Smart Agricultural Technology 13 (2026) 101730

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

# Effect of spraying drone flight parameters on vineyard canopy coverage and droplet deposition

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ARTICLE INFO

*Keywords:*
Drone spraying
UAV spraying
Spraying drone
Spraying UAV

ABSTRACT

Unmanned Aerial Vehicles (UAVs) are increasingly promoted as alternatives to conventional plant protection product (PPP) spraying in vineyards, yet limited evidence exists on how flight parameters and application configurations influence spray deposition under real vineyard conditions, especially within Europe. This study evaluated the performance of a DJI Agras T16 spraying drone across eight operational configurations combining two flight altitudes (2.0 and 2.5 m AGL), two flight speeds (1.0 and 1.5 m/s), and two aircraft positioning strategies (over-row and inter-row). Spray deposition, canopy coverage, and ground losses were quantified using water-sensitive papers (WSPs) positioned at multiple canopy heights and ground locations, while meteorological conditions were monitored, following methodologies adapted from the ISO 22,866/22,522 protocols. Results showed strong interactions among altitude, speed, flight path, and wind parameters, with over-row treatments concentrating deposition in upper canopy layers and inter-row treatments producing more homogeneous profiles but higher sensitivity to wind direction. Lower altitude flights (2.0 m) combined with slower speed (1 m/s) substantially increased ground deposition regardless of UAV positioning, whereas higher altitude (2.5 m) and speed values (1.5 m/s) reduced spray losses to the ground. The increase in pump output associated with higher speed under a constant application rate is expected to produce finer droplets, which can enhance penetration but may also elevate in-field drift risk. These findings demonstrate that UAV spraying performance depends on integrated optimisation of operational settings and environmental conditions. The results provide practical guidance for improving drone-based vineyard spraying and highlight the need for updated EU regulatory frameworks tailored to UAV application characteristics.

## 1. Introduction

Safeguarding crops is of crucial importance in crop production to protect plants from pests, diseases and environmental challenges and is implemented by practical treatments and specialised strategies [1]. For high-value crops such as vines, chemical control remains the primary method, relying on plant protection products (PPPs) such as pesticides and herbicides. These are applied either as a preventive measure before infestations occur or as curative applications, selectively targeting specific pests and diseases in early symptom stages to prevent significant crop damage [3]. Although conventional methods have undeniably laid the foundation of modern viticulture, they face several limitations as their efficacy can vary and may not always be optimal for large commercial vineyards. As viticulture expands globally, there is a growing demand for more efficient and reliable crop protection methods [5]. The continued reliance on conventional approaches highlights the need to address the limitations and complexities associated with PPP spraying applications, which continuously shape the evolving framework of viticultural techniques.

Proper pesticide application is crucial for pest management and agricultural efficiency, as over-application can lead to adverse effects, including soil fertility depletion and the emergence of pesticide-resistant insect species. Traditional spraying techniques remain essential in vineyard protection, but they face challenges that necessitate innovative solutions. Various established methods, despite their effectiveness, have many limitations, driving the need for more efficient and effective

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https://doi.org/10.1016/j.atech.2025.101730
Received 15 November 2025; Received in revised form 15 December 2025; Accepted 15 December 2025

vineyard practices. The main challenge in conventional spraying in vineyards, is achieving full spray coverage for the uniform application of PPPs, as vineyards are characterised by narrow row spacing and uneven canopy structure. Dense vegetation is responsible for inconsistent spray application because it is difficult for the droplets to reach inner canopy zones. Consequently, vineyards are prone to infestations and diseases, leading to destructive implications for both yield and quality.

Spraying drones are defined as any Unmanned Aerial Vehicle (UAV), operated manually or automatically, that is capable of applying agrochemicals at a desired rate close to the canopy (typically $< 5$ m). Spraying drones have emerged as valuable tools in crop production since they are suitable for remote sensing operations in multiple scenarios and scientific sectors [25]. Although these systems are highly automated, several safety concerns still exist, limiting their autonomous and widespread adoption use in the EU agricultural sector.

As drone regulations vary across the EU, drone spraying is outright banned in several countries, due to the lack of a clear regulatory distinction between low-altitude drone spraying and traditional air spraying, performed by manned aircraft at much higher altitudes, which results in high spray drift. In other Member States that deviate from the common EU framework established by Directive 2009/128/EC on the sustainable use of pesticides, exemptions and derogations can be granted for aerial spraying (including by UAVs) upon providing the necessary documentation and demonstrating the scope of each application, provided that clear advantages for human health and the environment are shown and appropriate risk-mitigation measures are applied. France and Germany for example, both allow drone spraying in specific circumstances (e.g. steep fields, where the risk of traversing with a terrestrial vehicle is too high for the safety of the operator), while countries where low-altitude aerial spraying is allowed (e.g. Portugal), specific PPPs can also be licensed for aerial applications. For this reason, an updated regulatory framework enabling the sustainable use of UAV-based PPP applications is essential. Agriculture stakeholders increasingly call for the update of the Sustainable Use of Pesticides Directive (SUD) to allow drone-based spraying, which could support pesticide reductions in line with the EU Farm to Fork Strategy. This strategy stipulates an EU-wide target of reducing the use and risk of chemical pesticides by 50 % by 2030 and, together with the Biodiversity Strategy, forms a core pillar of the European Green Deal (Directive 2009/128/EC). These policies place agriculture at the centre of EU efforts to address climate and environmental challenges, contributing to the UN 2030 Sustainable Development Agenda.

Drone spraying must be performed under Visual Line of Sight (VLOS) conditions, requiring operators to maintain visual contact with the aircraft throughout the flight. Safety distances and protective measures should also be observed to safeguard operators and nearby civilians. However, although legislation and strict guidelines exist, they are often difficult to enforce in practice. Internet connectivity is another critical aspect for drone spraying, as network coverage is often required to achieve high precision and accurate flight execution. Moreover, spraying drones must comply with aviation standards and procedures defined by ICAO, and any modifications to aircraft components must follow appropriate testing to validate flight capability and ensure safe operation (Regulations (EU) 2019/947 and 2019/945).

Nevertheless, spraying drones can perform low-volume, site-specific PPP applications, fly at low altitudes following complex patterns, and access difficult or sloped terrain [6,21]. On a similar note, despite their limited operational autonomy (related to both flight time due to Lithium batteries being their most common power source and small payload capacity, which requires frequent refuelling stations) [13], in recent years, modern, larger models have been developed, which are capable of covering approximately 20 m2/min and have liquid tanks ranging from 10 to 100 L.

Drones are capable of conducting spraying operations not only in open field crops, but also in three-dimensional (3D) crops, like vineyards. With their ability to freely operate either between or over vineyard lines [23] and navigate in crop rows with high accuracy [2], spraying drones enable optimised resource allocation while theoretically decreasing environmental impact due to smaller application volumes and water savings, making them particularly appealing for vineyard management. Moreover, spraying drones have proven valuable in steep fields where conventional machinery that can safely traverse the steep terrain are limited [7]. In such cases, a spraying drone can operate at low altitudes above crops in small fields or challenging areas not easily accessible by humans or ground-based equipment [27].

In addition to operational advantages, drone spraying significantly reduces operator exposure to PPPs [17] and preserves soil structure by eliminating compaction caused by ground machinery [20]. However, PPP applications are still often mismanaged due to the misconception that “more is better.” Combined with improper sprayer configuration, such as worn or unsuitable nozzles, incorrect pressure settings or non-optimised system calibration, these practices contribute to soil, water and air pollution and negatively affect biodiversity [9].

Spray drift significantly impacts neighbouring non-target plants, insects, and animals, even at considerable distances from the application area, while exposing nearby populations and agri-food consumers to PPP residues [14], often exceeding regulatory thresholds. Misplacement of fungicides, herbicides, and pesticides beyond the target is undesirable as it represents both product waste and a threat to sensitive, non-target areas. Spray application is complex, and currently there is no mechanism for operators to receive immediate feedback indicating whether coverage is adequate. Nozzle type, spray pressure and flight parameters have emerged as key determinants of canopy deposition and coverage [2], driving research toward optimising spray performance, including automatisation strategies based on Artificial Intelligence [15,22]. Among technical components, nozzles remain especially critical; although manufacturers have begun designing aerial-specific nozzles, standardisation has not yet been achieved.

The impact of drone rotor downwash air currents on canopy deposition is significant for arable, bush, and tree crops, as it helps move foliage and distribute droplets within the canopy, increasing the likelihood of reaching the innermost leaves [28]. However, challenges in infiltrating canopies, influenced by their configuration and thickness, have been documented in citrus orchards [24]. Spraying height is another important parameter: Qin et al. [19] found that flying at 5 m with a speed of 4 m/s improved droplet distribution in arable fields under specific environmental conditions.

Environmental factors also interact strongly with sprayer settings and droplet size [4]. Temperature, humidity, and wind speed influence droplet evaporation and drift, resulting in inconsistent performance under varying field conditions. Liquid properties such as viscosity and surface tension, especially relevant for biological PPPs or adjuvant-rich formulations, affect atomisation and nozzle performance when pump output changes. These factors should always be considered during calibration to maintain consistent spray quality. While greater pump output can increase spray density, it must be balanced with nozzle capacity, environmental conditions and energy constraints / flight autonomy to achieve uniform deposition while minimising droplet displacement and PPP losses.

