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Optimizing Vineyard Crop Protection: An In-Depth Study of Spraying Drone Operational Parameters

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Abstract

In modern agriculture, the precise and efficient application of agrochemicals is essential to ensure crop health and increase productivity while minimizing adverse environmental impacts. While traditional spraying methods have long been the cornerstone of crop protection, the introduction of unmanned aerial vehicles (UAVs), commonly known as drones, has led to a revolutionary era in agriculture. UAVs offer novel opportunities to improve agricultural practices by providing precision, efficiency, and safety in agrochemical applications. This study presents a comprehensive investigation into the use of UAV spraying technology to assess spray coverage and deposition in vineyards. Field trials were conducted using a commercial hexacopter spraying UAV, with water-sensitive paper samples serving as the primary tool for assessing canopy coverage and penetration. Analysis of these water-sensitive papers was performed using the DepositScan software, providing valuable insights into the effectiveness of different application techniques and parameters. The results of the study showed that inter-row application methods outperformed over-row applications and demonstrated superior canopy coverage. In addition, the study showed that a 2.5-meter flight altitude outperformed a 2-meter flight altitude, resulting in a better coverage rate across all canopy levels. A flight speed of 1 m/s proved to be more efficient than 1.5 m/s. A specific combination of operational parameters, namely 2.5 m flight altitude and 1 m/s flight speed showed promising results for both over-row and inter-row applications. This research underscores the transformative potential of UAV spraying in modern agriculture, demonstrating its ability to increase efficiency and reduce environmental impact in row crops, thus promoting environmentally sustainable crop protection practices. Moreover, our findings underscore the importance of optimizing the operational parameters of UAV spraying, which is also one of the most important open problems in conventional crop protection, to further advance agricultural practices.

Keywords: *spraying; UAV_spraying; canopy_coverage; spray_drift; vineyards.*

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Introduction

In modern agriculture, the accurate and efficient application of agrochemicals is crucial for maintaining crop health and increasing productivity while reducing negative environmental effects. Although conventional spraying techniques have been fundamental to crop protection for many years, the introduction of unmanned aerial vehicles (UAVs), commonly known as drones, has ushered in a transformative period in agriculture. UAVs present numerous new possibilities to enhance agricultural practices through precision, efficiency, and safety in chemical application.

Crop protection applications play a crucial role in safeguarding crops from the continuous threats posed by pests, diseases, and environmental challenges. These approaches include practical treatments and specialized strategies aimed at directly addressing and effectively managing pest infestations, diseases, and environmental adversities (Barzman et al., 2015). In high value crops, such as vines, chemical control remains the primary method for protecting crops, involving the use of plant protection substances such as pesticides and herbicides as needed (Bostanian et al., 2012). In vineyards, it is often used as a preventive strategy before infestations manifest, but can be also considered in early symptom stages for selectively targeting specific pests and diseases to prevent significant crop damage.

While conventional techniques have undeniably laid the foundation for viticulture, they come with inherent limitations. The effectiveness of these methods can vary, and they may not always be optimal for large commercial vineyards. As viticulture expands globally, there is a growing recognition of the need for more efficient and reliable crop protection methods (Bramley, 2022). The historical reliance on traditional methods in vineyards, though important, underscores the need to address the limitations and complexities associated with protective spraying applications. These concerns continuously shape the evolving framework of viticulture techniques.

Proper pesticide application is crucial for pest management and agricultural efficiency. However, over-application can lead to adverse effects, including soil fertility depletion and the emergence of pesticide-resistant insect species. Traditional spraying techniques have long been essential for grape crop protection, but they face ongoing challenges that necessitate innovative solutions. Various established methods, from knapsack sprayers to tractor-mounted systems, have been vital in managing pests, diseases, and weeds in vineyards. Despite their effectiveness, these methods have inherent limitations, driving the need for more efficient and effective vineyard practices.

The primary obstacle encountered in conventional vineyard spraying techniques is the attainment of comprehensive spray coverage. Vineyards are characterized by the presence of closely planted vines and a varied canopy structure, resulting in a unique environment that poses challenges for the uniform application of agrochemicals. The presence of dense vegetation frequently creates 'shaded' regions that are difficult to reach, leading to an inconsistent application. The absence of consistency in the vineyard's layout renders certain areas susceptible to infestations and illnesses, resulting in detrimental effects on both the quantity and quality of the harvest. The maintenance of consistent and homogeneous spray coverage is of utmost importance in vineyards because of their distinctive features, such as the topography and the closely spaced arrangement of vines (Sarri et al., 2019). Furthermore, in the context of "specialty crops" such as orchard trees, citrus, olive trees, and vineyards, the effectiveness of the spray application procedure is closely dependent on the unique characteristics of the canopy. The efficacy of the spraying process is significantly influenced by various aspects, including canopy structure, dimensions, and trellis systems (Balsari et al., 2008).

