UNIVERSITÀ DEGLI STUDI DI PADOVA
Department of Agronomy, Food, Natural Resources,
Animals and Environment

Second Cycle Degree (MSc)
in Sustainable Agriculture

Analyzing Spray Coverage and Deposition Using Spraying Drones in Vineyards

Supervisor
Prof. Francesco Marinello

Submitted by
Havva UYAR
Student n.
2049608

ACADEMIC YEAR 2022/2023

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Abbreviations and acronyms

UAVs	Unmanned Aerial Vehicles
IPM	Integrated Pest Management
PPPs	Plant Protection Products
EU	European Union
WHO	World Health Organization
PA	Precision Agriculture
PV	Precision Viticulture
GNSS	Global Navigation Satellite Systems
GIS	Geographic Information Systems
CAGR	Compounded Annual Growth Rate
SSCDS	Solid Set Canopy Delivery Systems
WSPs	Water Sensitive Papers
OR	Over-row
IR	Inter-row

Acknowledgement

I would like to express my sincere gratitude to the SFT group at the Agricultural University of Athens for their invaluable support throughout my research. Special thanks to Vasilis Psiroukis for his guidance and assistance during both the experimental and writing phases of my thesis. His expertise and dedication played a crucial role in the success of this work.

I extend my heartfelt appreciation to Professor Spyros Fountas for providing me with the opportunity to conduct the experiments central to my thesis and for guiding me through the entire process. Your mentorship has been instrumental.

I want to also acknowledge my partner, Dimitris Baroutis, for being my pillar of strength and support throughout all stages of this endeavor. Your encouragement and understanding were vital in keeping me motivated.

To my family and friends, your love, patience, and encouragement was a constant source of strength. I am thankful for your sincere belief in me.

Last but not least, I would like to express my appreciation to all those who have, in one way or another, contributed to my academic journey. Your support has been instrumental in shaping the work presented in this thesis. Thank you all.

Summary

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), or drones, has led to a revolutionary era in agriculture. UAVs offer novel opportunities to improve agricultural practices by providing precision, efficiency, and safety in chemical application.

This thesis presents a comprehensive investigation into the application of UAV spraying technology to improve spray coverage and deposition in vineyards. Field trials were conducted using a commercial hexacopter spraying UAV with a capacity of 16 liters for spraying, with water-sensitive papers serving as the primary tool for assessing coverage and deposition. Analysis of these water-sensitive papers was performed using DepositScan software, providing valuable insight 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. A flight speed of 1 m/s proved to be more efficient than 1.5 meters per second. Notably, specific treatments, such as Treatment A for over-row applications and Treatment E for inter-row applications, showed promising results due to their common operational parameters - a flight altitude of 2.5 meters and a flight speed of 1 m/s.

This research underscores the transformative potential of UAV spraying in modern agriculture, demonstrating its ability to increase efficiency and reduce environmental impact, 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.

1. Introduction

1.1 Viticulture: An Overview

Viticulture, the art and science of cultivating grapevines, is a cornerstone of the agricultural world, driven primarily by its pivotal role in the production of wine (Unwin, 2005). Beyond the production of wine, grapes find their way into a multitude of products, from grape juice to raisins and table grapes (Mullins et al., 1992). The practice of viticulture encompasses a wide spectrum of activities, including planting, pruning, irrigation, pest management, and harvesting (Winkler, 1974). Its significance extends well beyond the realm of commerce; it is deeply connected with cultural traditions, providing employment opportunities and generating revenue for countries that boast thriving wine production (Mullins et al., 1992).

Viticulture has a rich historical heritage dating back thousands of years, making it one of the oldest and most beloved farming practices (Valamoti et al., 2020). The importance of vineyards is not only limited to their contribution to the wine industry but also extends to their cultural and economic importance (Mullins et al., 1992; McGovern et al., 2003). The importance of vines in human culture has influenced the development of various cultivation and crop protection techniques to protect these precious vines from pests, diseases, and environmental stressors (Zadoks, 2013). Sustainable viticulture practices like organic vineyards, tillage, biopesticides, nano biopesticides, and precision viticulture are being adopted to reduce the use of pesticides, which can lead to cost savings for farmers (Bandinelli et al., 2020). However, protecting vines from pests, diseases, and weeds presents several challenges due to the unique layout and cultivation practices of the vineyards.

Throughout ancient civilizations, including the Egyptians, Greeks, and Roman Empire, early viticulturists acknowledged the value of grapevines (Harutyunyan & Malfeito-Ferreira, 2022) but relied on basic techniques for crop protection against pests and diseases. Manual intervention was one of the earliest forms of plant protection in vineyards, involving meticulous inspection and pruning to eliminate pests and diseases plant parts (Zadoks, 2013). While this approach offered a rudimentary form of pest control, it became less effective as vineyards expanded in size.

As agricultural understanding advanced, natural solutions such as sulfur and copper-based compounds became more popular in the Middle Ages and are still used in organic viticulture today (Lamichane et al., 2018). These substances offered a degree of control over fungal diseases and pests. However, the efficacy of these substances was not always reliable and required precise timing during application to prevent damage to the vineyards (Lamichane et al., 2018).