Despite increasing interest in UAV sprayers, limited evidence exists on how specific combinations of flight altitude, forward speed, and spray-path positioning jointly affect canopy penetration, drift potential, and spatial deposition patterns under real vineyard conditions. Previous studies analysed below, typically vary single parameters in isolation, leaving a gap in understanding multi-factor interactions in field environments, particularly in European vineyard systems.

### 1.1. Related work

Vineyards require prompt and effective treatments according to the different growth stages as they are exposed to several diseases during the year and to various climatic conditions, many of which are unfavourable. In previous vineyard research, very low spray application rates have often been proven insufficient to achieve the desired application efficiency [18].

Biglia et al., [2] evaluated the performance of a spraying UAV system in an experimental vineyard at full growth stage and compared it to a conventional sprayer mounted on a tractor. The UAV system consisted of a six-rotor DJI Matrice 600 Pro with a customised standalone sprayer system while the conventional system was an axial-fan sprayer. The results showed that flight mode contributed to improved spray application performance. Specifically, certain flight modes increased the average canopy deposition and reduced the average ground losses. It is noteworthy that these findings are contradictory to those of Giles & Billing, [8] who suggested a cross-flight orientation relative to the vine rows as the best flight mode to improve canopy deposition. Gilles and Billing [8] assessed the efficiency of a single-rotor spraying UAV in a commercial vineyard. In this study, the UAV flew at 3–4 m above the vines and at a speed of 5.5 m/s, resulting in a deposition rate of 47 L/ha. Two spraying configurations were tested: one with two flat fan nozzles active and one with three flat fan nozzles active. Spray deposition was determined by tracer analysis, while the application rate was determined directly through volumetric measurement of the discharged liquid.

In a similar setup, Sarri et al. [21] investigated the performance of a hexacopter spraying UAV, equipped with different types of nozzles in a commercial vineyard with a steep slope. The UAV demonstrated high operational capacity and performance compared to a conventional knapsack sprayer, though the authors listed several weaknesses associated with the use of spraying UAVs in vineyards, such as the low working pressure that resulted in certain canopy zones with low droplet coverage.

Wang et al., [26] compared the spray performance of three commercial spraying drone models equipped with hollow-cone nozzles (HCNs) and air-injector flat fan nozzles (AIN) in an artificial vineyard, analysing the deposition, spray drift, and mass balance. A critical area of focus was the optimisation of spray parameters, including spray volume, droplet size, droplet spread, and overall spray effectiveness, particularly for insect pest control [15]. These parameters had a significant impact on the efficacy of spraying. In vineyards, higher speeds around 3 m/s have proven to increase droplet deposition on the canopy, while reducing losses to non-target areas, especially when conventional spray nozzles are used. Similarly, Morales-Rodríguez et al., [16] compared conventional sprayers and spraying UAVs in vineyards and olive crops in Extremadura, Spain. This study evaluated economic requirements, efficiency, operating costs, and water and product usage to assess the advantages and disadvantages of each method. The research found that drone sprayers offered several benefits over traditional sprayers, including reduced water and PPP consumption, lower operational costs, and enhanced efficacy. However, UAVs also have limitations, such as higher initial investment costs, limited flight autonomy, and smaller payload capacity compared to conventional sprayers.

Together, these studies demonstrate that UAV spraying can be effective, but performance varies widely depending on flight configuration, platform design, environmental conditions, and nozzle setup. This variability reinforces the need for systematic, multi-factor field experiments such as the one presented here.

In this paper, the in-field spraying quality of UAV-based applications was evaluated, including canopy deposition, penetration, and ground losses between rows, across a range of operational configurations such as spraying altitude, flight speed, nozzle flow, and liquid deposition rates. To systematically test these factors, a novel experimental design was developed, incorporating methodological elements from ISO protocols 22,866 and 22,522. The study also examined inherent risks of drone spraying and potential mitigation strategies, aiming to support safe, efficient, and environmentally responsible UAV-based plant protection practices.

## 2. Materials and methods

### 2.1. Study area

The pilot area of this study was the experimental vineyard of the Agricultural University of Athens located in Spata, Greece (37°59′06″ N, 23°54′21″ E) (Fig. 1). The vineyard has 2.0 m row spacing with 1.6 m spacing of vines along the row to result in a density of 3125 vines per ha. The average vine height is about 1.5 m, with the leaves and grapes occupying the zone above ground between 0.3 and 1.5 m. The trials of the present study took place between July and August 2024. The growth stage corresponding to that period was Veraison (BBCH 81), and the Leaf Area Index (LAI), calculated by averaging the measurements from a total of 12 random sampling locations (vines) within the study lines with a LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences, USA).

### 2.2. Experimental design

Flight testing prior to the field trials took place in both the field segments of the pilot area (for the optimisation of spraying route planning), while equipment testing and configuration setup took place in a strictly controlled environment and fully isolated location. The aircraft flow meter was always calibrated prior to each set of replicates upon ensuring that no air was trapped within the system, and the 2 pumps were calibrated twice during the experimental season, once at the start of the period prior to the commence of the trials, and 20 days afterwards.

The drone used in these trials was an hexacopter Agras T16 (DJI, Shenzhen, China), equipped with eight (8) XR11001VS nozzles. The drone’s performance was evaluated in two different application methods under open-field conditions, namely by flying over the inter-row (over the 2 central vine lines, namely Row 2 and Row 3) and by spraying over a single central row (Row 2) while operating in different spraying settings (different altitudes Above Ground Level - AGL and aircraft speed / flow rate). Before every flight, an additional buffer area of at least 20 m was always sprayed, to ensure the spraying drone was not affected by start-up effects when entering the sampling zone. An overview of the experimental design and sampling points are provided in Fig. 2. Each replication was conducted using a constant application rate of 80 L/ha, which resulted in two different flow rates corresponding to the two travel speeds: 1.4 L/min for 1 m/s and 1.8 L/min for 1.5 m/s (see Table 1, experimental configurations).

The collectors used for sampling spray droplets were water-sensitive papers (WSPs) (76 mm × 26 mm, AAMS Salvarani), which capture spray droplets and instantly change colour upon contact with liquid. WSPs were selected because they provide reliable, low-cost, and standardised estimates of droplet coverage and are recommended in ISO-aligned field deposition studies. Three canopy WSPs were placed inside each row at three heights, stabilised to the trellis (Fig. 3): 0.3 m, 0.6 m, and 1.0 m above the lowest vegetation point, to evaluate the droplet distribution from the spraying drone. Ground WSPs mounted on dedicated wooden supports were used to evaluate droplets that did not reach the vine foliage and instead deposited on the soil between the vine rows. All trials were conducted with distilled water, and the WSPs sprayed by the spraying drone were collected one minute after the completion of each trial and stored in specifically designed thermo-insulated storage boxes for preventing sample changes due to moisture, and in individual sampling bags to prevent contact between papers.

The total number of experimental trials that constitute a measurement and all tested configurations (sets of operational parameters) are presented in Table 1, selected as generally acceptable and commonly used parameters across EU research [12]. Each iteration is replicated three times, resulting in a total of 24 measurements per dataset.