Furthermore, spray drift has long been a significant concern with conventional spraying techniques, particularly when using tractor-mounted airblast sprayers. Spray drift occurs when small droplets or aerosols are carried by air currents beyond the intended target area, posing a risk of environmental contamination. Conventional sprayers often lead to substantial pesticide losses and environmental damage. The increasing use of plant protection products (PPPs) in mechanized commercial vineyards has heightened concerns about pesticide residues in grapes

(Marucco et al., 2019). While these products are essential for crop protection, their excessive use raises valid concerns about residue levels. According to an EU report, the exceedance rate for pesticide residues in wine grapes has increased from 0.4% to 0.9% (EFSA, 2021). The presence of pesticide residues in wine grapes has significant implications for food safety and consumer health, highlighting the urgent need to reduce these residues in agricultural products.

Multi-rotor UAVs offer numerous advantages, which can address these inherent challenges within the viticultural sector. These benefits include but are not limited to their exceptional flexibility, independence from specific take-off locations and human drivers, and the ability to operate frequently even in high-temperature conditions. UAVs have shown excellent performance in navigating hilly terrain, densely forested areas, and turbulent air currents beneath their rotors, as demonstrated by Zhou et al. (2016). The use of UAVs for pesticide application has been increasing, particularly in China. These UAVs can cover approximately 20 square meters per minute and have liquid tanks ranging from 5 to 40 liters. In Japan, where small-scale farms are common, unmanned gasoline-powered helicopters have traditionally been preferred since 1990, as highlighted by Xiongkui et al. (2017). UAVs have overcome terrain limitations and reduced chemical exposure risks for farmers and workers compared to traditional methods (Pederi & Cheporniuk, 2015). Moreover, UAV spraying has proven valuable in steep vineyards where conventional machinery is limited (Delpuech et al., 2022). Low-volume drone sprayers can operate at low altitudes above crops in small fields or challenging areas not easily accessible by humans or ground-based equipment (Xiongkui et al., 2017). UAV spraying has become essential in modern agriculture due to efficient large-area coverage, reduced pesticide use leading to cost savings and environmental conservation, labor-saving automation, and the avoidance of soil compaction and crop damage (Ozkan, 2023). Furthermore, UAV sprayers have shown superior cost-effectiveness and efficiency (Pederi & Cheporniuk, 2015), as well as precise agrochemical application, enhanced spray coverage, and reduced resource wastage (Chen et al., 2022). Their ability to navigate crop rows with high accuracy allows growers to optimize resource allocation and minimize environmental impact, making UAVs particularly appealing for vineyard management (Biglia et al., 2022).

Despite these promising benefits, UAV-based spraying faces several challenges, such as short flight times, low autonomy, and high upfront costs (Pederi & Cheporniuk, 2015). Ongoing research aims to address these limitations by optimizing UAV technology for broader agricultural use (Valavanis & Vachtsevanos, 2015). Other researchers are developing site-specific spraying methods to reduce the payload on drones, relying heavily on image sensing technology and machine vision algorithms (Rasmussen et al., 2013). While UAVs can navigate complex terrains and collect accurate 3D models using depth sensors, their short flight times, particularly with larger payloads, pose challenges (Shilin et al., 2017). Drone sprayers also have higher initial investment costs and limited capacity compared to conventional sprayers. However, UAV sprayers are seen as a more sustainable and efficient alternative for vineyards and olive crops (Morales-Rodríguez et al., 2022). Legal considerations are also important, with regulations on UAV pesticide spraying varying by country (Myers et al., 2015). According to the European Commission's directive 2009/128/EC, the use of drones for spraying is allowed only under specific circumstances, such as when no viable alternatives are available or when drones offer clear advantages in reducing impacts on human health and the environment compared to conventional methods (European Commission, 2009).

Researchers have extensively investigated various operating parameters in UAV spraying to enhance canopy deposition and coverage across different crops, with a primary focus on crop protection. These efforts have led to significant advancements in agricultural practices, ushering in a new era of precision agriculture. As we delve into these findings, it becomes clear that these studies have not only refined the use of UAVs in crop protection but also provided valuable insights into improving the efficiency, sustainability, and cost-effectiveness of modern farming practices. A critical area of focus has been the optimization of spray parameters, including spray volume, droplet size, droplet spread, and overall spray effectiveness, particularly for insect pest control (Lou et al., 2018). These parameters greatly influence the efficacy of UAV spraying. Notably, factors such as nozzle type, spray pressure, and flight parameters have emerged as key determinants of canopy spray deposition and coverage (Biglia et al., 2022). For instance, in vineyards, higher speeds around 3.0 m/s have been shown to increase droplet deposition on the canopy while reducing losses to non-target areas, especially when conventional spray nozzles are used. However, very low spray application rates, such as 53.0 L/ha, have proven insufficient to achieve the desired application efficiency (Biglia et al., 2022). A study by Sarri et al. (2019) investigated the performance of a commercial UAV equipped with different types of nozzles in a small, high-slope terraced vineyard. This study compared the UAV's working capacity, droplet coverage, density, and size with those of traditional sprayers used in small mountain vineyards. Similarly, Morales-Rodríguez et al. (2022) compared conventional sprayers and UAV sprayers 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, UAV sprayers also had limitations, such as higher initial investment costs and limited capacity compared to conventional sprayers. The impact of UAV rotor downwash 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 (Zhan et al., 2022). However, challenges in infiltrating canopies, influenced by their configuration and thickness, have been documented in citrus orchards (Tang et al., 2018). Qin et al. (2018) also highlighted the significant influence of spraying height on droplet distribution, noting that specific combinations, such as a flight height of 5.0 meters and a flight speed of 4 meters per second, were particularly effective.