During the late 19th and early 20th centuries, the implementation of chemical pesticides brought about a revolutionary change in vineyard crop protection practices (Sabatier et al., 2019). Notably, the introduction of Paris Green in 1867 marked the initial use of chemical insecticides in the United States (Kogan, 1998). Subsequently, compounds like lead arsenate and the Bordeaux mixture gained popularity for their efficacy in pest and disease control, surpassing the effectiveness of traditional methods (Sabatier et al., 2019). As viticulture expanded globally, these chemical solutions played a crucial role in sustaining vineyards and ensuring viable wine production, allowing for the development of new mixtures with optimal proportions to combat unwanted organisms (Lamichane et al., 2018). However, the widespread adoption of chemical pesticides has raised concerns regarding their environmental impact and potential risks to human health.

The awareness of pesticide impacts on the environment and ecosystems grew substantially following the publication of Rachel Carson's groundbreaking book, "Silent Spring," in 1962 (Carson, 2009). Carson's extensive literature has effectively documented the adverse effects of pesticide usage on the ecosystem and human health. Evidence shows that pesticides can spread beyond the target area, contaminating surface water and seeping into groundwater (Carson, 2009). The detrimental consequences of pesticide use on non-target organisms, as well as pollution of the soil and air, have been well documented (Zhang et al., 2015).

Consequently, crop protection concerns and pesticide application have emerged as vital aspects concerning environmental contamination, operator safety, and food safety (EFSA 2018; Carvalho 2017). Furthermore, these factors hold significant implications for the economic balance of crop production (Damalas and Eleftherohorinos 2011), justifying the extensive research activities conducted in the past and currently ongoing. Today, viticulture has evolved into a sophisticated and highly specialized field, playing a vital role in the global agricultural sector.

1.2 Crop Protection in Viticulture

1.2.1 Conventional Crop Protection Methods

Viticulture has a long and rich history dating back thousands of years, and its cultivation has always involved the need to defend the vines from a wide range of threats, such as pests, disease, and environmental stressors (Zadoks, 2013). In the past, prior to the emergence of contemporary agricultural techniques, grape growers and farmers depended on various traditional measures to protect their valuable grapevines from pests and other threats (Winkler, 1974).

Indirect methods employed in the preservation of vineyard crops assume a critical function in the prevention and alleviation of pest and disease effects. These strategies incorporate various essential principles to bolster vine health and optimize environmental conditions. The initial step in variety selection entails the careful consideration and choice of grapevine types that exhibit resistance or tolerance to specific pests and diseases, thereby minimizing the necessity for intervention (Bettiga, 2013). The implementation of appropriate fertilization practices is crucial in order to provide vines with the necessary nutrients for robust growth, hence augmenting their ability to withstand adverse conditions. Efficient irrigation management practices are employed to regulate soil moisture levels, thereby mitigating the occurrence of conditions conducive to disease development and ensuring sufficient hydration during periods of drought (Rombough, 2002). The manipulation of pruning techniques has a significant impact on the density of the canopy and the circulation of air, hence mitigating the potential for the development and spread of fungal infections. Furthermore, meticulous land assessment, taking into account variables like soil composition and local climatic conditions, can effectively reduce the reliance on chemical inputs (Rombough, 2002). In aggregate, these indirect methodologies play a role in enhancing the overall resilience of the vineyard ecosystem, facilitating the adoption of sustainable and ecologically sound grape farming techniques while concurrently supporting the vitality of the plants and the production of grapes of superior quality (Perria et al., 2022).

Direct methods are of significant importance in protecting vineyards from the persistent risks posed by pests, diseases, and environmental adversities. These tactics encompass practical treatments and specialized strategies that are designed to directly address and effectively manage pest infestations, diseases, and environmental challenges (Barzman et al., 2015). Vineyard managers utilize many techniques to promote the well-being and efficiency of grapevines while simultaneously mitigating their environmental footprint (Diti et al., 2020). The aforementioned methods comprise a range of control measures, including physical, bio-technical, biological, and chemical approaches, each of which possesses distinct tactics and applications (Barzman et al., 2015). In the subsequent parts, we shall thoroughly examine each category to ascertain their respective contributions towards the efficacious safeguarding of vineyard crops.

Physical control methods in vineyard crop protection employ various techniques to directly manage pests and diseases. Mechanical control includes agricultural measures such as tillage and mulching, which serve to disrupt pest life cycles and mitigate weed competition (Provost et al., 2016). Thermal control employs heat treatments as a means to eradicate pests or diseases with notable efficacy, particularly in regions characterized by low temperatures (Treptow et al., 2017). The utilization of electromagnetic control involves the application of electromagnetic radiation to interfere with the behavioral patterns of pests (Ibrahim et al., 2013). The aforementioned direct approaches offer practical remedies for addressing pests and diseases through direct modifications of their surroundings or behavior, hence diminishing the necessity for chemical interventions (Vincent et al., 2003).

Biotechnical control methods in vineyards harness the power of biological and chemical signals to influence the behavior of pests. One highly effective approach is the utilization of sexual confusion, which employs pheromone-based traps to disrupt the mating patterns of specific pests, thereby significantly diminishing their numbers (Thiery et al., 2023). Another technique involves the use of food traps designed to lure pests away from grapevines by using appealing baits and traps. These methods take advantage of the innate behaviors of pests to safeguard the vineyard, presenting environmentally friendly alternatives to conventional chemical treatments (Lucchi et al., 2018).