### 2.3. Meteorological conditions

Weather conditions were measured continuously during each test

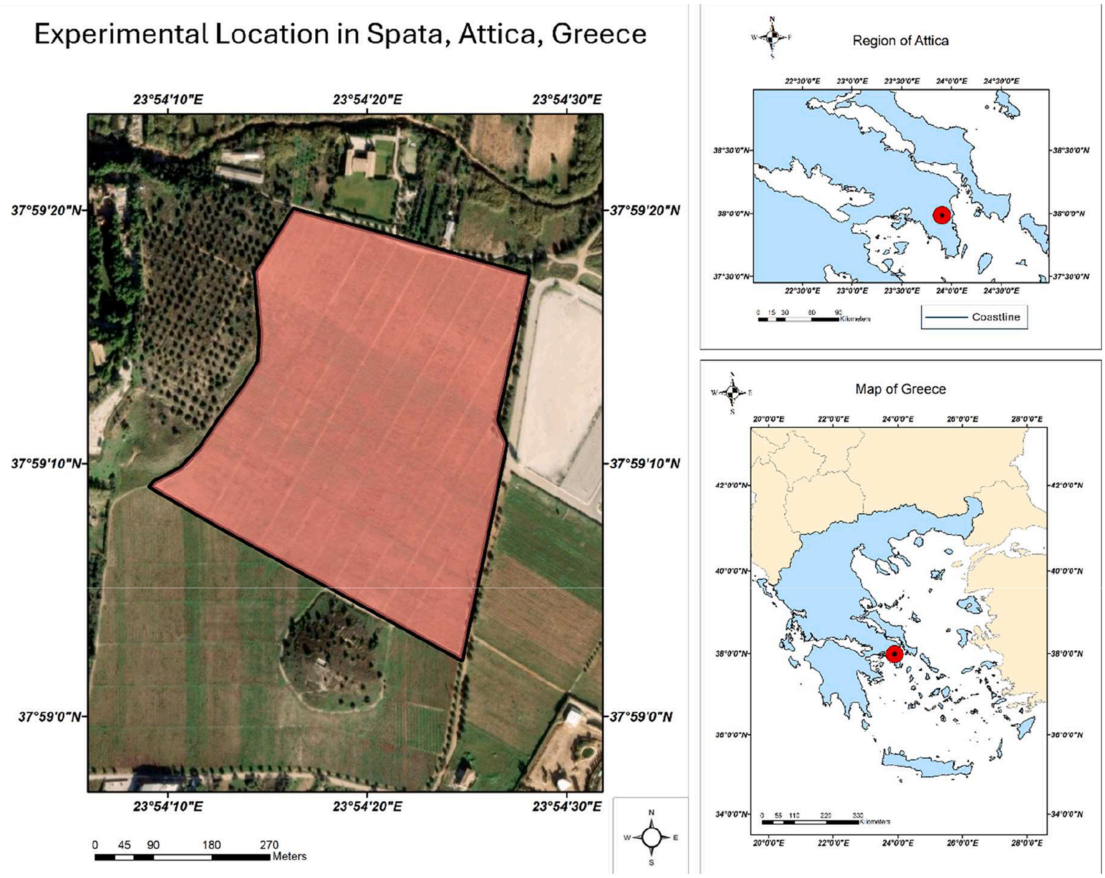

**Fig. 1.** The location of the experimental site, the experimental vineyard of AUA in Spata, Attica, Greece.

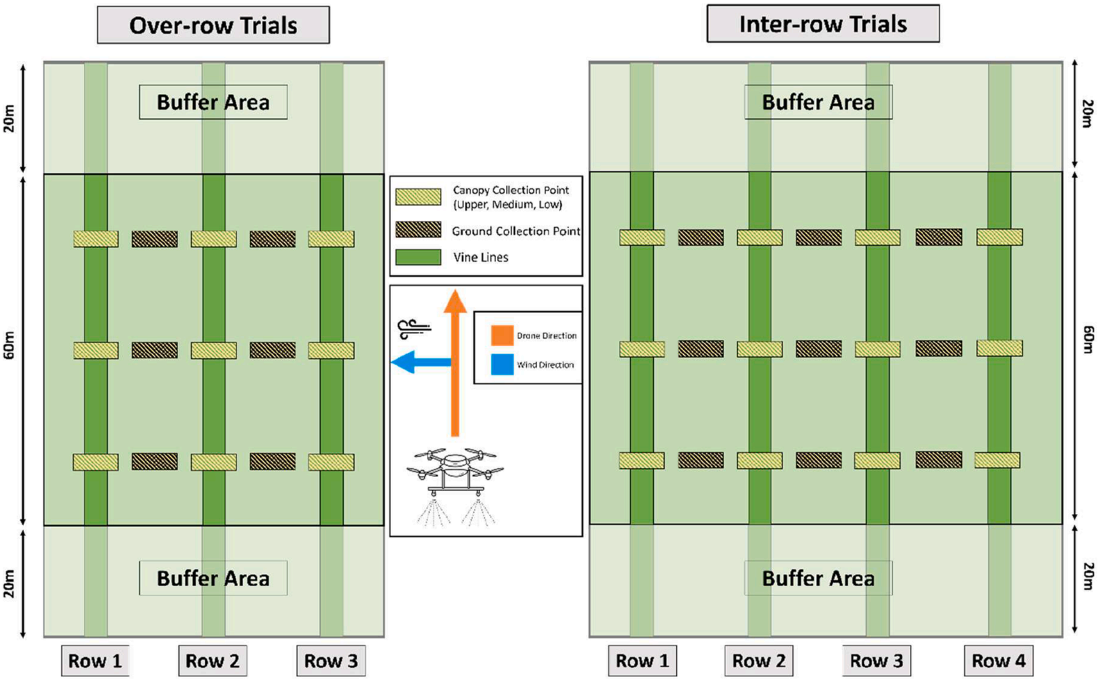

**Fig. 2.** The experimental design for over-row and inter-row trials, alongside the spraying drones line of path and the ideal (perpendicular to the vine lines) wind direction.

**Table 1**
The operational configurations of each trial.

| Treatment | Altitude (AGL) (m) | Speed (m/s) | Position |
|---|---|---|---|
| A | 2.5 | 1 | Over-row |
| B | 2.5 | 1.5 | Over-row |
| C | 2 | 1 | Over-row |
| D | 2 | 1.5 | Over-row |
| E | 2.5 | 1 | Inter-row |
| F | 2.5 | 1.5 | Inter-row |
| G | 2 | 1 | Inter-row |
| H | 2 | 1.5 | Inter-row |

The droplet spectra (expressed in Volume Mean Diameter – VMD values) obtained for each specific operational speed value are presented below: D[v,0.1] = 123 μm, D[v,0.5] = 245 μm, and D[v,0.9] = 419 μm for a flow rate of 1.4 L/min (corresponding to the Treatments with a Speed value of 1 m/s); and D[v,0.1] = 117 μm, D[v,0.5] = 229 μm, and D[v,0.9] = 469 μm for a flow rate of 1.8 L/min (corresponding to the Treatments with a Speed value of 1.5 m/s).

using a portable ultrasonic anemometer, positioned near the test site 15 m upwind of the flight path (to avoid turbulence caused by the spraying drone's rotors). The sensor height was 1.5 m above ground, and measurements were recorded at 1 Hz. The vector perpendicular to the vine rows was measured as 40° (northeast). For each trial, the deviation of the wind direction from this perpendicular was calculated from those values.

The field experiments were carried out based on thresholds adapted from the ISO protocols 22,866:2005 and 22,522:2005, which set general criteria on the conditions for spray measurements within and outside the field's boundaries. To this end, all measurements were decided to be carried out under the following conditions: ambient air temperature between 5 °C and 35 °C, wind speed at 1 m above the canopy of at least 0.5 m/s and no greater than 2.5 m/s (with no >10 % of wind-speed readings outside that range) and the mean wind direction at 90° ± 30° relative to the spray track. The averaged wind speed and direction values for each trial can be found in Table 2. In addition, the restriction that relative humidity shall remain below 70 % for the duration of the trial was also imposed. If the ambient temperature dropped below 10 °C or rose above 35 °C, or if relative humidity exceeded 70 %, the trial was deemed invalid and was set to be repeated under suitable environmental conditions.

### 2.4. Sample analysis

Collected WSP samples were analysed using the DepositScan software (USDA-ARS, Ohio, USA). As part of the analysis process, all WSPs were scanned using a flatbed scanner at a resolution of 600 dpi, following the settings required for accurate droplet-deposit recognition. Each sample was placed individually on the scanner bed with consistent orientation to ensure uniform image quality. The scanned images were saved in a lossless TIFF format and directly imported into DepositScan, which automatically quantified droplet number, size distribution, coverage, and deposit density for each sample by converting stain diameter to droplet volume using established spread-factor equations and calibration curves provided by the developer.

**Table 2**
The wind-related environmental conditions during each trial, averaged across all three (3) replicates.

| Treatment | Wind Speed (m/s) | Wind direction (°) | Deviation to perpendicular (°, Absolute value) |
|---|---|---|---|
| A | 1.7 | 42 | 2 |
| B | 1.1 | 33 | 7 |
| C | 1.3 | 30 | 10 |
| D | 0.6 | 47 | 7 |
| E | 1.1 | 43 | 3 |
| F | 2.3 | 38 | 2 |
| G | 0.6 | 48 | 8 |
| H | 1.5 | 31 | 9 |

