

Reduction of UAV pesticide drift through adaptive wind speed and flight altitude strategies

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Abstract: Pesticide application is vital in modern agriculture, with global use reaching 3.70 million tonnes in 2022. Unmanned Aerial Vehicles or UAVs have emerged as a more efficient, precise, and cost-effective method for pesticide spraying, surpassing traditional methods. However, concerns about pesticide drift and worker health risks remain significant despite advancements. This study evaluated adaptive UAV pesticide spray protocols aimed at minimizing drift in rice fields. Utilizing the DJI Agras T10 drone sprayer equipped with XR11001 flat spray nozzles, experiments were conducted under varying wind speeds and flight altitudes. Spray performance was assessed using water-sensitive paper, measuring percent coverage, droplet density, and deposition within (on-target) and beyond (off-target) the spray swath. Results indicated that flight altitude significantly influenced on-target deposition, with its quadratic effects impacting on-target droplet density and on-target spray uniformity. When combined with flight altitude, wind speed affected off-target droplet density and significantly altered off-target drift behavior. Most off-target pesticide drift occurred within 4 meters outside the swath width and decreased significantly beyond this distance. Using Response Surface Methodology, optimal conditions were identified, achieving over 99.72% desirability at 1.2 meters flight altitude and wind speed ranging from 2.0 to 2.99 m s⁻¹. The confirmation test resulted in an actual off-target percent coverage of 0.03%, off-target droplet density of 0.4 droplets cm⁻², and off-target deposition of 0.0091 µL cm⁻², all of which are within the acceptable range. Therefore, the model is validated and deemed reliable for predicting off-target drift.

Keywords: UAV pesticide application, pesticide drift, wind speed, flight altitude, DJI Agras T10

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1 Introduction

Pesticide application is a cornerstone of modern agricultural practices, enabling farmers to protect their crops from pests, diseases, and other detrimental factors that can reduce yields. Globally, pesticide use in agriculture reached 3.70 million tonnes (Mt) of active ingredients in 2022, reflecting a 4% increase from 2021, a 13% rise over the past decade, and a

doubling since 1990 (FAO, 2024). In the Philippines, pesticide use has been closely tied to the intensification of agriculture since the 1950s. Despite a 60% increase in global fertilizer use from 1961 to 2022, crop production growth outpaced fertilizer inputs, resulting in a 10% decline in fertilizer intensity per ton of yield, indicating that increasing fertilizer application does not proportionally increase yields (Sharafi et al., 2025).

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In addition, the off-target movement of pesticides beyond the intended application area, known as pesticide drift, poses significant environmental and human health risks. This phenomenon is especially concerning in areas with high agricultural activity, such as the Philippines, where pesticide use is widespread. Pesticide drift can contaminate water bodies, degrade soil, and damage non-target plants and animals. The adverse effects of pesticide drift extend beyond the application site, potentially affecting surrounding ecosystems and communities (Ray and Shaju, 2023).

In recent years, unmanned aerial vehicles (UAVs), or drones, have emerged as an innovative tool for pesticide application. UAVs provide farmers with a more efficient, precise, and cost-effective method of spraying, offering numerous advantages over traditional ground-based and aerial methods. Despite these benefits, concerns about the potential for UAV pesticide spraying to contribute to pesticide drift, particularly in regions with unpredictable wind patterns and varying environmental conditions (Bautista et al., 2024).

Many studies have examined parameters affecting on-target deposition, including droplet size, wind speed, and flight altitude (Dengeru et al., 2022; Chen et al., 2022; Önler et al., 2023). High wind speeds increase pesticide volatilization, causing chemicals to disperse and contaminate non-target areas (Boonupara et al., 2023). UAV operational parameters such as flight altitude also influence droplet penetration and distribution. Studies have shown that lower flight altitudes enhance on-target deposition by reducing drift. Khankandi et al. (2025) used a machine vision-based droplet detection system to measure UAV spray patterns under static and field conditions, and found that lower flight altitudes reduce drift and improve on-target deposition.

The integration of UAV technology in agriculture has significantly reduced pesticide drift and improved application efficiency, with studies showing that drones need less than half the distance to achieve 90%

spray coverage compared to conventional sprayers (Sánchez-Fernández et al., 2023). Optimized parameters, such as flight altitude, contribute to better spray coverage and on-target deposition (Güneş and Hasegawa, 2025; Gatkai et al., 2025). However, despite these advancements, concerns remain about pesticide drift and residue, which pose health and environmental risks. Prolonged or repeated exposure to pesticides, including those applied via UAVs, can lead to chronic health effects such as neurotoxicity, endocrine disruption, mutagenicity, and an increased risk of cancer and organ dysfunction (Shekhar et al., 2024; Ahmad et al., 2024). Therefore, without proper optimization and regulation, the risks associated with UAV-based pesticide applications may outweigh their benefits.

This study aims to evaluate how wind speed and flight altitude affect UAV pesticide application, with the goals of minimizing drift, ensuring effective pest control, analyzing drift patterns, and developing a standardized spray protocol for the Davao Region.

2 Materials and methods

This study was conducted at the rice field of the University of Southeastern Philippines, Tagum Unit, located in Apokon, Tagum City, Davao del Norte (7.417997° N, 125.828983° E). The field experiments took place from late March to early April 2025.

To set up the experiment, the field was laid out using wooden sticks, water-sensitive paper, and an automatic weather station (AWS). A 6-meter on-target spray grid was established perpendicular to the prevailing wind direction, accompanied by a 10-meter off-target drift sampling area extending downwind. Each sampling lane contained two sampling points, selected randomly through a Latin Square design. This configuration resulted in 12 on-target and 14 off-target sampling points.