The research aimed to address a critical aspect of modern viticulture by conducting a comprehensive analysis of UAV spraying efficiency and deposition in a vineyard located in Spata, Greece. Our primary goal was to contribute valuable insights into optimizing UAV-based spraying practices for vineyard management, focusing on both over-row and inter-row spraying strategies. The primary objective was to investigate how operational parameters, specifically flight height and speed, interacted and influenced the deposition of spray liquid within the intricate vineyard canopy under a constant application rate. This study also aimed to explore the effects of over-row and inter-row spraying techniques on spray deposition, providing essential knowledge for vineyard practitioners to enhance canopy coverage across different canopy height levels. To achieve these goals, extensive field trials were conducted in an experimental vineyard setting. These trials involved using a UAV equipped with an 8-nozzle spraying system. Water-sensitive papers (WSPs) were strategically placed at three (3) height levels within the vineyard canopy to capture the deposition patterns of the sprayed liquid during each flight. The collected samples were analyzed using image analysis software designed for WSPs. Finally, statistical analyses were employed to interpret the deposition data, providing insights into the performance of UAV-based spraying techniques in vineyard applications, particularly in addressing the unique challenges posed by over-row and inter-row sections.

Materials and Methods

The research was conducted at the organic vineyard of the Agricultural University of Athens farm located in Spata, Greece, which is situated at coordinates 37°59'04.6"N 23°54'19.6"E (Figure 1). The average annual temperature is 17.3°C, and the region receives approximately 450 mm of precipitation annually. The vineyard has a 2.0 m row spacing and 1.6 m spacing of vines along the row, resulting in a density of 3125 vines per ha. The vineyard is primarily composed of the Savatiano (Vitis Vinifera L.) grape variety, which is the dominant indigenous variety of the Attiki region. Savatiano constitutes approximately 70% of the total vine cultivation in the area and is the most widely planted grape variety in Greece due to its unique characteristics and historical significance (Despina et al., 2022). The average height of the vines is approximately 1.3 m, with leaves and grapes occupying the zone between 0.3 and 1.4 m above ground level.

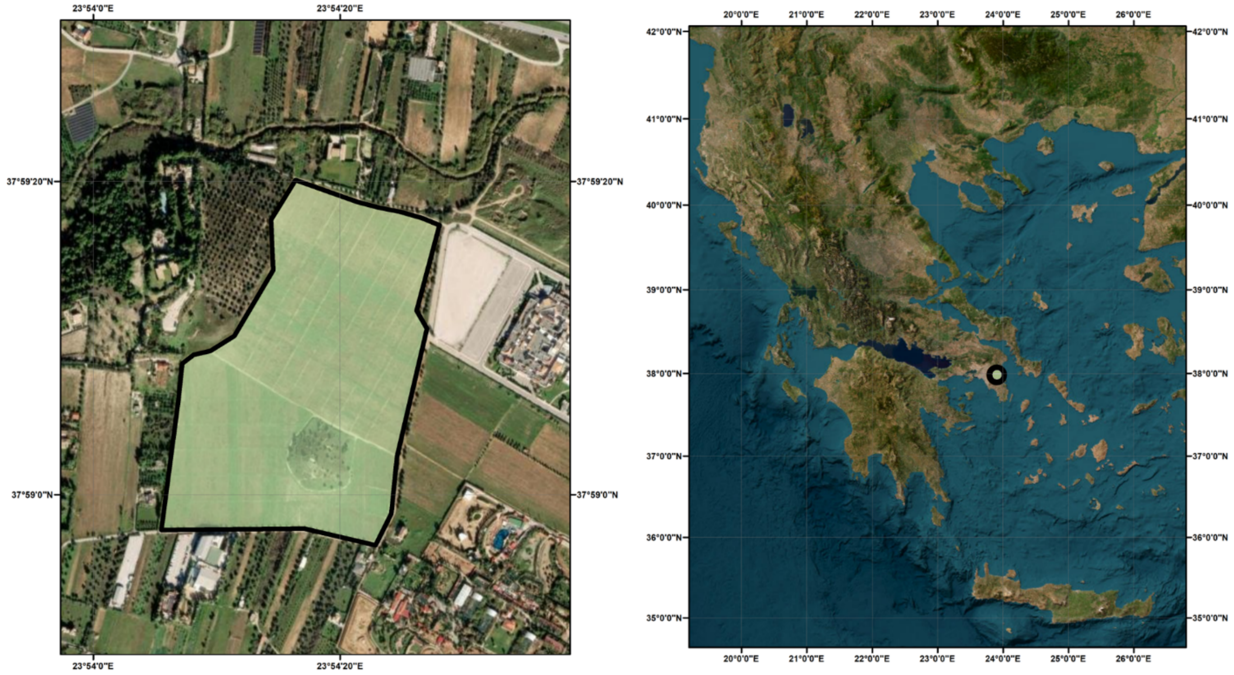

Figure 1. The location of the experimental vineyard in Spata, Greece.