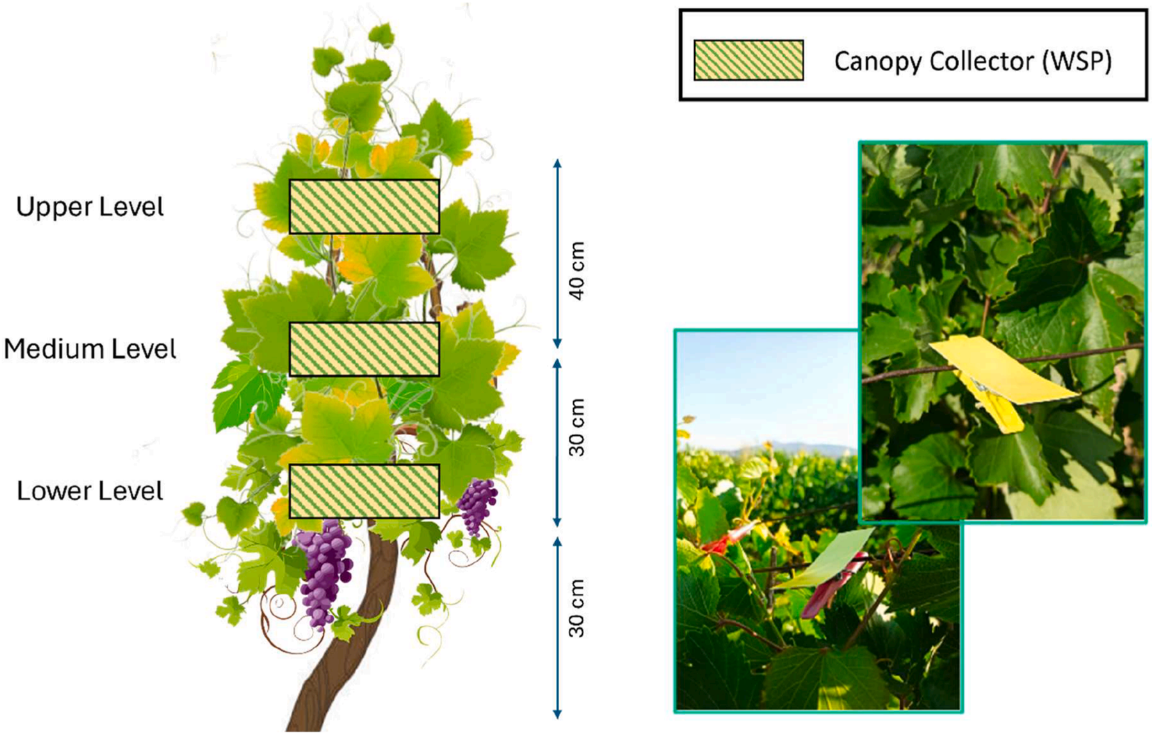

**Fig. 3.** The sampling strategy and collectors' positioning in every sampling point.

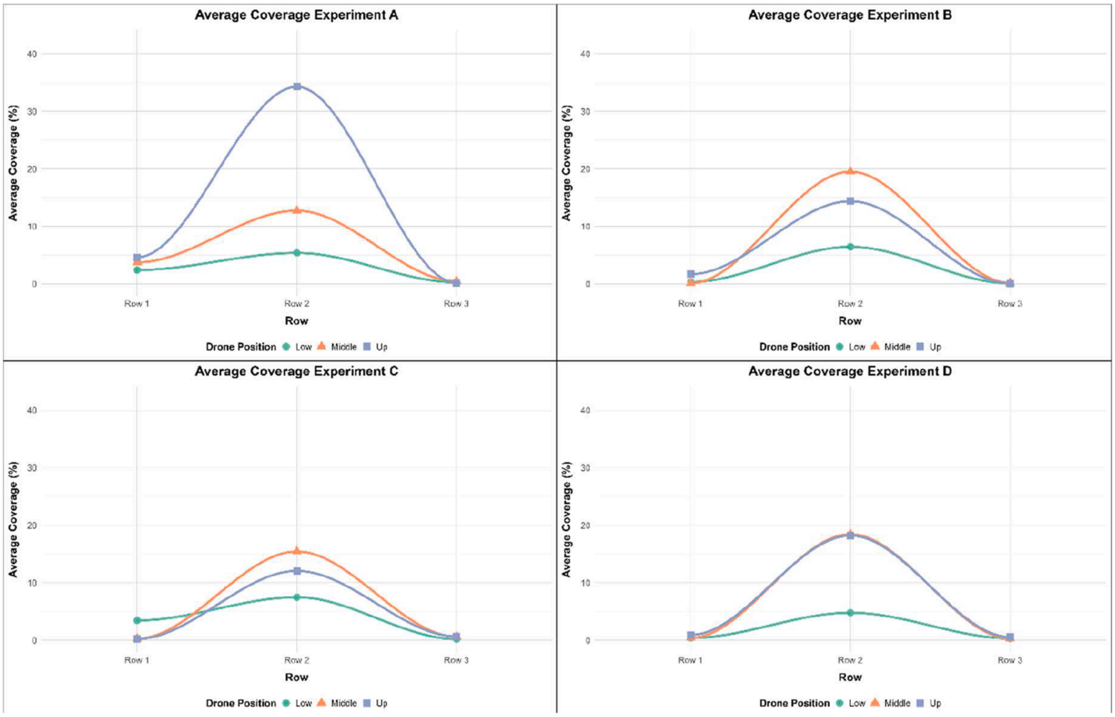

**Fig. 4.** The individual coverage curves of each over-row trial per row and canopy height.

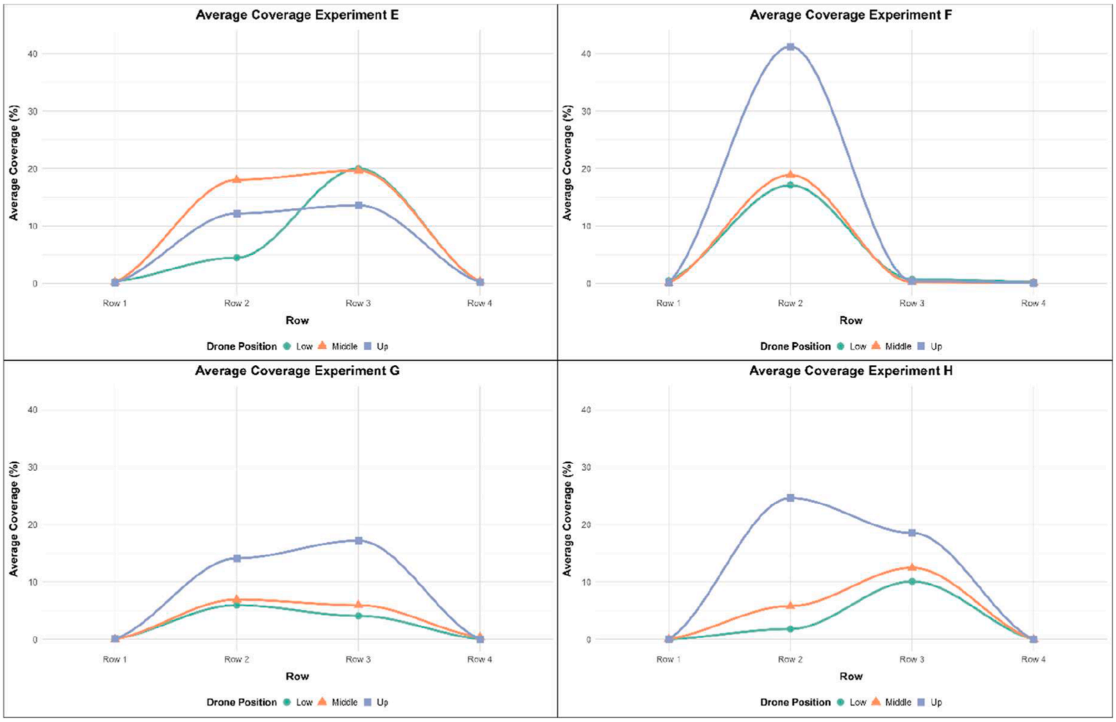

**Fig. 5.** The individual coverage curves of each inter-row trial per row and canopy height.

## 3. Results

### 3.1. *Canopy coverage curves*

The aggregated average Canopy Coverage results from all field trials are presented in Fig. 4 (Over-row treatments) and Fig. 5 (Inter-row treatments). Across all four Over-row spray applications (Treatments A - D), spray coverage consistently peaked at Row 2 for all canopy positions, with substantially lower deposition at Rows 1 and especially Row 3, which is expected considering the wind direction would naturally transfer most of the droplets towards the other two (2) rows (1 and 2) which follow the wind vector. Treatments conducted at 2.5 m AGL (A and B) produced slightly higher peak coverage in the upper canopy compared with the 2 m AGL treatments (C and D), while increasing application speed from 1.0 to 1.5 m/s (A to B and C to D) shifted coverage patterns between canopy positions but did not markedly change the overall spatial trend. Overall, the aggregated results show a consistent deposition gradient, with maximum interception occurring at the central row and a steep decline toward the outer row.

Across the Inter-row applications (Treatments E–H), spray coverage followed distinct spatial patterns compared with the over-row trials. In Treatments E and G, deposition increased gradually from Row 1 to a peak at Row 3, with the middle and upper canopy positions receiving the highest coverage. In contrast, Treatments F and H showed coverage concentrated primarily at Row 2, especially in the upper canopy, where Treatment F produced the highest single-position value observed across all inter-row trials. Coverage at Row 4 was minimal for all treatments, indicating limited lateral transport beyond the target zone. Overall, both altitude and speed influenced the magnitude and distribution of deposition, with higher altitude (2.5 m) contributing to greater upper-canopy coverage and higher speed (1.5 m/s) amplifying central-row deposition.

Overall, the combined effects of flight height and speed on the spray profile through spray coverage and deposition (calculated through the WSP analysis by the same software) values are presented in Fig. 6. At an aircraft speed of 1.0 m/s, increasing the altitude from 2.0 m to 2.5 m AGL resulted in a reduction in both coverage and deposition, indicating a lower proportion of droplets reaching the sampling surface. In contrast, at an aircraft speed of 1.5 m/s, coverage and deposition increased with greater flight altitude. Across both speeds, the highest coverage and deposition occurred at 2.5 m and 1.0 m/s, while the lowest deposition levels were observed at 2.5 m and 1.5 m/s. On the other end, both altitude configurations with a, aircraft altitude of 2.0 m AGL showed more consistent results and lower variability due to change in the sprayer’s speed.