The UAV used in this study was a DJI Agras T10 fitted with four XR TeeJet Extended Range Flat Spray nozzles (XR11001 Orange). During the preparation of the insecticide solution, appropriate personal protective equipment (PPE) was worn. The pesticide

used was Karate 2.5 EC (lambda-cyhalothrin), prepared at the manufacturer's recommended dilution of 1.15 mL per liter of water. Although the pH of the tap water used was not measured in this study, existing literature suggests that lambda-cyhalothrin remains stable in water with pH ranging from 5.0 to 7.0 and tends to degrade in alkaline environments. Hence, future research is encouraged to include pH adjustment to optimize pesticide stability.

2.1 Wind speed

Wind speed was categorized into three levels: 0–0.99 m s⁻¹, 1–1.99 m s⁻¹, and 2–2.99 m s⁻¹.

Table 1 Operational parameters variation

Parameters		Variations	
Wind Speed	A1	A	A3
	0-0.99 m s ⁻¹	A2	2-2.99 m s ⁻¹
		1-1.99 m s ⁻¹	
Flight Altitude	B1	B	B3
	1 m	B2	4 m
		2.5 m	

To monitor environmental conditions during UAV operations, an automatic weather station (AWS) was deployed at the field site. The AWS recorded real-time data on wind speed, temperature, and humidity throughout each spraying session.

The experimental optimization was conducted using the Stat-Ease 360 software (version 23.1.8, 64-bit) employing response surface methodology (RSM). An Optimal (Custom) Design was adopted, consisting of 21 experimental runs based on combinations of wind speed and flight altitude as independent variables.

The response variables analyzed included percent coverage (%), droplet density (deposits cm⁻²), deposition volume (μL cm⁻²), droplet size (μm), and uniformity – where the last two responses were applicable to on-target samples only. Regression models were fitted to the data, and analysis of variance (ANOVA) was used to evaluate the significance of each factor and their interactions. Optimization criteria were set to minimize off-target drift (percent coverage, density, and volume).

After optimization, one treatment identified as optimal from the RSM model was selected for a verification run to validate the model's predictive

2.2 Flight altitude

Flight altitude was varied at three levels: 1 m, 2.5 m, and 4 m, with 2.5 m considered the average height, while the lower and higher altitudes were tested to evaluate their effects on pesticide drift and deposition. Studies by Ranabhat and Price (2025) have shown that lower flight heights of around 1.5-2 m above the rice canopy reduce drift and improve deposition efficiency, whereas García-Munguía et al. (2024) reported that altitudes above 2.5 m increase off-target spray. The operational parameter variations are summarized in Table 1.

accuracy. The accuracy of the model was assessed using a 95% confidence level. Prediction error was calculated using the formula:

$$PE = \frac{(HV - LV)}{HV} \quad (1)$$

Where PE is the prediction error, HV is the higher value, and LV is the lower value.

For data gathering, the water-sensitive papers were scanned using a high-resolution scanner (600 dpi) and analyzed using ImageJ software (version 1.38x, Java 1.6.0_02) with the DepositScan™ 1.2 plugin. The software measured critical spray parameters including percent coverage, droplet density, and deposition volume for both on-target and off-target samples. Additionally, for on-target samples, droplet size and uniformity were measured. Uniformity was determined using the equation:

$$Uniformity = \frac{(DV9 - DV1)}{DV5} \quad (2)$$

Where DV1: 10% of the spray volume is in smaller droplets, DV5 (VMD): half of the volume is in droplets smaller, and half in larger ones, DV90: 90% of the spray volume is in smaller droplets.

2.3 Statistical analysis

The statistical analysis was conducted using a second-order polynomial regression model in the

context of Response Surface Methodology. This model was used to investigate the effects of the two independent variables (wind speed and flight altitude) on the drift response variables. The analysis considered linear, quadratic, and interaction effects. ANOVA was performed for each response to determine the significance of the contributing factors, with statistical significance established at a p -value of less than 0.05.

2.4 Establishment of UAV spraying protocol

Based on the optimized spraying conditions and findings from this study, a UAV spraying protocol was developed for rice production in Davao del Norte. It was modeled after existing literature, particularly the UAV guidelines proposed by Varma et al. (2022), but

was adapted to the local setting and specific findings from this experiment.

3 Results and discussion

3.1 On-target spray application

ANOVA results in Table 2 indicated that none of the regression models for on-target spray application were statistically significant ($p > 0.05$), suggesting that wind speed and flight altitude had limited influence on on-target performance under the tested conditions. However, marginal effects were noted for the interaction between wind speed and altitude on percent coverage ($p = 0.0547$), wind speed squared on droplet density ($p = 0.0630$), and altitude squared on droplet size ($p = 0.0654$). The wide spray swath may have reduced the sensitivity to detect these effects.

Table 2 Summary of prob-value of ANOVA for on-target application

Source	On-target Percent coverage (%)	On-target Density (deposits cm^{-2})	On-target Deposition ($\mu\text{L cm}^{-2}$)	On-target Droplet Size (μm)	On-target Uniformity
Model	0.1849	0.2670	0.1966	0.1439	0.4003
A-Wind Speed	0.7276	0.6328	0.8370	0.8954	0.8814
B-Flight Altitude	0.2622	0.3135	0.5076	0.7688	0.7320
AB	0.0547*	0.1753	0.6815	0.6039	0.1517
A ²	-	0.0630*	0.5574	0.4820	0.8867
B ²	-	0.4751	0.1531	0.0654*	0.9026
A ² B	-	-	0.4213	0.5035	0.8891
AB ²	-	-	0.6906	0.9781	0.8043
A ³	-	-	0.8264	0.9119	0.8544
B ³	-	-	0.5565	0.8540	0.6662

Note: Asterisks* indicate marginal significance ($p < 0.10$).