Biological control methods in vineyard crop protection entail the deliberate introduction of indigenous or exotic natural enemies of pests with the aim of regulating their populations. In order to sustain a harmonious ecosystem, the farmer employs the practice of introducing predators and parasitoids, such as ladybugs and parasitic wasps, which actively prey on detrimental pests (DeBach & Rosen, 1991). Pathogens such as biological control agents that specifically target pests, can be used as a means to decrease insect populations (Anderson, 1982). In addition, the introduction of competitive pests can be employed as a strategy to mitigate the negative effects of harmful pests by facilitating competition for limited resources. This approach serves to further diminish the overall impact of the harmful pests (Flint & Dreistadt., 1998). Biological management approaches utilize natural mechanisms to regulate insect populations, enhancing the overall health of vineyards (Rombough et al., 2002)

Chemical control continues to be the primary approach for safeguarding crops in vineyards, involving the use of plant protection substances like pesticides and herbicides as required (Bostanian et al., 2012). Chemical control is frequently employed as a final measure, with the aim of selectively targeting particular pests and diseases in order to mitigate substantial harm to crops. Integrated Pest Management (IPM) strategies integrate the use of chemical control measures in many other ways, aiming to minimize disturbance to the environment of the vineyard (Bentley, 2009).

Although it is undeniable that these conventional techniques have established the basis for viticulture, they are not exempt from their inherent constraints. The efficacy of these technologies exhibits variability, and their appropriateness for extensive commercial vineyards may not always be optimal. With the expansion of viticulture worldwide, there is an increasing acknowledgment of the necessity for enhanced efficiency and dependability in crop protection methods (Bramley, 2022). The historical dependence on traditional methods in vineyards, although undoubtedly important, also highlights the need to address the limitations and intricacies involved in the use of protective spraying applications. These concerns continually influence the developing framework of viticulture techniques.

1.2.2 Challenges in Conventional Spraying Methods

Proper application of pesticides plays a pivotal role in pest management and upholding agricultural efficiency. Nevertheless, application in excessive amounts can result in a cascade of unfavorable outcomes. This includes the depletion of soil fertility, which not only compromises agricultural productivity but also leads to the emergence of insect species that are resistant to pesticides. Excessive spraying application can further exacerbate the challenges faced by farmers by causing increased toxicities and economic losses within the agricultural sector (Gill & Garg, 2014; Cesco et al., 2021). These results underscore the importance of implementing responsible pesticide management practices (Hanif et al., 2022). Conventional spraying techniques have long been the cornerstone of grape crop protection. However, these methods encounter persistent obstacles that require the development of novel and innovative approaches. The utilization of several established methods, ranging from knapsack sprayers to mechanized systems mounted on tractors, has played a crucial role in effectively managing pests, diseases, and weeds in vineyards. Their use, however, has revealed several inherent limitations that have been the driving force behind the search for greater efficiency and effectiveness in vineyard practices.

Spray Coverage: 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; Rosell and Sanz, 2012; Palleja and Landers, 2015).

Spray Drift and Environmental Concerns: The issue of spray drift has been a persistent concern in the context of conventional spraying techniques, particularly when utilizing airblast sprayers that are affixed to tractors. The phenomenon of spray drift arises when small droplets or aerosols are transported by air currents to locations that extend beyond the originally intended target region. The activity in question presents a potential hazard of inadvertent environmental pollution. This environmental dilemma has raised concerns about its potential impact on ecosystems, soil integrity, and water pollution, making it necessary to explore more ecologically sustainable alternatives. The prevailing method, predominantly employing airblast sprayers mounted on tractors, has emerged as the primary preference because of its capacity to effectively infiltrate the foliage and cover expansive regions. Nevertheless, the matter of spray drift remains a significant concern and has the potential to result in inadvertent environmental pollution (Grella et al., 2017). Conventional sprayers have a tendency to result in substantial pesticide losses and inflict environmental harm. The implementation of mechanized spraying techniques is necessary in order to mitigate the negative impacts on both human health and the environment, as well as to effectively tackle the issue of labor shortages (Chen et al., 2021).

Pesticide Residues and Food Safety: The prevalence of pesticide residues in grapes has become a growing concern due to the rising utilization of plant protection products (PPPs) in mechanized commercial vineyards, facilitated by the widespread adoption of conventional spraying techniques (Marucco et al., 2019). These products play a crucial role in safeguarding crops; however, their excessive use raises legitimate concerns about the presence of pesticide residues in grapes. Based on the EU report on pesticide residues in food, the exceedance rate for pesticide residues in wine grapes has shown an increase from 0.4% to 0.9%. (EFSA, 2021). The identification of pesticide residues in wine grapes carries substantial consequences for the safety of food and the well-being of consumers, hence emphasizing the urgent necessity to reduce residue levels in agricultural commodities.

Inefficient Application: The issue of inefficiency in the application of pesticides has long been a recurring concern linked to conventional methods of crop spraying. Unless the sprayers are accurately calibrated to correspond with specified targets and environmental conditions, there is a potential for substantial wastage of applied agrochemicals. The aforementioned inefficiencies underscore the imperative requirement for accuracy in spray treatments in order to mitigate both resource waste and adverse environmental consequences. Furthermore, it is worth noting that a minimal proportion of the overall PPPs are efficiently delivered to the intended target when employing airblast sprayers for the application of PPP on tree and shrub crops. The issue becomes more apparent when the sprayers are not appropriately configured to align with the specified target and prevailing climatic circumstances (Grella et al., 2022). The main factor contributing to this lack of effectiveness is the composition of the spray, which encompasses droplets, aerosols, and/or vapors, contingent upon the chemical characteristics of the pesticide product being used. These components have the potential to be transported by atmospheric air currents. Spray drift and off-target losses have been recognized as the primary consequences of this phenomenon (Grella et al., 2017; Kasner et al., 2021).