The unmanned aerial vehicle used in this study was a DJI Agras T16. During the experimental iterations, the environmental conditions were arranged in accordance with ISO 22866 and tailored for use with UAVs. To this end, all flights were conducted within a controlled range of 25 to 35 degrees Celsius to minimize the impact of temperature fluctuations on spray deposition. Wind speeds were monitored using a portable Ultrasonic Wind Instrument, to ensure that all trials were conducted with a wind speed lower than 3 m/s and in favorable direction (perpendicular to the vine lines ±10 ° North) which was positioned at a distance of 20 meters from the application area (directly above the vineyard canopy, stabilized at 2 meters above ground) to avoid any potential interference with the spraying process. Data was recorded at a frequency of 1 measurement per second (1 Hz) and subsequently averaged for each iteration.

The study examined different combinations of the following variables: spraying height (2 and 2.5 meters above ground level), flow rates per nozzle (1.4 and 1.8 liters per minute), correlated with flight speeds (1 m/s and 1.5 m/s), and spraying positions (inter-row and over-row). All experiments were conducted with a consistent deposition rate per hectare (80 L/Ha). The experiment comprised eight distinct treatment combinations, which analyzed the interaction between flight height (H), flight speed (S), and row placement (OR for Over row and IR for Inter row). Table 1 details the specific configurations for each treatment. Throughout the experiment, each Treatment was repeated 3 times, in rapid succession to minimize deviations in environmental conditions).

Table 1. The overview of the experimental design followed, across all iterations.

Treatment	Factors	Factor Values
A	H1 – S1 – OR	2.5 (m) – 1 (m/s) – Over Row
B	H1 – S2 – OR	2.5 (m) – 1.5 (m/s) – Over Row
C	H2 – S1 – OR	2.0 (m) – 1 (m/s) – Over Row
D	H2 – S2 – OR	2.0 (m) – 1.5 (m/s) – Over Row
E	H1 – S1 – IR	2.5 (m) – 1 (m/s) – Inter Row
F	H1 – S2 – IR	2.5 (m) – 1.5 (m/s) – Inter Row
G	H2 – S1 – IR	2.0 (m) – 1 (m/s) – Inter Row

H	H2 – S2 – IR	2.0 (m) – 1.5 (m/s) – Inter Row

In this study water-sensitive papers (WSP) measuring 0.76 mm x 26 mm were utilized as collectors. These papers were selected for their ability to intercept spray droplets and undergo immediate color changes upon contact with liquid. In order to assess the distribution of sprayed droplets, three canopy WSPs were carefully positioned within each row at three distinct heights, all secured to the trellis structure. These heights were fixed at 0.3 meters (Lower), 0.6 meters (Middle), and 0.9 - 1 meter (Upper) (Figure 2). Following collection, each WSP sample was carefully placed in individually labeled sealed bags. Each label included detailed information about the specific spray treatment, replication, and the exact sample location. These sealed bags were then promptly stored in a container to prevent potential color changes caused by moisture. Subsequently, the samples were transported to the laboratory for further analysis.

Figure 2. An example of the WSP placement strategy (Left) and an indicative field sample (Right)

In the laboratory, the analysis of WSPs was conducted using a high-resolution 600-dpi scanner. This scanner was employed to generate digital images of the WSPs, which were then analyzed using the DepositScan software developed by the United States Department of Agriculture. DepositScan software is specifically designed to measure droplet deposits in digital images and assess critical parameters such as coverage percentage. In this study, the primary focus was on the analysis of a critical factor in spraying applications, namely Coverage %, with the ultimate goal of evaluating efficiency and quality in the context of UAV-based vineyard spraying operations. All results from the DepositScan software were analyzed through two-way ANOVA using RStudio and Python for data visualization.

Results

Over-row Applications

Figure 3 presented the accumulated results for each individual Treatment. In order to investigate the variations in canopy coverage, statistical tests were conducted for the "Speed" and "Height" factors using Tukey post-hoc analysis. The results revealed that, for the "Speed" factor, better mean coverage percentages were achieved by a 1 m/s speed, with an average of 4.37% across all experiment sites, as opposed to the 1.5 m/s speed, which exhibited a mean coverage of 3.0% across the sites examined. Similarly, the Tukey post-hoc test also showed that a 2.5-meter flight altitude demonstrated a higher coverage rate (4.38%), surpassing the coverage rate observed at a 2-meter flight altitude (3.0%).