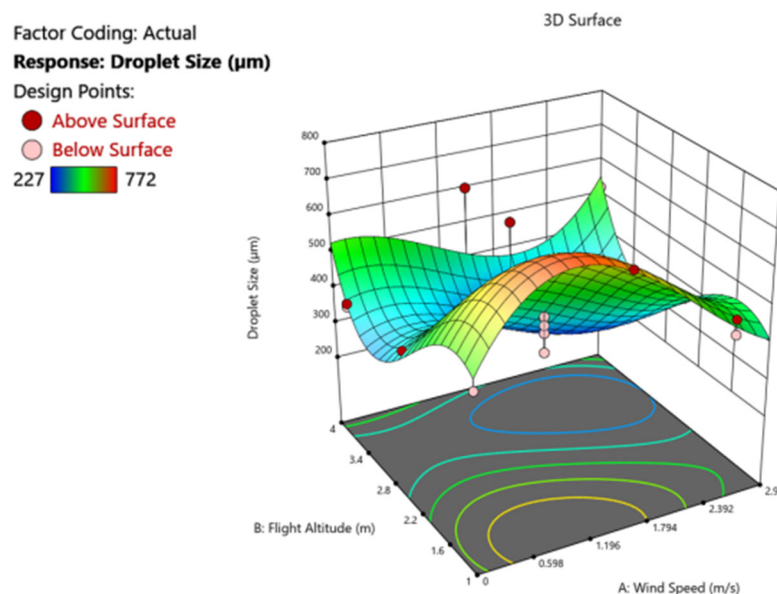


Figure 1 3D surface plot showing the effect of wind speed and flight altitude on on-target droplet size

Further analysis of droplet size, in Figure 1, showed that the volume median diameter (VMD) ranged from 227 μm to 772 μm , falling within American Society of Agricultural and Biological Engineers (ASABE) medium to ultra-coarse spray classifications, a widely recognized standard for droplet size in agricultural spraying. Larger droplets (500-700 μm) formed at low wind speeds ($<1.5 \text{ m s}^{-1}$) and low flight altitudes (1.0 m–2.0 m), ideal for soil-applied pesticides due to reduced drift and deeper penetration. In contrast, smaller droplets (200 μm –400 μm) were produced at higher altitudes (2.5 m–3.8 m) and moderate wind speeds ($1.5\text{--}3.0 \text{ m s}^{-1}$), suitable for foliar applications that require thorough leaf coverage. These findings suggest that droplet size can be optimized by adjusting flight parameters to meet specific pest control needs.

3.2 Off-target spray drift

The influence of wind speed and flight altitude on off-target spray drift was examined to assess how these

parameters affect pesticide movement beyond the intended application area, as shown in Table 3. Overall, the model was statistically significant for off-target percent coverage, droplet density, and deposition. Results showed that wind speed alone did not significantly influence any off-target parameter. In contrast, flight altitude (B) significantly affected percent coverage and droplet density, but not deposition at the linear level. The quadratic and cubic terms of flight altitude, on the other hand, significantly influenced deposition, revealing a nonlinear altitude-related drift pattern. Furthermore, the interaction between wind speed and flight altitude was statistically significant across all off-target parameters – percent coverage, droplet density, and deposition – demonstrating their combined influence on drift behavior. These findings highlight the importance of optimizing both wind speed and flight altitude to minimize off-target spray drift and enhance application precision.

Table 3 Summary of prob-value of ANOVA for off-target spray drift

Source	Off-target Percent coverage (%)	Off-target Density (deposits cm^{-2})	Off-target Deposition ($\mu\text{L cm}^{-2}$)
Model	0.0020	0.0032	0.0035
A-Wind Speed	0.3747	0.3297	0.4700
B-Flight Altitude	0.0121	0.0175	0.1202
AB	0.0021	0.0035	0.0117
A ²	0.4676	-	0.7958
B ²	0.0258	-	0.0234
A ² B	-	-	0.4069
AB ²	-	-	0.3442
A ³	-	-	0.4080
B ³	-	-	0.0178

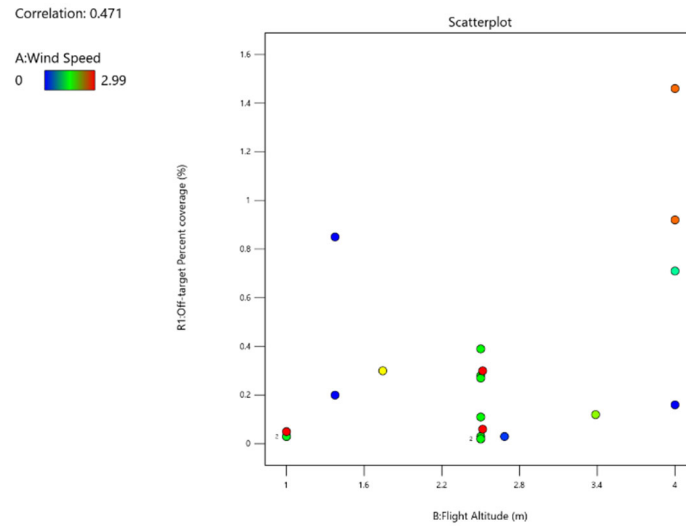
Note: Bold values indicate statistically significant effects ($p < 0.05$).

3.2.1 Off-target percent coverage

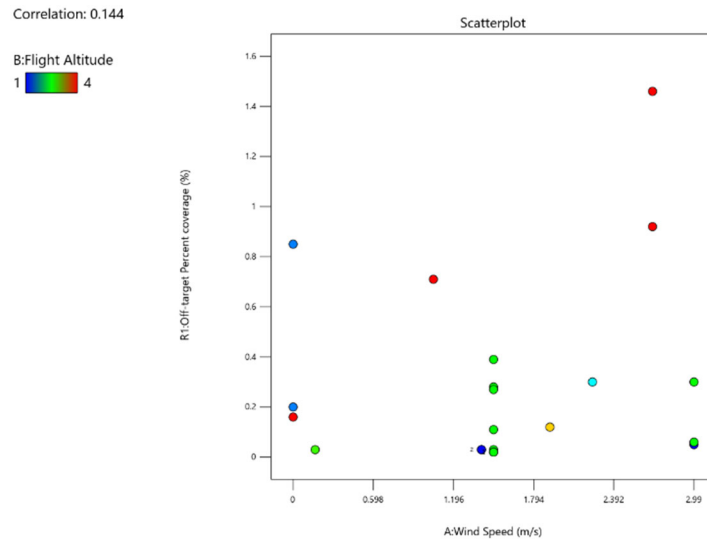
The effect of wind speed and flight altitude on off-target percent coverage revealed that higher wind speeds consistently increased spray drift, especially at greater flight altitudes (Figure 2). At low wind speeds ($0\text{--}0.99 \text{ m s}^{-1}$), drift remained minimal across all altitudes, indicating precise spray application. As wind speed increased to moderate ($1\text{--}1.99 \text{ m s}^{-1}$) and high levels ($2\text{--}2.99 \text{ m s}^{-1}$), off-target percent coverage rose significantly, particularly at higher altitudes,