### 3.2. Ground coverage

The aggregated average Ground Coverage results from all field trials are presented in Fig. 7 (Over-row treatments) and Fig. 8 (Inter-row treatments). Ground coverage of spray droplets differed substantially among the four flight configurations. Treatments flown at the higher altitude (2.5 m; A and B) resulted in generally lower ground deposition across corridors and lanes. Treatment A (1.0 m/s) produced slightly higher deposition in Corridor 1 compared to Corridor 2, while increasing speed at the same altitude (Treatment B, 1.5 m/s) shifted deposition patterns but did not substantially increase overall ground coverage. Reducing altitude to 2 m (Treatments C and D) led to noticeably greater deposition on the ground, particularly in Treatment D (1.5 m/s), which showed the highest and most widespread coverage across both corridors, with a marked peak in Corridor 1–Lane B.

In Inter-row trials, the highest levels of ground coverage were consistently associated with the lower-altitude flights (2 m). Treatment G (2 m, 1.0 m/s) produced the highest overall deposition, particularly concentrated in Corridor 2–Lane C. Treatment H (2 m, 1.5 m/s) also resulted in elevated ground deposition across the central corridor, though somewhat less pronounced than in Treatment G. Flights performed at 2.5 m (Treatments E and F) demonstrated lower and more evenly distributed deposition, with Treatment F (2.5 m, 1.5 m/s) showing slightly increased deposition in Corridor 2–Lane C relative to the others at this altitude. Across all treatments, deposition tended to concentrate in the central spraying corridor directly beneath the flight path.

Overall, ground deposition varied less across configurations than canopy deposition, but lower altitudes consistently produced higher ground. Nevertheless, lower altitudes consistently resulted in higher ground coverage. The respective effect of operational parameters on ground coverage and deposition is presented in Fig. 9.

### 3.3. Effect of wind

Modelling both Over-row and Inter-row trials revealed complex three-way interactions among row position, wind direction, and wind speed on predicted coverage. In Inter-row trials, Row 3 exhibited the most pronounced response. Coverage approached 100 % at a wind direction of approximately 32° under the lowest wind speed (0.6 m/s), but declined sharply to near zero as wind direction shifted towards ∼47.5° Within this row, lower wind speeds (0.6–1.1 m/s) were generally associated with higher coverage. Rows 1 and 4 exhibited minimal coverage (∼0 %) across most wind directions; however, at the highest wind speed (2.3 m/s), coverage increased sharply, but only at wind directions above 43°, suggesting that at higher wind speeds, spraying begins to affect adjacent rows. Row 2 maintained low coverage (<25 %) with a slight increasing trend as wind direction increased. A schematic representation of the effect of Wind Speed and Direction in Canopy Coverage for Inter-row trials is presented in Fig. 10.

For the Over-row trials, Row 2 demonstrated the strongest effect, with coverage consistently decreasing as wind direction increased from 40° to 47.5° The lowest wind speed (0.6 m/s) initially yielded the highest predicted coverage (∼30 %). Row 1 displayed a weak positive trend, with coverage remaining below 10 % but slightly increasing at higher wind speeds (1.3–1.7 m/s) as wind direction increased. Row 3 showed a modest negative trend, with coverage highest at 30° (∼10 % at 1.7 m/s) and declining to zero across all wind speeds by 40°, again indicating that higher wind speeds promote lateral spread of spray to adjacent rows. A schematic representation of the effect of Wind Speed and Direction in Canopy Coverage for Over-row trials is presented in Fig. 11.

The wide confidence intervals observed in both experiments were expected, reflecting substantial uncertainty in model predictions due to the three-way interaction and the limited number of observations for each combination of factors.

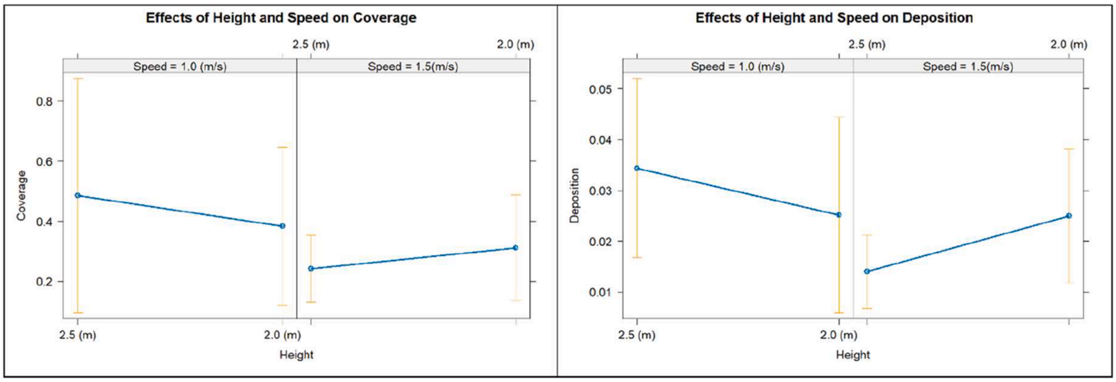

**Fig. 6.** The effect of the operational parameters (altitude and speed) on canopy coverage (left) and estimated deposition (right) across all trials.