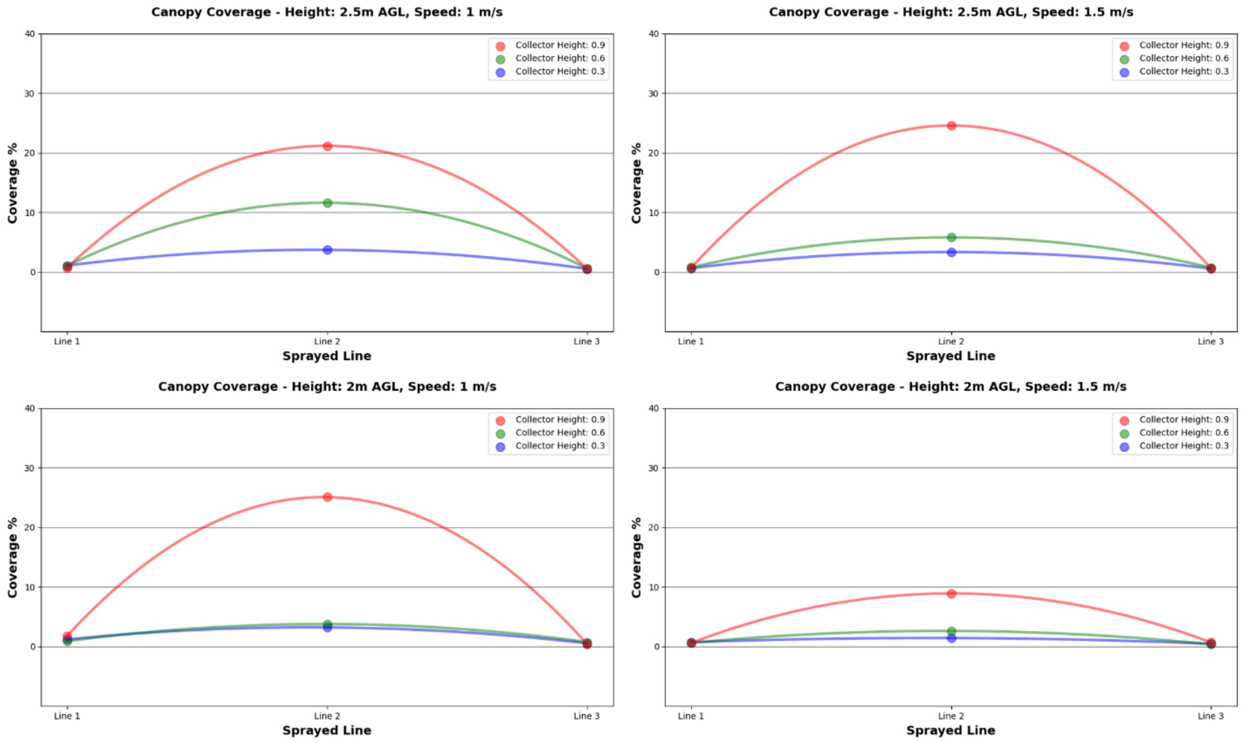

Figure 3. The coverage values achieved at the four (4) Inter-row treatments.

In order to identify which treatment achieved the highest performance, two-way ANOVA was conducted. Results indicated that the main effect of "Treatment" showed no statistically significant influence on "Coverage" ($p > 0.05$). Treatment A exhibited the highest mean coverage values, with a value of 4.56, followed closely by Treatments B and C, both showing similar mean coverages of 4.20 and 4.18, respectively. In contrast, Treatment D displayed a notably lower mean coverage of 1.82, positioning it as the least effective treatment within the over-row applications conducted in this study. Notably, Treatment A, with a flight altitude of 2.5 meters and a flight speed of 1 m/s, appeared to be the “optimal” configuration in terms of overall canopy coverage throughout the experiment. (Figure 4).

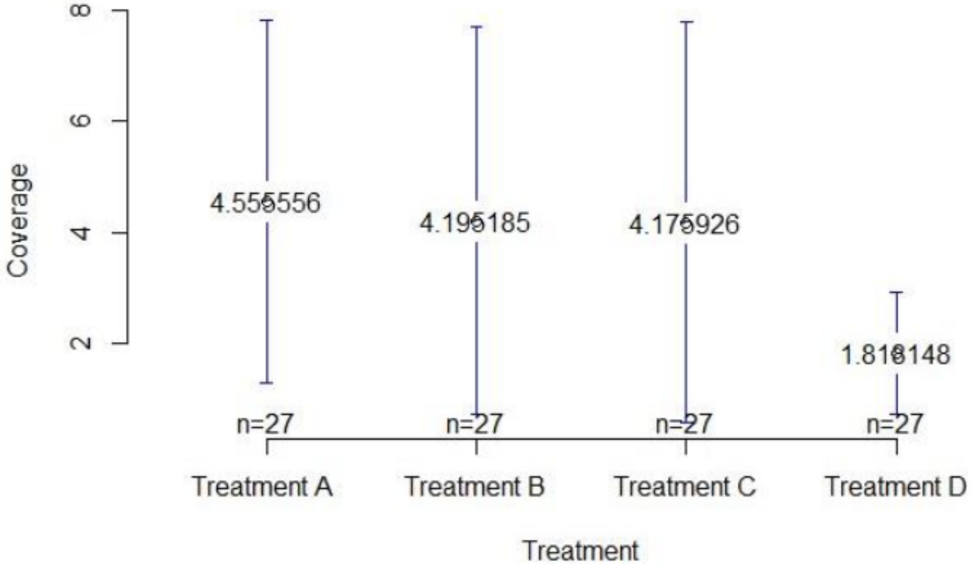

Figure 4. The mean coverage rate for each treatment across all Over-row Treatments, and across all iterations.