underscoring wind as a dominant factor in drift. When comparing across altitudes, the 4-meter height consistently showed the highest drift regardless of wind speed, suggesting that higher release points are more prone to off-target spray. The 1-meter altitude displayed less predictable drift behavior, possibly due to UAV-induced downwash turbulence, which can cause unexpected dispersal patterns even under low wind conditions. Overall, the findings highlight that both wind speed and altitude, along with UAV airflow

dynamics, play critical roles in influencing off-target spray movement.

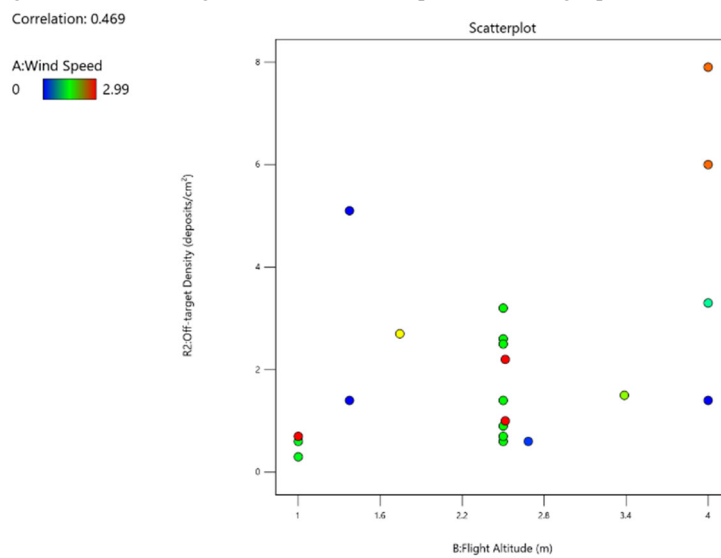


(a) Flight altitude vs. off-target percent coverage at different wind speeds

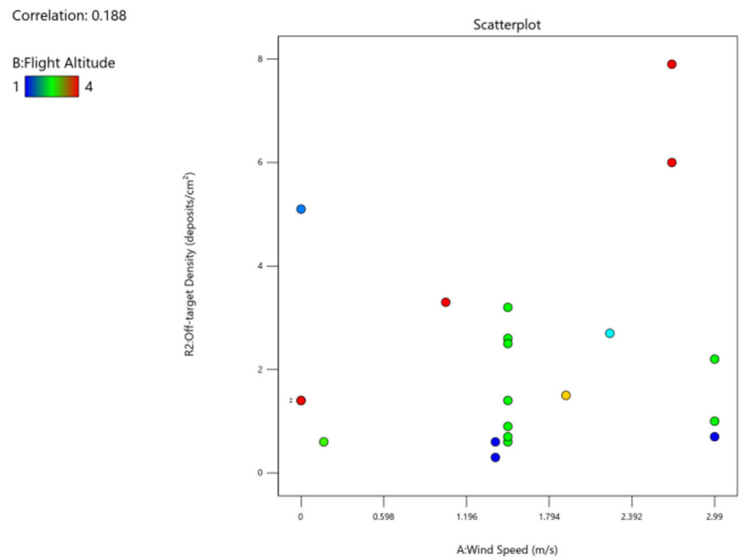


(b) Wind speed vs. off-target percent coverage at different flight altitudes

Figure 2 Effects of flight altitude and wind speed on off-target percent coverage