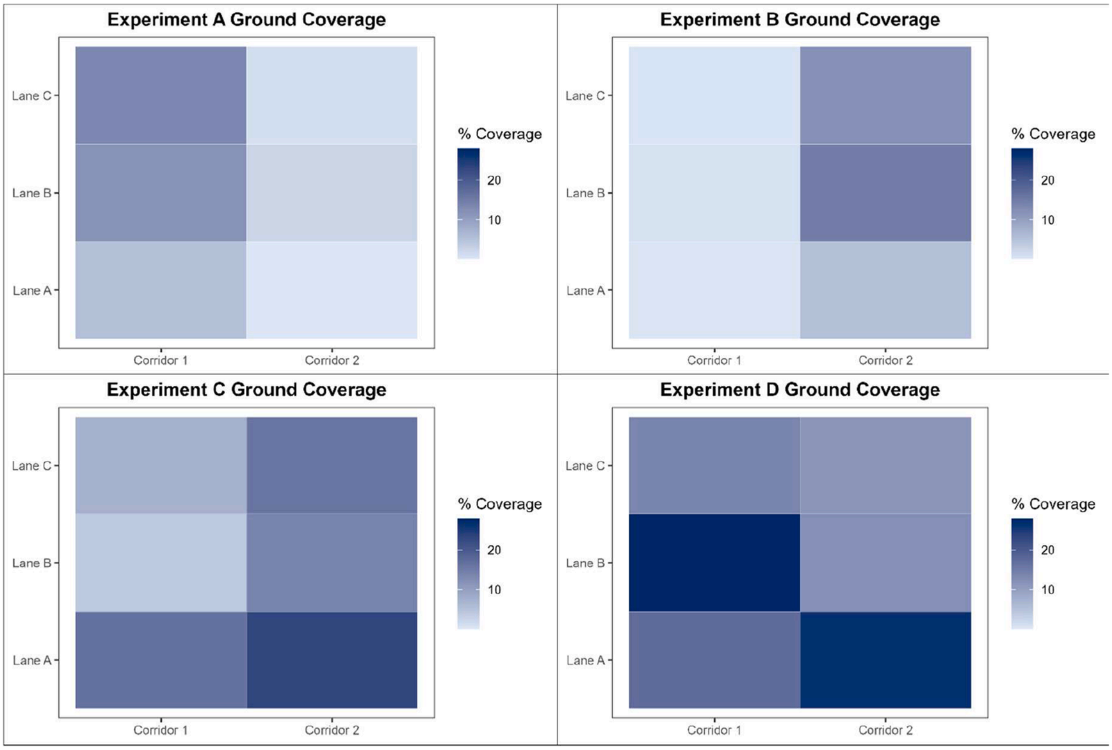

**Fig. 7.** The ground coverage heatmap graph for each over-row trial.

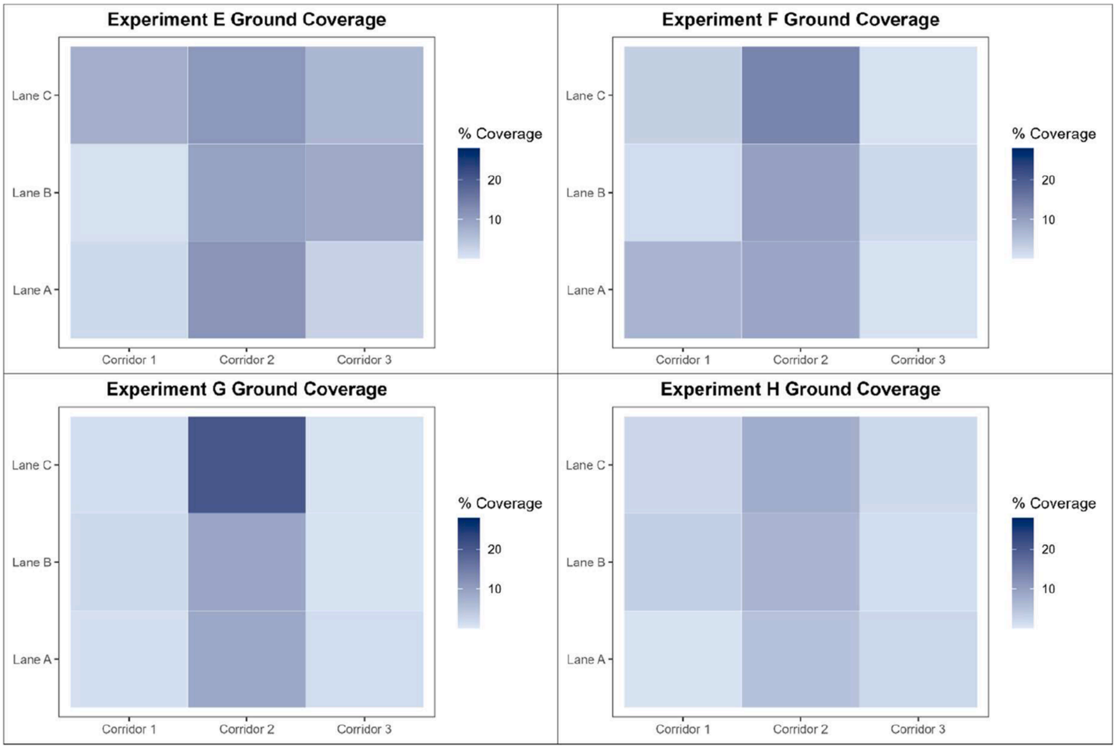

**Fig. 8.** The ground coverage heatmap graph for each inter-row trial.

## 4. Discussion

Overall, the upper canopy received the highest coverage in every treatment, followed by the middle and lower positions, another logical result and a known limitation for spraying drones in 3D crops – being unable to effectively cover the lower levels of canopy primarily due to low application volumes. The observed coverage patterns indicate that over-row applications preferentially deposit spray within the central portion of the canopy, regardless of altitude or speed, suggesting that canopy structure as well as airflow generated or assisted by drone

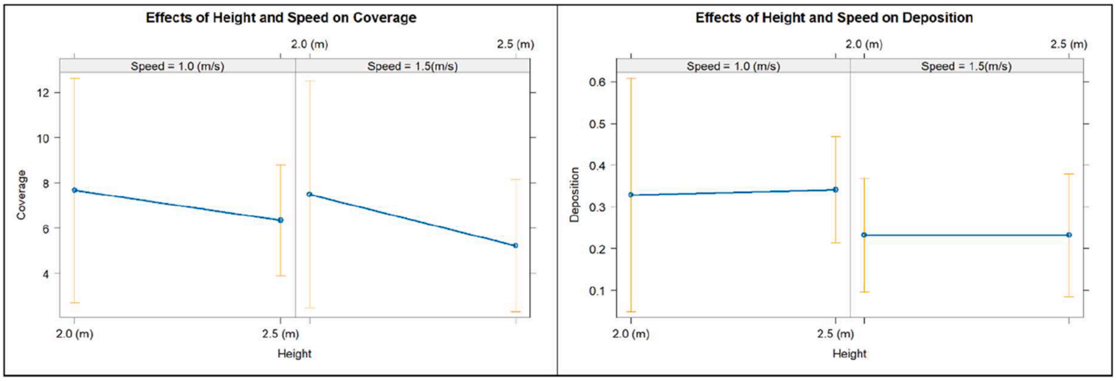

**Fig. 9.** The effect of the operational parameters (altitude and speed) on ground coverage (left) and estimated deposition (right) across all trials.

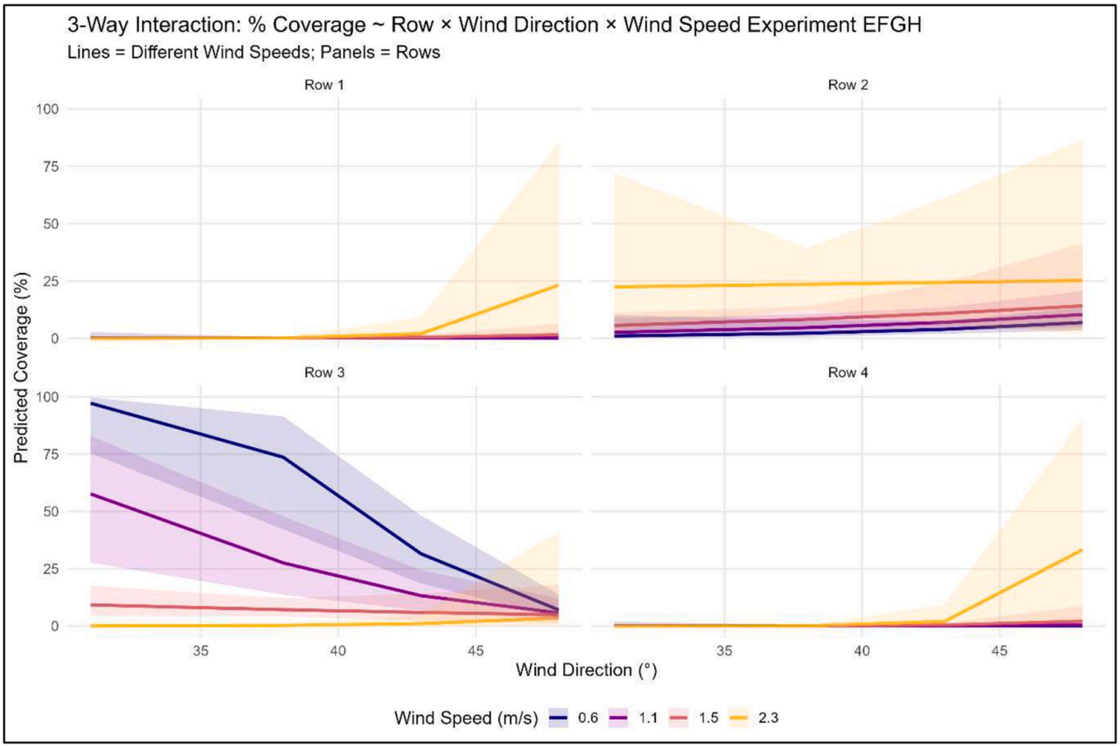

**Fig. 10.** The figure of the 3-way interaction in inter-row trials: % coverage ~ row × wind direction × wind speed in the different vineyard rows.

downwash dominate deposition outcomes in this configuration. Over-row flights concentrated deposition in the central row because the drone's downwash pushes droplets vertically into the upper canopy before redistributing them laterally. Higher altitudes (2.5 m) and lower aircraft speeds appeared to enhance upper-canopy coverage (Fig. 12), likely due to increased plume expansion and improved droplet penetration before entering the canopy. Moreover, lower speeds under a constant application rate translate to lower pump pressure and reduced atomisation, producing larger droplets that are more likely to deposit in upper canopy layers [23]. The inter-row deposition patterns demonstrate that spray distribution is strongly shaped by the interaction between flight parameters as well as environmental conditions. In contrast to Over-row applications, Inter-row applications exhibit significant differences between the two (2) target rows (Row 2 and Row 3) and their respective coverage rates. Especially in treatment F, a higher altitude treatment where the average wind speed in its replicates was the highest recorded across all trials (2.3 m/s), the differences between Rows 2 and 3 clearly demonstrate that, even under acceptable spraying conditions (<3 m/s), the final spray profile still remains susceptible to wind direction and speed. Inter-row flights produced more homogeneous vertical deposition patterns but were more sensitive to wind, as droplets must travel laterally across the canopy gap before interception. The sharp decline in coverage at Row 3 (Over-row) and Row 4 (Inter-row) across all trials is expected as it was always positioned upwind in all replicates, which made droplets less likely to travel in this direction.

In middle canopy levels, the first thing that we observe is a sharp decline in coverage rates, which is a phenomenon both known and expected (Fig. 13). Other similar studies have reported similar declines, and the main reason for this is attributed to the smaller application volumes of spraying drones, and therefore the fewer droplets which ultimately manage to penetrate within the canopy. Interestingly, in Over-row applications, the best-performing were the two higher-speed treatments, namely B and D, when due to the constant application rate, the pump output was increased so that the sprayer could "keep-up" and deposit the same amount of liquid within the area while cruising it faster. When the pump output of a spraying drone (or any spraying system in general) is increased while using the same number and type of nozzles, several spray characteristics change simultaneously. The higher