Impact on Human Health: The use of conventional spraying methods frequently necessitates farmers and/or farm workers operating in close proximity to potentially dangerous agrochemicals, exposing them to health hazards (Alavanja et al., 2014). Ensuring worker safety and reducing agrochemical exposure in any agricultural operation is of utmost importance, given the established association between pesticide exposure and various health complications (Rocha et al., 2015; Damalas & Eleftherohorinos, 2011). The primary spraying equipment used in conventional agriculture comprises manual compressed air and battery-powered knapsack sprayers. These tools necessitate the operator's direct contact with the pesticide during the application procedure, hence augmenting the likelihood of exposure (Tsouros et al., 2019). According to the World Health Organization (WHO), the act of manually spraying pesticides in agriculture fields is associated with an estimated one million instances of adverse health effects (Matthews, 2015). These impacts encompass a diverse array of health issues. The aforementioned statement underscores the pressing necessity for the development of safer and ecologically sustainable alternatives that can effectively safeguard the well-being of agricultural laborers and the broader ecology.

In modern agriculture, effective pest management is of paramount importance to ensure the production of high-quality produce (Popp et al., 2013). Consequently, the use and responsible management of PPPs play a central role in maintaining the economic viability of agriculture. Due to the adoption of a novel European regulatory framework, the landscape of PPP applications has undergone a significant transformation in recent years. This transformation began with the introduction of the European Directive on the Sustainable Use of Pesticides 2009/128/EC (Marchand & Robin, 2019), which marked a significant milestone in pesticide regulation and the promotion of sustainable practices. More recently, the Farm to Fork Strategy, which operates under the umbrella of the European Green Deal, has emerged as a catalyst for change. This strategy aims to reduce the overall use of agrochemicals by 50% by 2030 (EC, 2019). The need to address these challenges is now at the forefront of modern agriculture, where sustainability is paramount (Cataldo et al., 2021). The regulatory frameworks and strategies for sustainable pesticide use underscore the urgent need for innovative and efficient spraying solutions. As the demand for sustainable and environmentally friendly agricultural practices continues to grow, the integration of conventional spraying methods with new technologies is becoming not just an option but an imperative.

1.2.3 The Rise of Precision Viticulture

Precision agriculture (PA), a relatively new discipline within agronomy, first arose in the mid-1980s and has since gained recognition as one of the most significant advancements in the agricultural sector (Crookston, 2006). PA encompasses a wide range of techniques and technologies that are designed to adapt the management of crops to the spatial variability that exists within fields. This need is driven by the inherent variability of key factors in crop production, such as water and nutrition, which often vary significantly in space and time within an individual farm (Gebbers & Adamchuk, 2010). As a result, effective management decisions need to take these variations into account (Srinivasan, 2006; Balafoutis et al., 2017).

Precision viticulture (PV) is the segment of PA that is specifically dedicated to the management of vineyards. While PV represents a relatively recent discipline within viticulture, its trajectory has been marked by remarkable growth. It emerged in the 1990s, aiming to adjust vineyard management to the natural spatial variability present in vineyards, thereby enhancing economic and environmental sustainability (Santesteban, 2019). Viticulture is by nature highly heterogeneous, a consequence of structural factors such as pedo-morphological characteristics and dynamic factors such as management practices and seasonal weather patterns (Bramley, 2003). As a result, vineyards require precise agronomic management that is tailored to account for the spatial variability within the vineyard (Proffit et al., 2006). As the international wine market becomes more competitive, the need for higher-quality vineyard management has become paramount. This imperative has led to a comprehensive review of agricultural techniques and has catalyzed a profound transformation in viticulture. The rise of PV has been shaped by a confluence of factors, reflecting a dynamic evolution in the way vineyards are managed. The primary goal is to maximize both the quality and sustainability of vineyards through a dual strategy: reducing the consumption of production inputs such as energy, fertilizers, and chemicals while minimizing input costs and preserving the environment. PV has emerged as a critical component of this strategy, offering a differentiated management approach aimed at addressing the specific needs of individual sites within the vineyard (Matese & Filippo Di Gennaro, 2015).

Implementing PV involves adjusting fertilizer, phytochemical, and water application rates to meet the specific needs of each area within a field (Srinivasan, 2006). This site-specific management strategy recognizes and addresses the unique needs of each area, moving away from the conventional approach of treating fields as uniform entities. In doing so, it increases the efficiency of agricultural input use and, when implemented correctly, results in cost savings and increased benefits (Hedley, 2015; Yost et al., 2017). Furthermore, it promotes resource-efficient practices from both an environmental and food security perspective by preventing the overuse of agricultural inputs, limiting nutrient and pesticide runoff, conserving water, and reducing unnecessary phytochemical use (Gebbers & Adamchuk, 2010; Hedley, 2015; Wu and Ma, 2015).