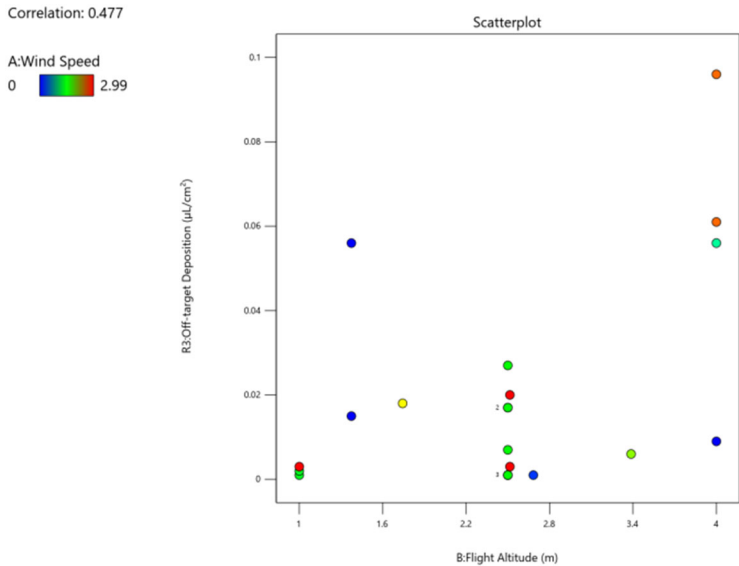


(a) Flight altitude vs. off-target density at different wind speeds

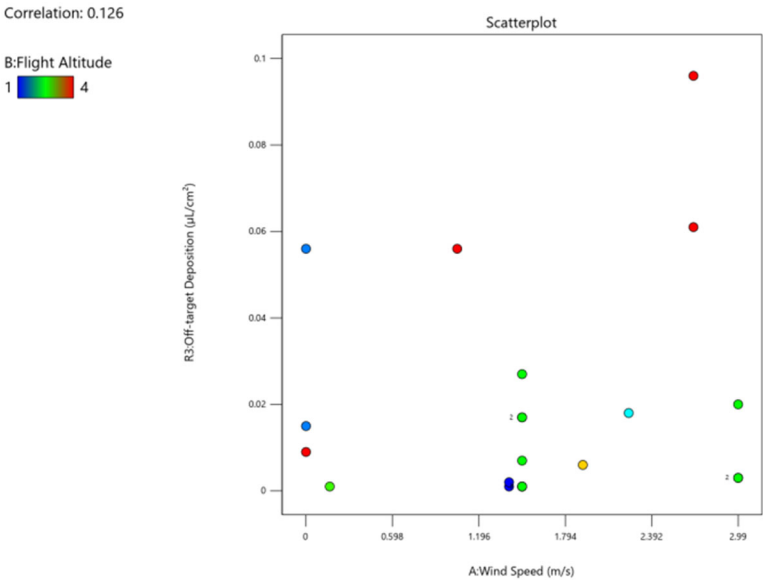


(b) Wind speed vs. off-target density at different flight altitudes

Figure 3 Effects of flight altitude and wind speed on off-target density



(a) Flight altitude vs. off-target deposition at different wind speeds



(b) Wind speed vs. off-target deposition at different flight altitudes

Figure 4 Effects of flight altitude and wind speed on off-target deposition

3.2.2 Off-target density

The influence of wind speed and flight altitude on off-target droplet density shows that higher wind speeds and greater altitudes result in increased drift (Figure 3). At low wind speeds ($0-0.99 \text{ m s}^{-1}$), off-target droplet densities remain minimal across all altitudes, with slight variability at 1.3 m. As wind speed rises to moderate ($1-1.99 \text{ m s}^{-1}$), density increases, particularly at 2.5 m and more notably at 4 m. Under high wind conditions ($2-2.99 \text{ m s}^{-1}$), the 4 m altitude exhibits the highest off-target densities, reaching up to $8 \text{ droplets cm}^{-2}$, indicating significant drift. At the 1 m altitude, droplet densities stay low regardless of wind speed, while higher altitudes show sharp increases with rising wind speed. These patterns confirm that both wind speed and flight altitude are key factors influencing droplet drift intensity and distribution.

3.2.3 Off-target deposition

Wind speed and flight altitude both significantly affect off-target deposition (Figure 4), with altitude having a more dominant influence. At low wind speeds ($0-0.99 \text{ m s}^{-1}$), off-target deposition is minimal across all altitudes, including 4 m. However, as wind speed increases to moderate ($1-1.99 \text{ m s}^{-1}$) and high levels ($2-2.99 \text{ m s}^{-1}$), off-target deposition at 4 m becomes notably higher and more variable, indicating increased drift. Even under calm conditions, the 4 m altitude

shows elevated off-target deposition, likely due to UAV-induced airflow. In contrast, lower altitudes such as 1 m and 2.5 m consistently result in lower and less variable off-target deposition. These results highlight that flight altitude alone can significantly contribute to drift, and this effect is amplified when combined with wind. Similar findings by Liu et al. (2021) affirm that higher wind speeds and application pressures increase off-target deposition, underscoring the importance of optimizing both wind and altitude to reduce spray drift.

3.3 Optimization using RSM – optimal (custom) design

The study utilized Response Surface Methodology (RSM) with a custom design to optimize UAV spray operating parameters – specifically wind speed and flight altitude – to minimize off-target spray drift indicators, including off-target percent coverage, droplet density, and deposition. A total of 64 optimal configurations were identified, achieving an average desirability of 99.72%. A confirmation test conducted at a wind speed of $2-2.99 \text{ m s}^{-1}$ and a flight altitude of 1.2 meters produced actual off-target values of 0.03% for percent coverage, $0.4 \text{ droplets cm}^{-2}$ for droplet density, and $0.009 \mu\text{L cm}^{-2}$ for deposition. These values closely matched the predicted results, with prediction errors of 9.23%, 8.79%, and 9.45%, respectively, and were validated within a 95% confidence interval, as shown in Table 4.

Table 4 Confirmation results analysis

	Predicted Mean	95% PI low	Data Mean	95% PI high	Prediction Error (%)
Off-target Percent Coverage (%)	0.0231686	-0.362857	0.0255253	0.409194	9.23
Off-target Density (deposits cm^{-2})	0.456263	-1.73923	0.416140	2.65176	8.79
Off-target Deposition ($\mu\text{L cm}^{-2}$)	0.0100973	-0.021729	0.0091	0.0419236	9.45

Regression analysis revealed that wind speed (A) and flight altitude (B) affected off-target drift indicators differently. For off-target percent coverage, flight altitude and its quadratic effect, as well as the interaction between wind speed and altitude, had significant positive effects, while wind speed alone was not statistically significant. In the case of off-target droplet density, both wind speed and flight altitude were significant predictors with positive

coefficients, and their interaction term also contributed to the observed variation. However, higher-order terms did not show statistical significance. Off-target deposition, on the other hand, it was most influenced by the interaction term and the quadratic and cubic terms of flight altitude, suggesting complex, nonlinear behavior with respect to altitude. Wind speed had a negative coefficient but was not statistically significant on its own.