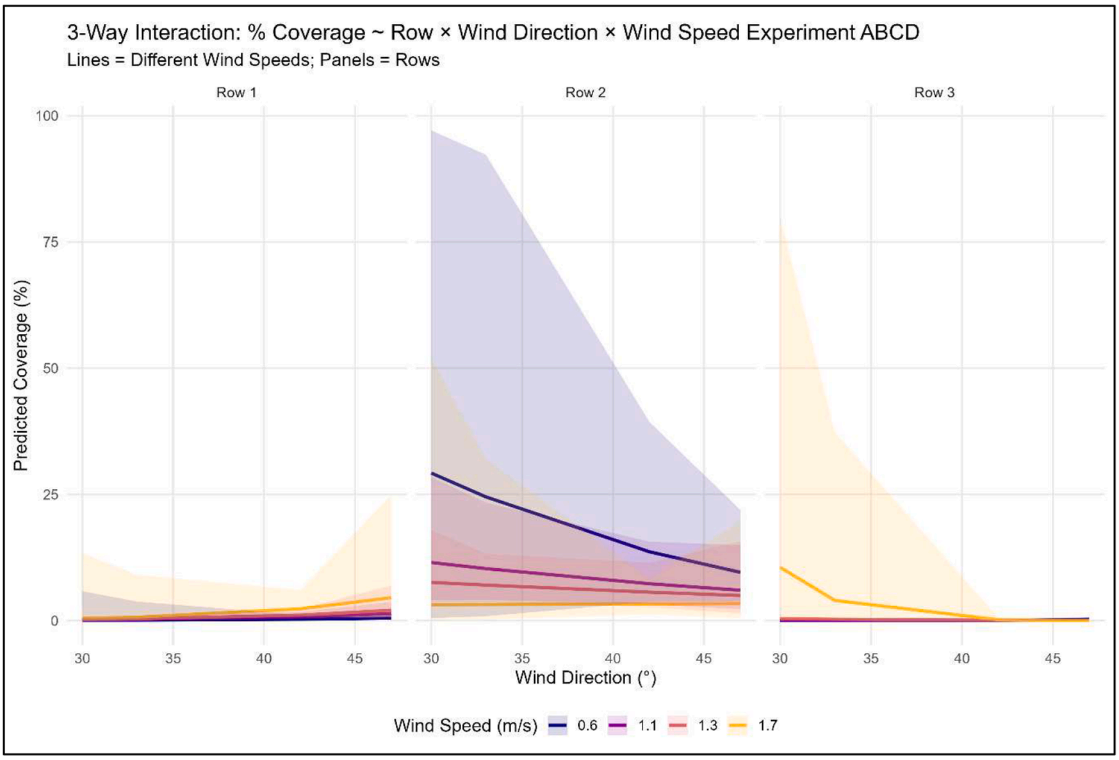

**Fig. 11.** The figure of the 3-way interaction in over-row trials: % coverage ~ row × wind direction × wind speed in the different vineyard rows.

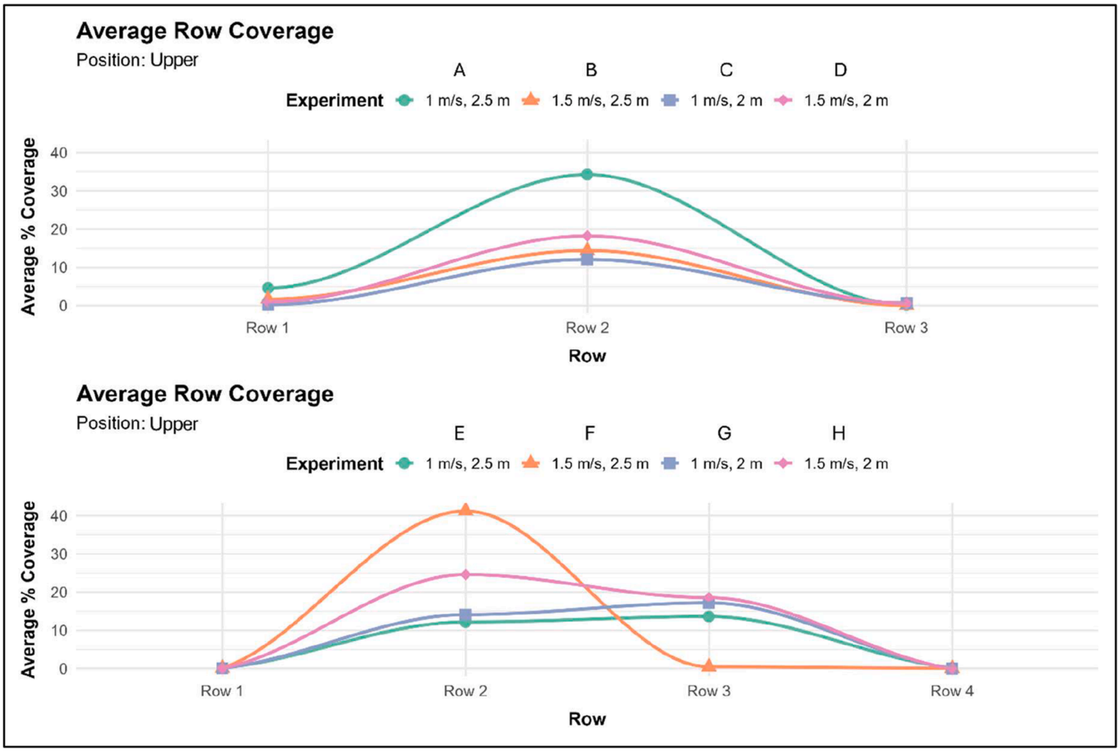

**Fig. 12.** A compilation graph summarising the data from Figs. 4 and 5 on Upper canopy layers coverage.

flow rate forces more liquid through each nozzle, raising system pressure according to the square-root relationship between flow and pressure. As pressure increases, the liquid exits the nozzle at higher velocity, producing finer droplets and a denser spray cloud. This can enhance surface coverage and improve penetration into lower canopy layers, but it also increases the risk of drift losses due to lighter droplets being more easily carried by wind, while also simultaneously elevating ground losses when flown too low. Interestingly, ground coverage was very low in Treatment B but highest in Treatment D among the Over-row applications. This suggests that finer droplets deposited from a shorter

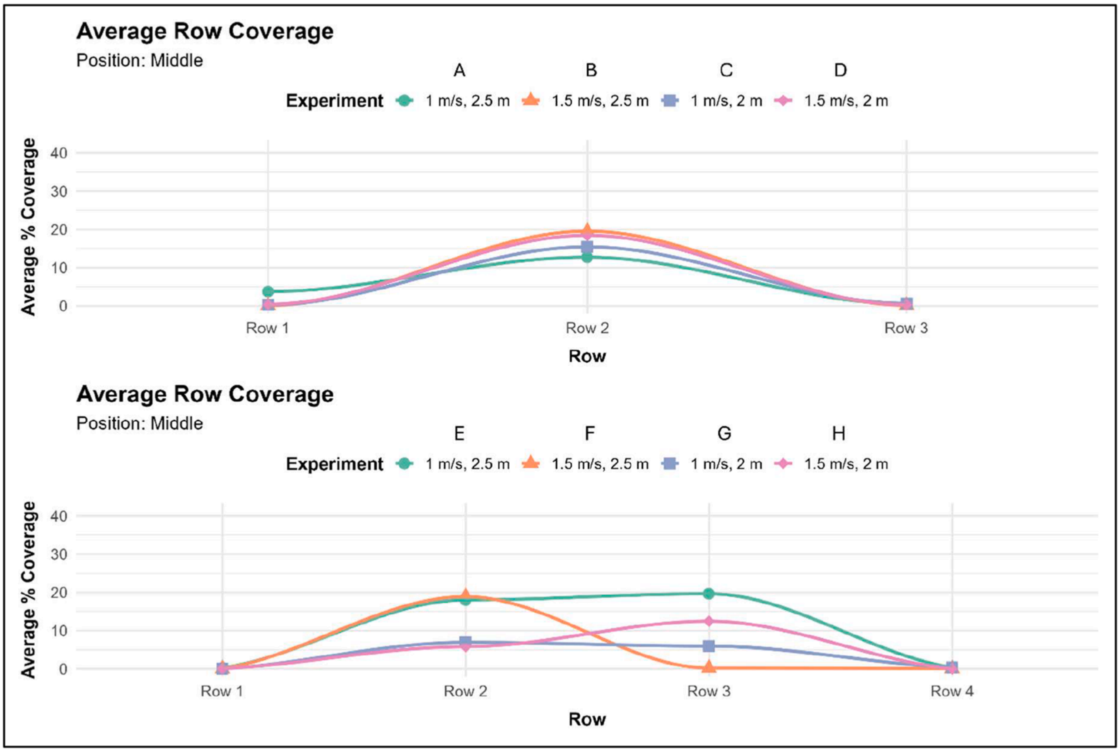

**Fig. 13.** A compilation graph summarising the data from Figs. 4 and 5 on Middle canopy layers coverage.

distance may reach the ground more quickly and with greater momentum, due to both the reduced spray height and the increased pump pressure. Under these conditions, droplets have less time to be entrained by aircraft-induced turbulence or natural wind and are therefore less likely to be intercepted by the canopy, resulting in greater residue accumulation on the ground. Drone spraying systems are particularly sensitive to atomisation changes, especially when using XR flat-fan or centrifugal nozzles that respond sharply to pressure variations. In Inter-row applications, treatment E (the same operational parameters as Treatment A, the best performing Over-row treatment in upper canopy layers) was the best performing one, achieving both higher coverage rates, but also consistency between the target Rows 2 and 3. Treatment F, the high-speed high-altitude trials, continued to demonstrate variance in the coverage rates between the target rows at this canopy layer too.