A key factor in this change has been the introduction of new technologies into vineyard management. The development of tools to monitor and control various aspects of vine growth has been facilitated by recent technological advances. Remote and proximal sensors have emerged as powerful tools for investigating vineyard conditions, including water and nutrient availability, plant health, pathogen infestation, and soil parameters. Precision viticulture takes advantage of these technological innovations with the goal of using a wide range of available observations to describe vineyard spatial variability at high resolution. It makes use of this information to provide recommendations that increase the efficiency of management in terms of quality, production, and sustainability (Matese & Filippo Di Gennaro, 2015). The emergence of PA has been dependent on significant technological advances in a number of areas. These advancements included the development of relatively accurate and affordable Global Navigation Satellite Systems (GNSS), the creation of Geographic Information Systems (GIS) to manage and analyze spatial data, and the increasing availability of remotely sensed geo-located information such as satellite imagery. Advances in technology have also included the development of variable-rate technologies. Campos et al. (2019) conducted site-specific monitoring of vineyard spraying using a prescription map obtained with a UAV. They compared the resulting application map with conventional spray methods, assessing the potential pesticide savings achieved. Campos et al. (2019) developed a variable rate technology for UAV spraying applications in vineyards based on prescription maps. This innovative system could modify working parameters in real-time based on the map values and the sprayer's position, achieving a reduction of 45% in the application rate compared to conventional spraying. This technological convergence has increased research efforts in this area, contributing to exponential growth in the global PA market value. In 2022, the global precision agriculture market was valued at approximately $7.6 billion. Looking ahead, IMARC Group expects the market to grow to approximately $15.3 billion by 2028, with a compounded annual growth rate (CAGR) of 11.3% from 2023 to 2028. This growth can be attributed to several factors, including the widespread use of smartphones and access to internet services, the increasing use of technology in agriculture, and the growing engagement in public-private partnerships[1].

Essentially, precision viticulture represents an innovative approach to vineyard management where technology and tradition converge to ensure grape production sustainability, productivity, and quality while reducing environmental impact. The integration of monitoring technologies, particularly the use of unmanned aerial vehicles, plays a key role in realizing this vision. The agricultural sector is expected to significantly benefit from the utilization of UAVs thanks to the growing demand for precision agriculture and smart farming (Chen et al., 2021). UAVs are poised to revolutionize the way vineyards are protected from pests, diseases, and other threats. UAVs have the ability to collect high-resolution data and efficiently cover large areas. This dynamic combination of technology and heritage holds great promise for safeguarding the foundation of quality wine production.

1.3 Unmanned Aerial Vehicles (UAVs) in Agriculture

1.3.1 The emergence of UAVs

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have embarked on a transformative journey that is reshaping multiple industries. While UAVs have a century-old history, their pivotal role in agriculture is a relatively recent phenomenon. Originating from military and surveillance use after World War II, UAVs have progressively found their niche in the civilian realm, with agriculture emerging as an exceptionally promising field. Today, the agricultural sector stands on the brink of a technological revolution driven by UAVs, with Goldman Sachs predicting that agriculture will become the second-largest user of drones globally within 2025 (Kesteloo, 2020). UAVs, as mobile robots, provide a low-cost alternative for detection technology and data analysis techniques (Norashma et al., 2019; Honrado et al., 2017). Various types of UAVs, including low-cost options, can collect high-resolution data from different

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[1] IMARC Group. (2023). Precision Agriculture Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2023-2028 (No. 5820760). https://www.imarcgroup.com/precision-agriculture-market (Last accessed on November 1, 2023).

spatial points. While UAVs are yet to be applied comprehensively in precision agriculture, they are increasingly becoming instrumental in sustainable agricultural practices and profitability. Additionally, UAVs significantly reduce the need for human resources while enhancing measurement precision.

UAVs present a straightforward, expeditious, and economically viable alternative for agricultural operations, even under unfavorable meteorological circumstances. The utilization of advanced monitoring techniques enables more precise, frequent, and cost-effective monitoring of crops, hence facilitating the provision of up-to-date, high-quality information. This information serves to enhance the understanding of crop enhancement strategies and draw attention to inefficient or unproductive practices. The utilization of infrared cameras on UAVs to enhance the extraction of information from captured imagery is a justifiable approach (Otto et al., 2018). The widespread utilization of unmanned aerial vehicles in the context of agricultural mapping enables producers to promptly access real-time information regarding the health of crops within a defined area. This allows them to identify specific regions that require immediate care based on actionable data. The integration of contemporary technical advancements into viable solutions for the agricultural and forestry industries necessitates collaboration among researchers, specialized enterprises, and producers (Shendryk et al., 2020). UAVs are of significant importance in multiple facets of crop monitoring, employing high-resolution cameras that are coordinated with a global positioning system. These cameras are capable of capturing images that are subsequently subjected to analysis using additional software, yielding significant insights, particularly in the context of tall crops such as maize (Mogili et al., 2018). UAVs equipped with thermal imaging technology have the capability to identify water stress in agricultural crops, hence facilitating the optimization of water resource allocation (Otto et al., 2018; Hassler & Baysal-Gurel, 2019). Nutritional stress in crops can be identified through the detection of potential deficits during the vegetative state (Shendryk et al., 2020). In addition, UAVs have the capability to detect diseases and pests at an early stage, as well as assist in the application of phytosanitary agents. Moreover, UAVs offer an accurate quantification of the number of plants present on a farm, eliminating the need for extrapolations. This capability is valuable in identifying issues and evaluating the extent of damage caused by diverse occurrences, such as fires.