The regression models used to predict these outcomes varied, shown in Table 5 and Table 6. Off-target percent coverage was best represented by a quadratic model, indicating a curvilinear relationship with flight altitude:

$$\text{Off-target Percent Coverage (\%)} = 0.119952 + 0.077832A + 0.238491B + 0.4264AB + 0.0938236A^2 + 0.308287B^2 \quad (3)$$

Off-target droplet density followed a linear interaction model, where both wind speed and altitude contributed linearly to increased drift:

$$\text{Off-target Density (deposits/cm}^2\text{)} = 2.12977 + 0.505178A + 1.30136B + 2.30784AB \quad (4)$$

Off-target deposition required a more complex quadratic model involving both linear and higher-order terms, particularly those associated with altitude, highlighting a more nuanced response to changing spray conditions:

$$\text{Off-target Deposition (\mu L/cm}^2\text{)} = 0.0101832 - 0.0206061A - 0.0446584B + 0.0228457AB - 0.00214118A^2 + 0.0208652B^2 - 0.0112953A^2B + 0.0133372AB^2 + 0.0243716A^3 + 0.076064B^3 \quad (5)$$

Table 5 Coefficient table (Intercept to A²)

	Intercept	A	B	AB	A ²
Off-target Percent Coverage (%)	0.119952	0.077832	0.238491	0.4264	0.0938236
p-values		0.3747	0.0121	0.0021	0.4676
Off-target Density (deposits cm ⁻²)	2.12977	0.505178	1.30136	2.30784	
p-values		0.3297	0.0175	0.0035	
Off-target Deposition (μL cm ⁻²)	0.0101832	-0.0206061	-0.0446584	0.0228457	-0.00214118
p-values		0.4700	0.1202	0.0117	0.7958

Table 6 Coefficient table (B² to B³)

	B ²	A ² B	AB ²	A ³	B ³
Off-target Percent Coverage (%)	0.308287				
p-values	0.0258				
Off-target Density (deposits cm ⁻²)					
p-values					
Off-target Deposition (μL cm ⁻²)	0.0208652	-0.0112953	0.0133372	0.0243716	0.076064
p-values	0.0234	0.4069	0.3442	0.4080	0.0178

Three-dimensional surface plots further illustrated the relationships among the variables. For off-target percent coverage (Figure 5), the plot demonstrated minimal drift at low wind speeds and low altitudes, with drift increasing as both variables rose. Similarly, off-target droplet density (Figure 6) increased steadily with wind speed and altitude, with the lowest values observed at the lowest settings. In the case of off-target deposition (Figure 7), the response surface showed a more symmetrical and smoother pattern, with a clear local minimum at moderate altitudes and low wind speeds, and maximum deposition observed when both wind speed and altitude were high. These results emphasize the importance of managing both wind speed and flight altitude to reduce spray drift, with flight altitude emerging as the more dominant factor influencing off-target movement in UAV pesticide

application.

3.4 Spatial analysis of off-target spray drift

The spatial analysis, in Table 7, showed that off-target spray drift is significantly influenced by wind speed (A), flight altitude (B), and their interactions within the first 6 meters from the spray path. At 0-1 meters, strong interaction and nonlinear effects were observed, particularly from AB, B², and A²B terms. From 1-2 meters, flight altitude and its squared term remained dominant, with AB continuing to influence all drift metrics. Between 2-4 meters, more complex and higher-order effects such as AB² and B³ became significant, especially for off-target droplet density and off-target deposition. At 4-6 meters, only wind speed and its cubic term significantly affected off-target droplet density. Beyond 6 meters, no significant effects were observed for any drift metrics, indicating that off-

target drift becomes negligible under the experimental conditions tested. This spatial analysis underscores that drift mitigation strategies should prioritize

optimizing UAV flight parameters within the 0–6 meter near-target zone.

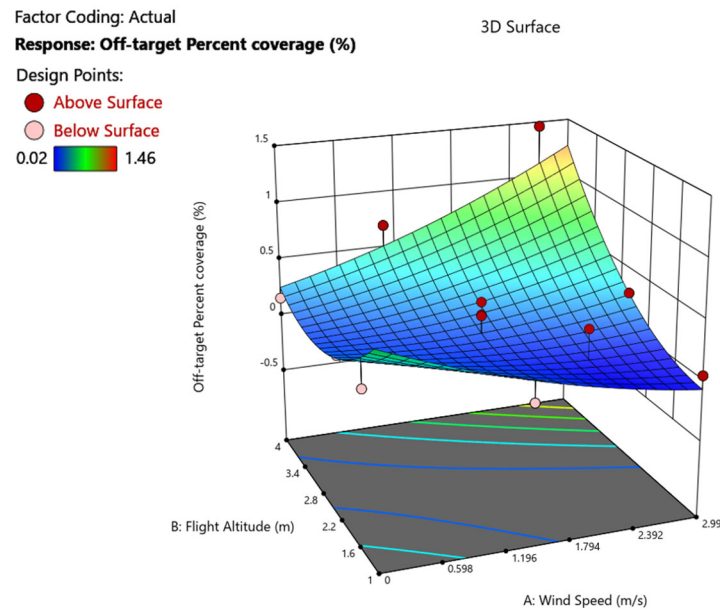


Figure 5 3D surface plot showing the effect of wind speed and flight altitude on off-target percent coverage

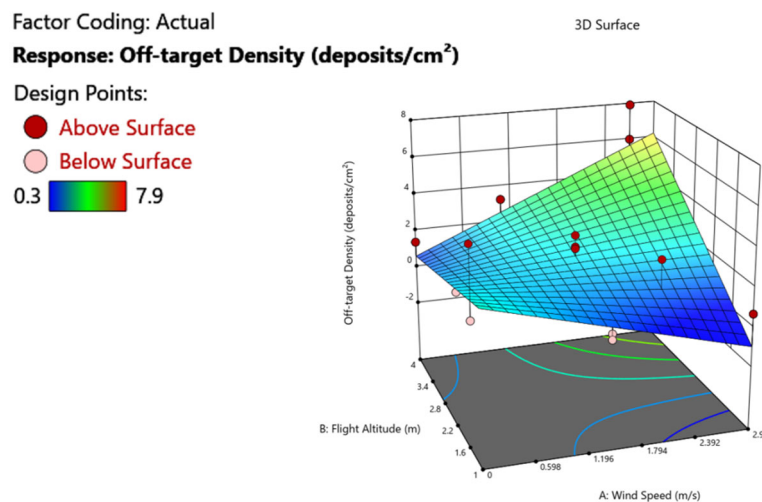


Figure 6 3D surface plot showing the effect of wind speed and flight altitude on off-target density