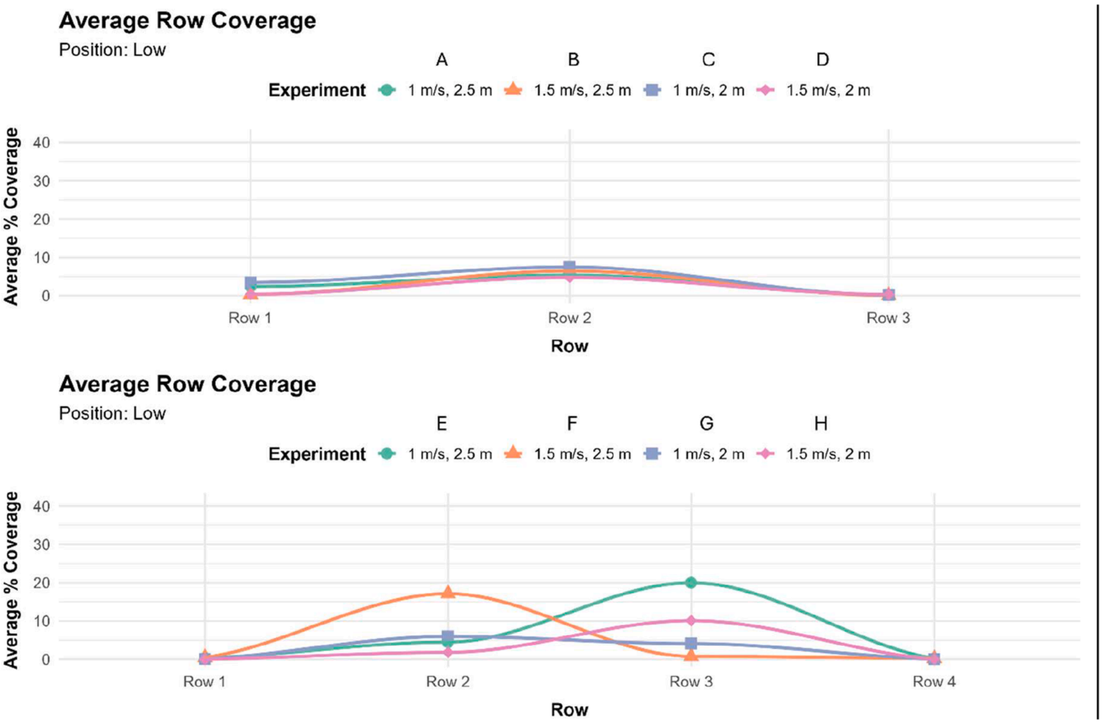

**Fig. 14.** A compilation graph summarising the data from Figs. 4 and 5 on Lower canopy layers coverage.

Finally, in Lower canopy layers, the phenomenon where droplets fail to reach the lower canopy levels becomes even more apparent in Over-row applications, where coverage rates do not exceed 10 % at any trial. On the other hand, all Inter-row trials, show minimal changes compared to their coverage profile in Middle layers, indicating that, although more susceptible to wind and environmental phenomena (the effect of wind continues to manifest in Treatment F), this application strategy can yield superior results when a homogeneous spraying profile is desired (Fig. 14).

Regarding Ground Coverage, as high droplet accumulation on the ground represents spray loss and a reduction in canopy targeting efficiency, the results suggest that flying closer to the canopy (2 m AGL) increases undesirable ground deposition regardless of airspeed. Overall, the “worst performing” treatments were Treatment D (2 m, 1.5 m/s) in Over-row applications and Treatment G (2 m, 1 m/s) in Inter-row applications, indicating that increased downwash and turbulence intensify ground loss under these conditions. Conversely, stronger performance (lower ground deposition) was observed in the treatments flown at 2.5 m, with Treatments A and E (both at 2.5 m, 1 m/s), and Treatment B and F (both at 2.5 m, 1.5 m/s) offering the most favourable deposition profile in Over-row and Inter-row applications accordingly. Higher altitudes allowed greater plume expansion, increasing upper-canopy interception but also raising drift susceptibility due to longer airborne time. These findings emphasise the importance of maintaining sufficient elevation during vineyard or 3D crop spraying in general, to reduce environmental losses and improve application efficiency.

Overall, the results indicate that UAV applications can achieve coverage in the upper canopy layers comparable to conventional sprayers in vineyards. Numerous studies report coverage values of approximately 40 % under ideal conditions, which aligns with the values observed in the upper canopy in our experiment. However, at lower canopy levels, the relatively lower application volume of UAV sprayers results in reduced coverage, with a clear decrease from middle to lower canopy layers. In contrast, conventional sprayers tend to produce a more homogeneous spray distribution across all canopy heights [10,11]. Therefore, spraying UAVs are an ambiguous technology with numerous benefits, however, their adoption should always be considered carefully, for each specific use case, as inherent limitation of this technology can mitigate its efficiency.

### 4.1. Limitations & future work

*This study has several limitations. It evaluates a single UAV platform, one nozzle type, and a restricted set of environmental conditions. Only distilled water was used as the spray medium, thus excluding formulation-dependent effects on atomisation and deposition. The canopy architecture represents a single Mediterranean vineyard system, which may differ from other grapevine training forms or 3D crop structures. All of these factors can be focal points for future research that could examine different PPP formulations, canopy densities, UAV hardware configurations, pump/nozzle technologies, and a broader range of climatic conditions to generalise these findings across diverse real-world scenarios. Finally, in-field fractions are not the only fraction that should be considered when evaluating spraying applications. Droplet displacement, commonly known as spray drift is a highly critical aspect of all spraying applications. Numerous trials have also been completed in parallel by the author team and have been published as a separate piece of research, however, similar to the limitations presented in this study, the same gaps remain for drift studies, which should be prioritized in the broader spraying UAVs domain, as they are necessary drivers and invaluable insights for potential regulatory changes within the EU member states.*

## 5. Conclusions

This study demonstrates that operational parameters in drone spraying, including flight path configuration, aircraft positioning, altitude, flight speed and pump output, exert a significant influence on spray profile and overall application efficiency. Because the drone spraying system functions as a dynamic and interconnected unit, altering a single parameter results in a broader systemic impact on droplet formation, drift potential and deposition uniformity. The findings show that increasing pump output (through an increase in flight speed while maintaining a constant deposition rate) leads to reduced droplet size and a greater risk of ground losses when combined with lower-altitude operations. These interactions highlight the importance of achieving an appropriate balance between pump output and nozzle capacity to maintain a stable droplet profile, minimise displacement and ensure uniform target coverage and deposition. Variations in speed and altitude also produced clear differences in deposition within the tested range, further demonstrating the influence of these parameters on spray performance. Overall, the results underscore the need for integrated optimisation of operational parameters to support effective, efficient and environmentally responsible drone spraying. Finally, the known limitation of spraying drones to effectively reach internal canopy layers in 3D crops was also observed, and the indicative results suggest that this constraint may be mitigated to some extent through adapted spraying strategies. Based on the evaluated configurations, operators should avoid low-altitude (potentially $<2.0$ m) flights at higher speeds (1.5 m $s^{-1}$), as this combination consistently produced the highest ground losses and the least efficient canopy targeting.

From a regulatory standpoint, the EU currently lacks dedicated provisions for drone spraying, as existing regulations were developed for conventional ground-based and manned aerial application systems. These frameworks do not account for the unique flight characteristics, deposition dynamics or drift behaviour associated with spraying drones, which creates uncertainty for operators and hinders wider adoption. Moreover, the outright ban in several EU member states also prohibits PPP manufacturing companies to develop drone-specific products, creating a dire situation where numerous EU farmers purchase a drone without knowing that drone spraying for crop protection is illegal, and also use PPP products designed for conventional machineries (which operate at much higher application volumes). In light of the technical insights provided by this study, there is a clear need for updated EU regulatory guidance that reflects the specific operational characteristics of drone spraying and provides science-based criteria for safe and effective implementation. Regulators should consider establishing UAV-specific spray buffer zones, altitude limits and weather thresholds distinct from those applied to manned aerial or ground sprayers, to account for the unique aerodynamic behaviour and drift dynamics of UAV-based applications.

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All authors agree that:

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## CRediT authorship contribution statement

**Vasilis Psiroukis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Aikaterini Kasimati:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Konstantinos Nychas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Konstantinos Dagres:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **George Papadopoulos:** Writing – review & editing, Investigation, Formal analysis. **Evangelos Anastasiou:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Spyros Fountas:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

In accordance with Elsevier's policies on transparency, research integrity, and responsible reporting, the following statements provide detailed information regarding funding sources, acknowledgments, and any potential conflicts of interest relevant to this manuscript. These disclosures ensure clarity for readers and reviewers and affirm that the research has been conducted and reported in an ethically sound and unbiased manner.

## Acknowledgments

The study was part of the project "Innovations in Plant Protection for sustainable and environmentally friendly pest control, InnoPP - TAEDR-0535675″ that is funded by the European Union- Next Generation EU, Greece 2.0 National Recovery and Resilience plan, National Flagship Initiative "Agriculture and Food Industry". Research trials' funding provided by the European Union's Horizon Europe research and innovation programme ICAERUS (Grant agreement ID: 101060643).

## Data availability

Data will be made available on request.

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