Central to the transformation of agriculture by UAVs is the remarkable advancement in sensor and imaging capabilities that modern UAVs offer. These advanced sensors empower farmers with real-time data collection, crop health monitoring, and precise decision-making tools that were once unimaginable. These capabilities encompass multispectral and thermal imaging, LiDAR, and hyperspectral analysis (Khanna et al., 2015; Tsouros et al., 2019). By detecting early signs of crop stress, nutrient deficiencies, and pest infestations, UAVs enable proactive interventions to optimize agricultural productivity (Khanna et al., 2015). Throughout the crop growth cycle, from planting to harvest, UAVs are invaluable for collecting data on soil characteristics, crop nutrient stress, weed infestations, insect populations, and disease outbreaks (Ozkan, 2023). The integration of UAV technology into agriculture brings forth rapid and precise field condition assessments. Farmers can obtain overhead images of their fields, zoom in on specific areas, and promptly identify those requiring immediate attention (Kazi et al., 2023).

Beyond convenience, UAV deployment reduces costs, minimizes labor requirements, and enhances production efficiency, making them indispensable tools for both farmers and the broader agricultural industry (Tsouros et al., 2019). All the aforementioned set UAVs as valuable tools for farmers and the broader agricultural industry. Despite challenges like limited battery life, payload constraints, and weather sensitivity, the potential benefits of data-driven decision-making, resource optimization, and enhanced production significantly outweigh these limitations.

Numerous studies have highlighted the transformative impact of UAVs in agriculture. They have been employed in detecting pest and disease symptoms on olive trees, mapping palm tree plantations, identifying signs of red palm weevil infestations, and excelling in multispectral photogrammetry, thermal scanning, irrigation management, soil fertility monitoring, and harvest planning (Psirofonia et al., 2017). UAVs have also shown promise in targeted pesticide application, providing compelling evidence of their efficiency (Li et al., 2021). Recent technological advancements, such as easily accessible high accuracy positioning systems (such as RTK modules), have significantly improved the accuracy of spray applications, especially variable-rate applications (Lian et al., 2019). The improvement in accuracy has led to a reduction in the risks of environmental and human contamination, enhanced efficacy of PPPs, and boosted food quality and safety (Sabzevari and Hofman, 2022).

Unmanned aerial vehicles are widely employed in the domain of crop protection, namely in the spraying of PPPs aimed at protecting plants, and they have introduced a paradigm shift in crop protection practices (Valavanis & Vachtsevanos, 2015; Radoglou-Grammatikis et al., 2020). Innovative techniques, such as Solid Set Canopy Delivery

Systems (SSCDS) and aerial spraying from UAVs, have gained prominence, particularly in complex agricultural scenarios where mechanization of spray applications is challenging (Biglia et al., 2022; Chen et al., 2021). The potential advancements of UAVs in the field of agriculture go beyond their existing capabilities, with a particular focus on precision spraying. As technology continues to evolve, UAVs are poised to play a pivotal role in revolutionizing agriculture, ensuring sustainable, efficient, and technologically advanced farming practices that address the challenges of the modern agricultural landscape.

1.3.2 UAV Spraying: Benefits and Challenges

With the global population projected to reach nine billion by 2050, the use of fertilizers and pesticides is set to increase inevitably to meet this demand, all while land resources remain finite (Béné et al., 2015; Zhang et al., 2015). Yet, crop spraying, a labor-intensive and resource-demanding activity, has prompted the adoption of aircraft, specifically drones, due to their speed and efficiency in pesticide application (Berner & Chojnacki, 2017).

Benefits

Multi-rotor UAVs offer several advantages, including their compact size, exceptional flexibility, independence from specific take-off locations and human drivers, and the ability to operate frequently even in high-temperature conditions. UAVs have demonstrated strong performance when navigating through hilly terrain, densely forested areas, and even turbulent air currents beneath their rotors, as evidenced by Zhang et al. in 2016. The utilization of UAVs for pesticide distribution has been on the rise, particularly in China. These multi-rotor UAVs exhibit a working capacity of approximately 20 square meters per minute and possess liquid tanks ranging from 5 to 40 liters. Conversely, in Japan since 1990, where small-scale farms predominate, unmanned gasoline-powered helicopters have traditionally been the preferred choice, as highlighted by Xiongkui et al. (2017). UAVs have overcome terrain limitations and reduced chemical exposure risks for farmers and workers when compared to traditional methods (Pederi & Cheporniuk, 2015; Zhu et al., 2019; Rahman et al., 2021). Moreover, the coverage rate achieved through UAV spraying has proven to be particularly valuable in steeply sloping vineyards where conventional machinery faces limitations (Delpuech et al., 2022). The potential uses of low-volume drone sprayers involve their ability to operate at low altitudes above crops grown in small fields or in geographically challenging areas that are not easily accessible by humans or ground-based plant protection equipment (Xiongkui et al., 2017; Tirrò et al., 2013).