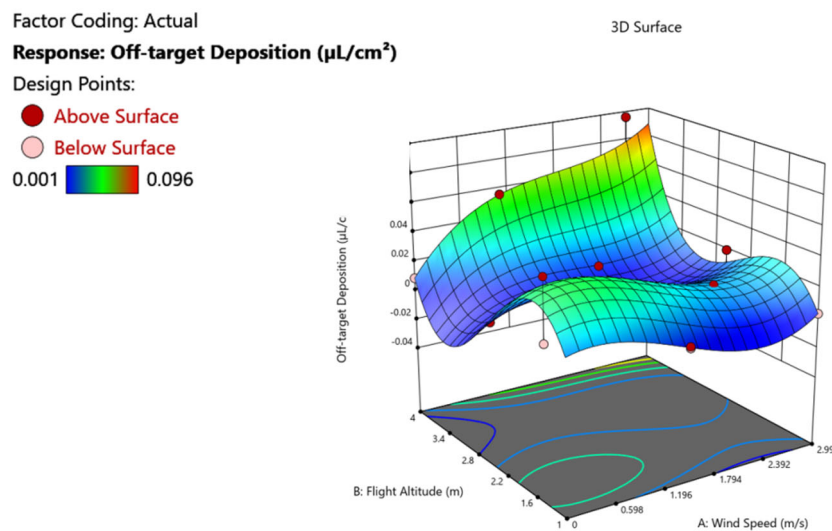


Figure 7 3D surface plot showing the effect of wind speed and flight altitude on off-target deposition

Table 7 Significant factors affecting off-target parameters across the seven segment distances

Segment (m)	Off-target Percent Coverage (%)	Off-target Density (deposits cm ⁻²)	Off-target Deposition (μL cm ⁻²)
0-1	AB, B ²	B, AB	B ² , A ² B
1-2	B, AB, B ²	B, AB	B, AB, B ²
2-3	B, AB	AB, AB ² , B ³	AB
3-4	AB, B ² , B ³	B, AB	B, B ² , B ³
4-6	none	A, A ³	none
6-8	none	none	none
8-10	none	none	none

Note: A-Wind speed; B-Flight Altitude

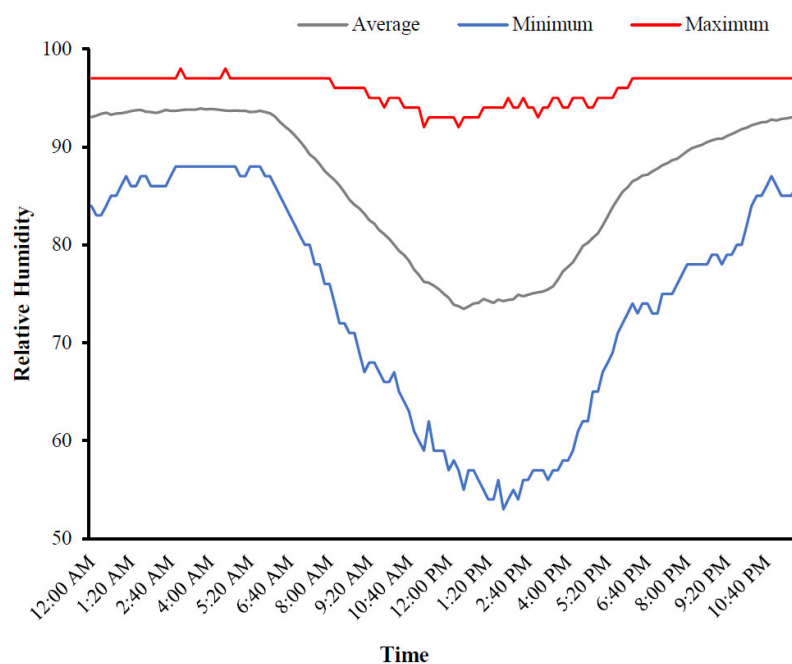


Figure 8 Relative humidity from field AWS data (November 2024 to February 2025)

3.5 Development of a site-specific UAV spray protocol for drift reduction

3.5.1 Flight altitude

An optimal flight altitude of 1.2 meters above the rice canopy was determined to minimize off-target drift. This height leverages UAV downwash for better droplet penetration, as supported by studies by Khankandi et al. (2025), Güneş and Hasegawa (2025), and García-Munguía et al. (2024).

3.5.2 Time of spraying

In compliance with Civil Aviation Authority of the Philippines (CAAP) (2024) regulations, UAV operations were limited to 5:30 to 18:00, as night flights require special permits and compliant lighting systems.

3.5.2.1 Humidity

AWS field data (Figure 8) showed relative humidity consistently above 53%, indicating all spraying periods were within acceptable conditions for effective application and reduced drift.

3.5.2.2 Wind speed

The safe and optimal spraying wind speed was identified as 2.00 to 2.99 m s⁻¹. AWS data (Figure 9) revealed that these conditions typically occurred before 10:00 and from 16:30 to 21:30.

3.5.2.3 Temperature

To avoid phytotoxicity, spraying was advised when temperatures were below 29.5°C. This condition was typically met from 5:30 to 8:30 based on AWS data (Figure 9), making it the ideal spray window.