The results showed that OR applications were naturally much more efficient in targeting the middle row positioned below the aircraft, and at higher canopy levels (Figure 5). Two-way ANOVA was performed to investigate the influence of various factors on the "coverage" variable in the middle row upper canopy, where the highest coverage values were observed, and is more likely to be targeted when using spraying UAVs in row crops. The factors included were "speed" and "height", with the results revealing that neither the "speed" factor nor the "height" factor showed statistically significant associations with "coverage" in middle row upper canopy. Furthermore, the interaction between "Speed" and "Height" was not found to have statistically significant effects. Subsequently, post-hoc tests were conducted to reveal differences between levels of "speed" and "height." Concerning "Speed," the analysis highlighted that a flight speed of 1 m/s resulted in a higher mean coverage of 23.12%, compared to the mean coverage of 16.7% associated with a speed of 1.5 m/s in the middle row upper canopy. Regarding "height," it was observed that a flight altitude of 2.5 meters led to a superior mean coverage of 22.87%, in contrast to the mean coverage of 16.98% observed at a 2-meter flight altitude.

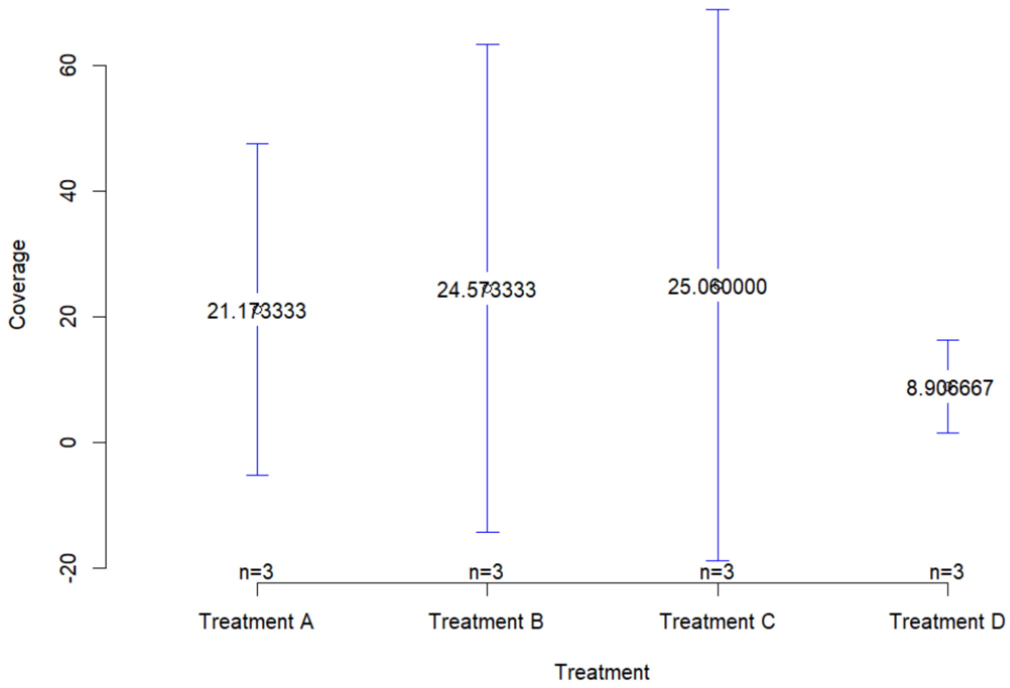

Figure 5. The canopy coverage percentage of over-row applications over the middle row, and at upper canopy.

Inter-row applications

Figure 6 presented the accumulated results for each individual Treatment. Following a similar analysis approach in IR applications, the mean coverage values for these levels were: Row 1° (0.93), Row 2° (9.75), Row 3° (18.18), and Row 4° (0.39).