UAV spraying has earned its stripes in modern agriculture, driven by several key factors, namely efficient coverage of large areas, reduced pesticide use leading to cost savings and environmental conservation, automation that saves labor, and the avoidance of soil compaction and crop damage (Ozkan, 2023; Berner & Chojnacki, 2017). Moreover, when utilized effectively, UAV sprayers have demonstrated their superior cost-effectiveness and efficiency (Pederi & Cheporniuk, 2015; Xiao et al., 2019; Lou et al., 2018), alongside numerous other advantages, including precise and targeted agrochemical application, enhanced spray coverage, and reduced resource wastage (Chen et al., 2022; Stark et al., 2013; Rahman et al., 2021). The ability of UAVs to navigate crop rows with exceptional accuracy empowers growers to optimize resource allocation and minimize environmental impact, making them particularly appealing for vineyard management (Biglia et al., 2022).

According to Huang et al. (2013), the utilization of drone spraying offers several benefits, including enhanced maneuverability, reduced operational costs associated with labor, and the avoidance of physical harm to crops and soils caused by tractor wheel impact. Extensive research on various crops, including rice, wheat, corn, cotton, pepper, and sugarcane, underscores the potential of UAV applicators to revolutionize crop protection strategies (Berner & Chojnacki, 2017). UAVs' biological efficacy in aerial treatments has been successfully demonstrated in numerous studies (Qin et al., 2016; Lou et al., 2018; Meng et al., 2018). By achieving adequate and homogeneous spray deposition throughout the canopy volume, UAV spraying shows promise for effectively controlling pests and diseases in various crops (Giles and Billing, 2015; Meng et al., 2020). These successful outcomes emphasize the potential of UAV spraying as a viable and effective crop protection method.

In comparison to conventional methods, UAV spraying excels in precision, efficiency, and safety, further substantiating its adoption in agriculture (Wang et al., 2023). UAVs have the ability to use a very small amount of solution, saving water, not requiring a landing strip, reducing the risk of contamination to pilots (Jiang et al., 2022; Guo et al., 2019; Hu et al., 2022), and having no limitations related to terrain shape, field size, crop patterns, or turning space (Xu et al., 2022). Drones provide extensive coverage of vast areas, reduced pesticide usage, labor efficiency, rapid response time, and timely operations conducted far in advance of pest infestations surpassing economically viable levels with a commitment to environmental safety (Huang et al., 2018; Meng et al., 2018; Shamshiri et al., 2018).

In contrast to manned aerial applications, UAV-based systems offer a more cost-effective ownership and operational alternative. They also enable the application of treatments at much lower altitudes, which can be easily tailored to differentiated field layouts found in diverse crop cultivation areas and on steep slopes. Additionally, UAVs have the capability to execute precise, site-specific farm management tasks with exceptional accuracy, and significantly reducing the drift (Chen et al., 2021). The utilization of UAVs in orchards holds significant promise due to their ability to offer flexible labor options, reduce operational expenses, and minimize environmental effects (Rahman et al., 2021). Nevertheless, it is crucial to thoroughly assess these potential advantages before employing UAVs for pesticide applications in order to gain a comprehensive understanding of the necessary configurations and operational dynamics (Ribeiro et al., 2023). These features, along with the integration of sensors and advanced software, contribute to precise spray applications in agriculture (Hassler & Baysal-Gurel, 2019; Rahman et al., 2021).

According to Valavanis & Vachtsevanos (2015), UAVs offer distinct advantages compared to ground-based vehicles like tractors, particularly in terms of mobility. They are significantly faster, being 40 times swifter than traditional backpack sprayers, making them a viable replacement. The use of UAV sprayers leads to a remarkable 90% reduction in water consumption and a substantial 30–40% decrease in insecticide usage.

Nonetheless, the adaptability of UAVs extends beyond spraying, with applications in crop disease observation, yield estimation, environmental monitoring, and forestry remote sensing (Subramanian et al., 2021). These diverse applications underscore the versatility and potential of UAVs in advancing agricultural practices. These multifaceted advantages, as demonstrated in the research, underscore the value and relevance of UAV technology in modern agricultural practices (Rahman et al., 2021).

Challenges

Despite these promising benefits, UAV-based spraying encounters a series of challenges, such as short flight times, low autonomy and high upfront costs (Pederi & Cheporniuk, 2015; Xiao et al., 2019; Valavanis & Vachtsevanos, 2015). Ongoing research efforts aim to address these limitations by optimizing UAV technology for broader accessibility in the agricultural sector (Valavanis & Vachtsevanos, 2015; Stark et al., 2013). Other researchers have focused more on developing methods for site-specific spraying to reduce payload upon the drone, all of which rely heavily upon image sensing technology and machine vision algorithms (Rasmussen et al., 2013; Sandler, 2018; Xiao et al., 2019). While UAVs can navigate complex terrains and collect accurate 3D models using depth sensors, their short flight times, particularly with larger payloads, pose challenges (Valavanis & Vachtsevanos, 2015; Shilin et al., 2017). Drone sprayers exhibit relatively higher initial investment expenses and restricted capacity in comparison to conventional sprayers. In general, the findings indicate that unmanned aerial vehicle sprayers possess the capacity to serve as a more sustainable and efficient substitute for traditional sprayers inside vineyards and olive crops (Morales-Rodríguez et al., 2022). Legal considerations also come into play, with varying regulations surrounding the use of UAVs for pesticide spraying across different countries (Myers et al., 2015; Ayamga et al., 2021). According to the European Commission's directive 2009/128/EC, which provides a framework for promoting the sustainable use of pesticides, the use of drones for spraying purposes is permitted only under specific circumstances (European Commission, 2009). These circumstances include situations where no viable alternatives are available or where clear advantages can be demonstrated in terms of reduced impacts on human health and the environment, as compared to the conventional land-based application of pesticides.