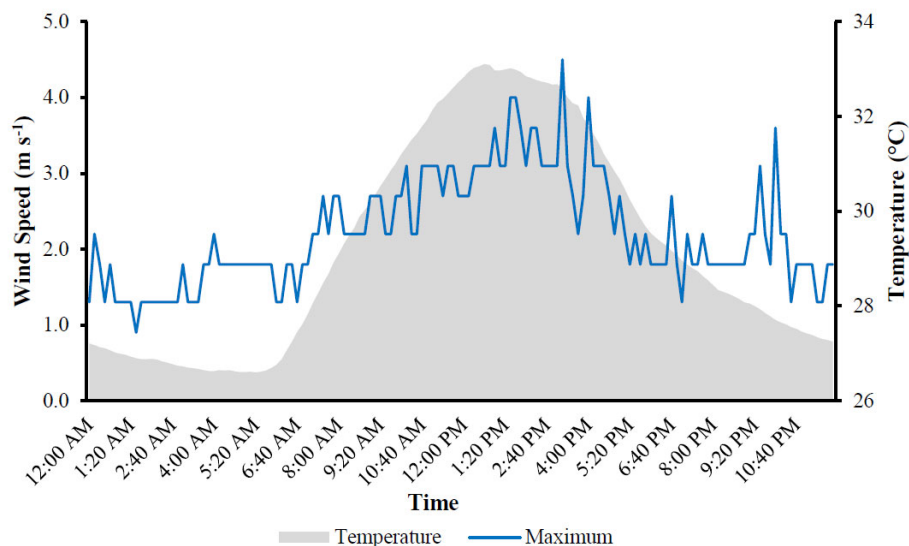


Figure 9 Wind speed and air temperature from field AWS data (November 2024 to February 2025)

Table 8 Standard Drone Aerial Spray Protocols for Minimal Drift in Rice in Davao del Norte

Standard Drone Aerial Spray Protocols for Minimal Drift in Rice	
Particulars	Standard Operating Protocol
Location	Rice Field at the University of Southeastern Philippines, Tagum Unit, Apokon, Tagum City, Davao del Norte
Crop	Rice
Sampling Height	1 meter above ground
1) Drone Spray Parameters	
Drone model	DJI Agras T10
Nozzle type	XRTEEJet Extended Range Flat Spray (XR11001 Orange)
Number of nozzles	4
Flight speed	2 m s ⁻¹
Optimum flight height above crop canopy	1.2 m
Optimum time of spray	5:30 AM to 8:30 AM
2) Pesticide Formulation	
Pesticide used	Karate 2.5 EC (Insecticide, Yellow Label)
Dilution ratio	1.15 mL L ⁻¹
3) Meteorological Conditions	
Temperature range	Below 30°C
Humidity range	Greater than 50%
Optimum wind speed	Less than 3 m s ⁻¹
4) Buffer Zone	
Distance	6 m

Table 9 Simulated Off-Target Pesticide Deposition at Increasing Wind Speeds (1-5 m s⁻¹) at a Constant Flight Altitude of 5 m

Wind speed (m s ⁻¹)	Flight altitude (m)	Off-target Percent coverage (%)	Off-target Density (deposits m ⁻²)	Off-target Deposition (μL cm ⁻²)
1	5	11.32	206,809	10.2
2	5	13.81	327,253	10.6
3	5	16.49	447,697	11.2
4	5	19.36	568,141	12.1
5	5	22.41	688,585	13.5

Table 10 Simulated Off-Target Pesticide Deposition at Increasing Flight Altitudes (1-5 m) at a Constant Wind Speed of 4 ms⁻¹

Wind speed (m s ⁻¹)	Flight altitude (m)	Off-target Percent coverage (%)	Off-target Density (deposits m ⁻²)	Off-target Deposition (mL m ⁻²)
4	1	4.18	146,832	1.5
4	2	7.05	252,159	2.1
4	3	10.54	357,486	3.8
4	4	14.64	462,814	7.0
4	5	19.36	568,141	12.1

3.5.3 Distance for buffer zone

A 6-meter buffer zone was established based on observed droplet drift, which did not exceed this distance under certain conditions. Recent field measurements in a commercial vineyard showed that spray drift from UAV applications was highly concentrated near the field boundary and declined sharply within the first 5 m, and under optimized operational settings with a buffer, drift became negligible beyond 10 m downwind, demonstrating that appropriate UAV settings and buffer distances can effectively limit off-target movement (Psiroukis et al., 2025).

3.6 Final standardized UAV spray protocol

Based on the analyses above, a standardized UAV spray protocol was developed to minimize off-target drift in rice fields in Davao del Norte. Table 8 summarizes the recommended operational and environmental parameters.

3.7 Future risk assessment using model Equations

Simulations using regression models were conducted to assess the environmental and health risks under extreme, non-optimal conditions – specifically wind speeds up to 5 m s^{-1} and flight altitudes up to 5 m. At a constant altitude of 5 m, increasing wind from 1 to 5 m s^{-1} doubled percent coverage and tripled deposit density and volume, shown in Table 9. Similarly, at a constant wind speed of 4 m s^{-1} , raising altitude from 1 m to 5 m caused a sharp increase in all drift indicators, with deposition volume rising from 1.5 to $12.1 \mu\text{L cm}^{-2}$, shown in Table 10. These findings highlight the high sensitivity of drift to altitude and wind, confirming that small changes can lead to large-scale off-target chemical movement. The results align with prior studies (Tudi et al., 2021; Sawyer et al., 2024) warning about pesticide entry into the food chain and contamination of the environment. While UAVs reduce applicator exposure (Yan et al., 2021), they do not eliminate off-target risks, reinforcing the need for strict operational controls.

4 Conclusion

In conclusion, this study demonstrated that while

wind speed and flight altitude did not have significant effect on-target spray deposition under the tested conditions, they had a substantial and statistically significant impact on off-target spray drift. Higher wind speeds and flight altitudes increased the extent of drift, with nonlinear and interaction effects further influencing deposition patterns. The optimization process identified ideal operating conditions – wind speeds of 2 to 2.99 m s^{-1} and a flight altitude of 1.2 meters – that minimized drift while maintaining effective coverage. Spatial analysis confirmed that off-target drift was primarily confined within 6 meters from the spray swath, supporting the establishment of a 6-meter buffer zone. Simulation results further highlighted that high flight altitudes posed greater risks for environmental contamination than wind speed alone. These findings underscore the need for carefully regulated UAV spray protocols that consider local meteorological conditions, flight parameters, and buffer zones to ensure safe, effective, and environmentally responsible pesticide application. Based on these results, a site-specific UAV spray protocol was developed that integrates optimal flight altitude, timing, environmental limits, and buffer zones to minimize drift in rice fields.

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