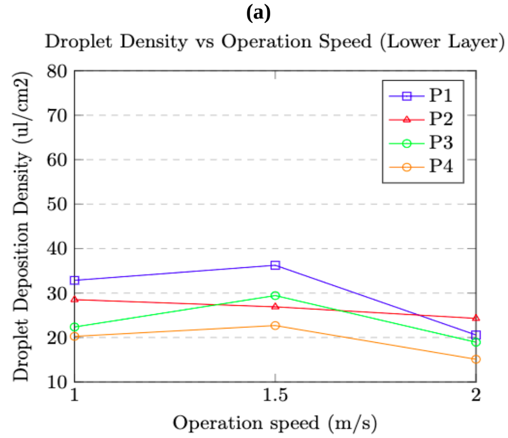
It shows the results of spray coverage between P1, P2, P3, and P4 on the experimental pineapple crop. Figure 8 (a) shows that an operation speed of 1.00 m/s obtained the highest coverage rate, achieving an 86.69% coverage.

Figure 8 (b) represents the lower layer of the pineapple leaves, showing the same sequence as the upper layer. Overall, the upper layers obtained more coverage than the lower layers because the upper layers were directly exposed to the UAV's nozzle without any obstacles.

The pineapple leaves are stiff and require a greater downwash force from the UAV rotors to allow the droplet to hit the lower layer. Due to turbulence, the best coverage is obtained when operating at the speed of 1.00 m/s.



(a)



(b)

Fig. 6 Droplet density on the (a) upper layer (b) lower layer

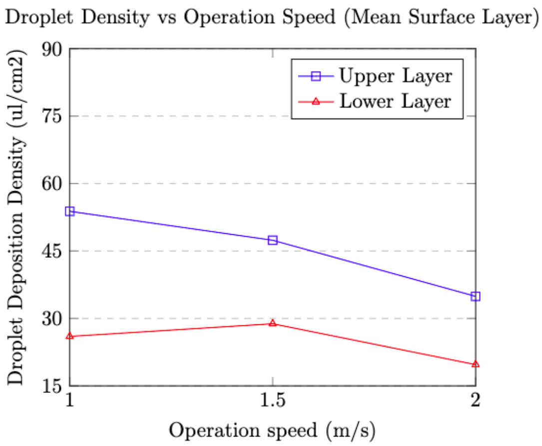


Fig. 7 Mean droplet density on pineapple leaves

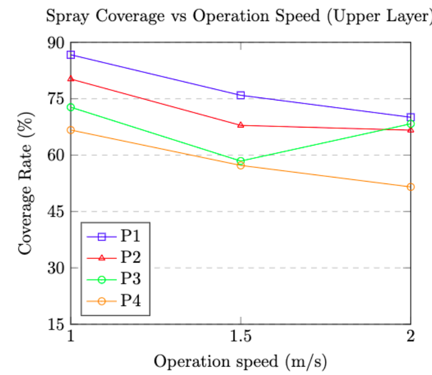
Furthermore, the surrounding wind pattern is a contributing factor in causing the droplets to drift away from the targeted area and are observed at operation speeds of 1.50 m/s and 2.00 m/s, with wind speeds reaching over 0.50 m/s. Moreover, [12] stated that flight height in lower natural wind speed majorly affects the penetration and uniformity of the deposited distribution of the droplets. The findings correlate with reports by [12] observing similar results with the spraying UAV in crop protection. This pattern is observed at the lower canopy at 2.0 m/s; the SC drops significantly from 53.16% at 1.0 m/s down to 39.68% at 2.0 m/s.

4. Conclusion

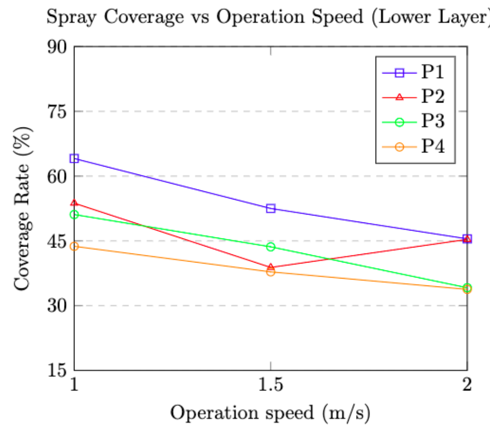
In summary, the droplet density and the spray coverage of a quadcopter UAV at different operation speeds of 1.00, 1.50, and 2.0 m/s with a fixed operation altitude of 2.00 m. The droplet density distribution decreases as the operation speed increases. The upper layer obtained better droplet density than the lower layer, as the upper layer was exposed directly to the UAV's nozzle without any obstacles. Furthermore, the pineapple leaves are a dense rosette structure, and the leaves interlock. Hence, the upper layer collects most of the droplets while the remaining droplets drop on the lower layer, supported by the downwash of the UAV's rotor. The requirements for the pineapple to be dosed properly correlate with the flight speed. Flying at 2.0 m/s does create a more distributed spray, but is it a 'sloppy' application as identified in this experiment? The low penetration will result in a low biological efficacy, meaning that even if the top layer is well covered and quick to apply. The lack of penetration does not benefit the plant. The downwash from the UAV propeller at 1.0 m/s is able to overcome the 'umbrella effect', reliably delivering the dose down to the plant. Despite the crosswind resulting in an asymmetrical application, it is a problem that can be mitigated through flight planning and wind observation. Ultimately, achieving a quality application, ensuring the active ingredients required to dose the plant with the right nutrients and protection, is more imperative than operational efficiency. This will result in a lower frequency of application and better growth through effective application. The quadcopter UAV with a 10 kg payload is recommended to operate at the speed of 1.00 m/s with an operation altitude of 2.00 m to obtain the best droplet density deposition and spray rate coverage result.

5. Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.



(a)



(b)

Fig. 8 Spray coverage on the pineapple leaves, (a)upper layer, and (b)lower layer

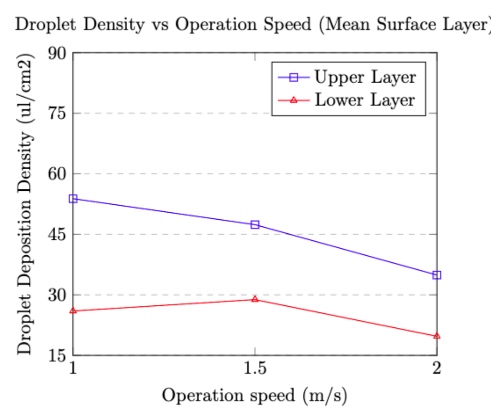


Fig. 9 Mean spray coverage on pineapple leaves

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