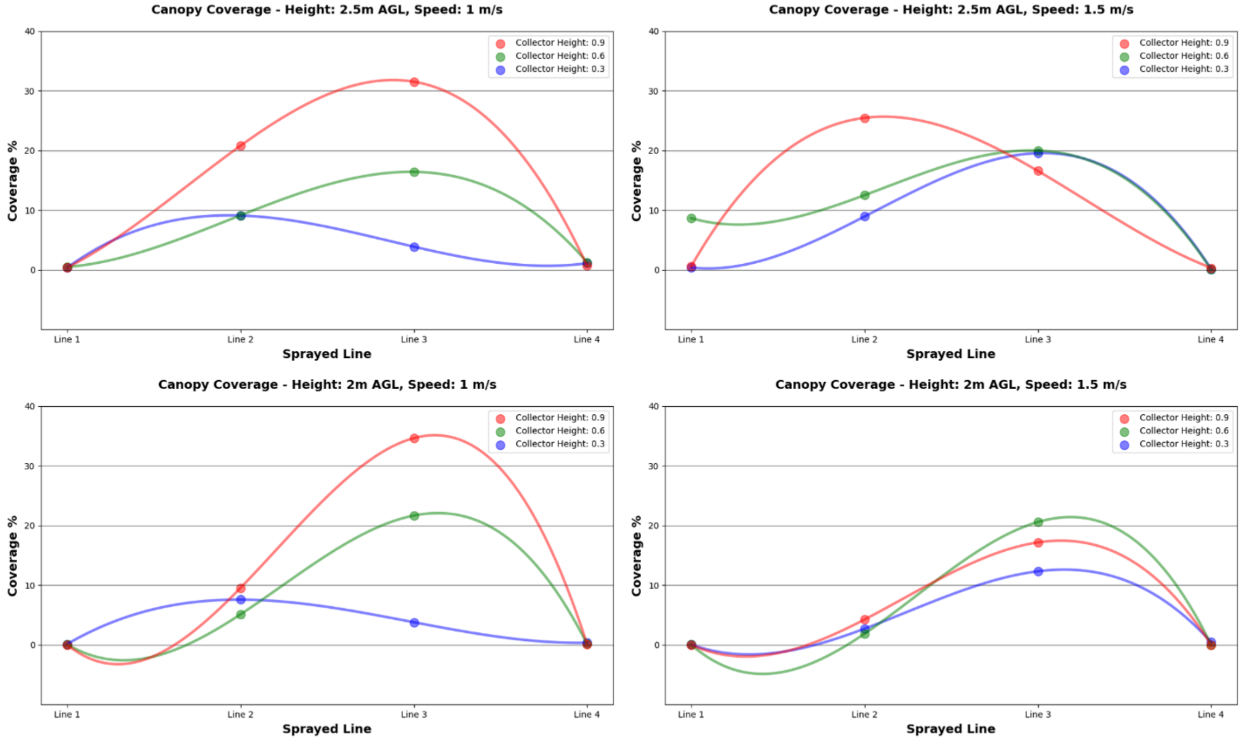

Figure 6. The coverage values achieved at the four (4) Inter-row treatments.

"Treatment F" had the highest mean coverage at 9.43, followed by "Treatment E" with a mean coverage of 7.93, and "Treatment G" with a mean coverage of 6.93. In contrast, "Treatment H" had the lowest mean coverage at 4.96 (Figure 7). This analysis demonstrates that "Treatment F" had the highest mean coverage, while "Treatment E" and "Treatment G" had relatively lower mean coverages, and "Treatment H" had the lowest mean coverage.

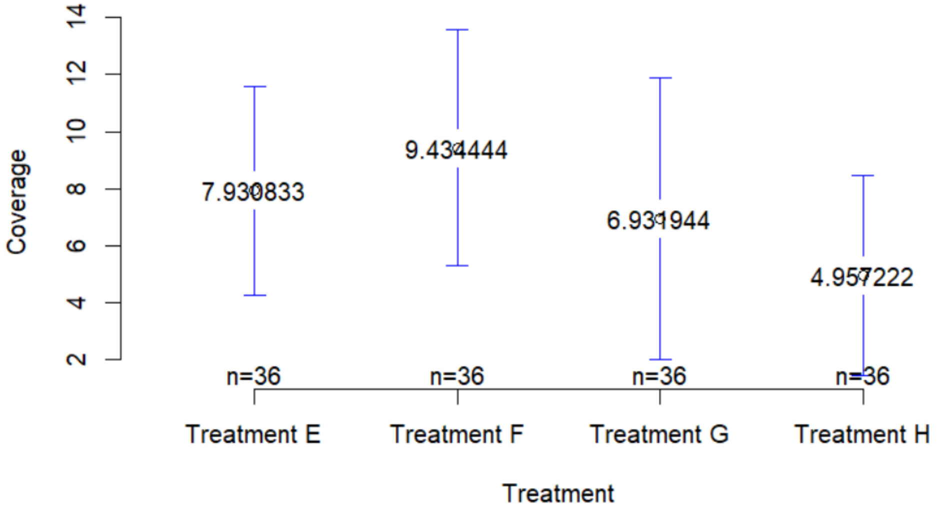

Figure 7. The mean coverage rate for each treatment across all Inter-row Treatments, and across all iterations.

The results indicated that, as expected, rows positioned below the UAV/nozzles had higher coverage rates, while "upper" canopy layers had the highest mean coverage, followed by "middle" and "lower" levels (Figure 8). Furthermore, a flight altitude of 2.5 m had higher mean coverage compared to 2m flights. Finally, in IR applications, the “speed” variable demonstrated no significant difference in overall canopy coverage according to the Tukey test. In all inter-row applications, the 2 internal rows (namely 2° and 3°) exhibited consistently higher canopy coverage, across all treatments.

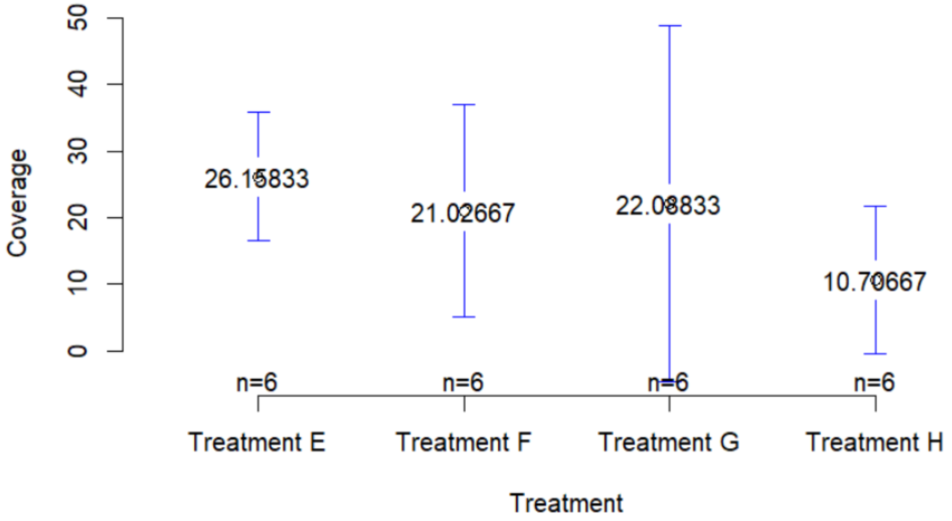

Figure 8. The mean coverage rate for rows 2 and 3, across all Inter-row Treatments, and across all iterations.

Discussion & Conclusions

Over-row Applications

A two-way ANOVA analysis and subsequent Tukey post hoc test did not reveal statistically significant differences between flight speed and altitude. However, a notable distinction in spray coverage was observed in the middle row of the upper canopy, with a consistently higher mean coverage of 19.93% across different treatments. This finding aligns with the UAV's over-row flight pattern, which predominantly covered the middle row of the vineyard. The wind direction, which was 'NW' in over-row applications, also influenced canopy coverage, leading to higher coverage in row 1 compared to row 3. The results indicated that a flight speed of 1 m/s yielded a superior mean coverage percentage of 4.37% compared to 3.0% at 1.5 m/s.

Slower flight speeds enhanced canopy coverage due to the correlation between flight speed and flow rates per nozzle. Regarding flight altitude, a 2.5-meter altitude exhibited a higher mean coverage of 4.38%, surpassing the 3.0% coverage rate at a 2-meter altitude. Higher altitudes resulted in improved deposition in the middle and lower canopy regions, enhancing overall mean coverage. The primary effect of "treatment" did not show a statistically significant influence on coverage. Treatment A exhibited the highest mean coverage at 4.56%, followed by Treatments B and C with similar coverages of 4.20% and 4.18%, respectively. Treatment D displayed the lowest mean coverage of 1.82%. Further statistical analysis of the middle row upper canopy showed no significant correlations between flight speed, altitude, and coverage. Treatment C emerged as the top-performing treatment, achieving 25.1% canopy coverage in the middle row upper canopy, closely followed by Treatment B, while Treatment D was the least effective. These findings underscore the importance of optimizing flight speed and altitude to enhance spray coverage in vineyard management. Slower flight speeds and higher altitudes tend to improve overall canopy coverage, particularly in the middle and lower regions.

Inter-row applications

In Inter-row applications, coverage was similarly highest in the upper canopy (10.1%) levels, followed by the middle (7.4%) and lower canopy (4.4%). The data highlighted that a flight altitude of 2.5 meters resulted in a higher mean coverage rate (8.7%) compared to a 2-meter altitude (6.0%). The "speed" factor showed that a flight speed of 1 m/s yielded slightly better coverage (7.43%) than 1.5 m/s (7.20%). These results suggest that higher flight altitudes and slower speeds generally improve canopy coverage.

For specific treatments, Treatment A showed the highest mean coverage (4.56%), followed by Treatments B (4.20%) and C (4.18%), with Treatment D (1.82%) being the least effective. Detailed analysis of the middle row upper canopy revealed that neither flight speed nor altitude had statistically significant correlations with coverage. However, a flight speed of 1 m/s achieved higher mean coverage (23.12%) compared to 1.5 m/s (16.7%), and a 2.5-meter altitude resulted in superior mean coverage (22.87%) compared to 2 meters (16.98%).

Overall, inter-row applications provided better canopy coverage compared to over-row applications. Treatment E (2.5 m altitude and 1 m/s speed) emerged as the most effective, achieving 26.2% coverage. This treatment was followed by Treatment G (22.1%), Treatment F (21%), and Treatment H (10.7%), with the latter showing the lowest performance. This pattern indicates that inter-row applications are particularly effective in uniformly covering the entire canopy, especially the middle and lower sections.

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