In conclusion, UAV spraying has ushered in a transformative era in precision crop protection. Ongoing research and innovation promise in advanced technologies, including remote sensing, variable-rate technologies, and spray drift models, are being explored to improve the efficiency of drone spraying to further enhance this technology, solidifying its role in sustainable and effective crop protection strategies (Valavanis & Vachtsevanos, 2015). The integration of UAVs into precision agriculture holds the key to meeting the demands of a growing global population while ensuring efficient and environmentally responsible agricultural practices.

1.3.3 Literature on Operational Parameters in UAV Spraying

Researchers have undertaken extensive investigations aimed at optimizing various operating parameters in UAV spraying to enhance canopy deposition and coverage across a range of crops, with a primary focus on crop protection. These efforts have resulted in significant advancements in agricultural practices, ushering in a new era of precision agriculture. As we delve into these findings, it becomes evident how these studies have not only fine-tuned the use of UAVs in crop protection but have also provided valuable insights into enhancing the efficiency, sustainability, and cost-effectiveness of modern farming practices.

One critical area of focus has been the refinement of spray parameters, which encompasses aspects such as spray volume, droplet size, droplet spread, and overall spray effectiveness, with particular attention to insect pest control (Lou et al., 2018). These parameters have a profound impact on the efficacy of UAV spraying. A notable discovery pertains to the influence of specific factors on canopy spray deposition and coverage. Among these factors, the type of nozzle, spray pressure, and flight parameters have emerged as key determinants (Biglia et al., 2022). For example, in vineyards, the use of higher speeds, around 3.0 m/s, has been demonstrated to increase droplet deposition on the canopy while simultaneously reducing losses to non-target areas, particularly when conventional spray nozzles are employed. However, it's essential to strike a balance as very low spray application rates, such as 53.0 L/ha, have proven insufficient to achieve the desired application efficiency (Biglia et al., 2022).

Researchers have extensively investigated diverse operational variables, including cruise speed, flight altitude, spray passages per row, nozzle dimensions, liquid pressure, and active nozzle count, with the aim of enhancing canopy deposition and coverage in distinct agricultural cultivations. (Martinez-Guanter et al., 2020). To enhance operational efficiency, it is recommended to optimize the configuration of spraying systems on drones to facilitate the delivery of sprays with high concentration and low volume. The spray rates utilized in UAV systems typically range from 1 to 2 liters per hectare (L ha–1), representing a substantial reduction of 25 to 50 times compared to conventional spray systems (Xue et al., 2016). According to Xue et al. (2016), in order to minimize spray drift, it is recommended that UAVs maintain a low altitude of 3-5 meters while employing small droplets for low-volume pesticide spraying.

The study conducted by Sarri et al. (2019) aimed to investigate the sprayer performance of a commercial UAV equipped with different types of nozzles in a small, high-slope terraced vineyard. The study compared the working capacity, droplet coverage, density, and size of the UAV with traditional sprayers used in small mountain vineyards. In the comparative analysis of nozzle performance, the study found that flat fan nozzles exhibited superior characteristics in terms of droplet size, spray angle, and spray coverage, making them well-suited for herbicide applications. In contrast, air induction nozzles, while producing larger droplets and reducing drift potential, had less favorable droplet size and spray angle characteristics, making them suitable for fungicide applications. Twin jet nozzles demonstrated intermediate performance across these parameters and were deemed appropriate for insecticide applications. Additionally, the study highlighted the advantages of these nozzles over traditional sprayers, emphasizing their lower energy consumption, reduced noise levels, lower maintenance costs, higher spraying efficiency, and lower environmental impact.

The study conducted by Morales-Rodríguez et al. (2022) compared conventional sprayers and UAV sprayers in vineyards and olive crops in Extremadura, Spain. The study evaluated factors such as economic requirements, efficiency, operating costs, and water and product usage to assess the advantages and disadvantages of each method. The findings of the research demonstrated that drone sprayers exhibited a number of benefits in comparison to traditional sprayers. These advantages encompassed reduced consumption of water and PPPs, decreased operational expenses, and enhanced efficacy. However, UAV sprayers also had some limitations, such as higher initial investment costs and limited capacity compared to conventional sprayers. Overall, the study suggests that UAV sprayers have the potential to be a more sustainable and efficient alternative to conventional sprayers in vineyards and olive crops.

In vineyards, employing high-speed (3.0 m/s) conventional spray nozzles was shown to enhance droplet deposition on the canopy while minimizing losses to non-target areas (Biglia et al., 2022). The impact of UAV rotor downwash on canopy deposition in arable crops is of great significance, as it also applies to bush or tree crops, where it facilitates the movement of foliage and the distribution of droplets into the canopy. This, in turn, enhances the likelihood of reaching the innermost leaves (Zhan et al., 2022; Guo et al., 2019). Nevertheless, the difficulties associated with infiltrating canopies, which are affected by their configuration and thickness, have been documented in citrus orchards (Tang et al., 2018).

Additionally, the choice of UAV path and flight mode in relation to planting systems and tree shapes plays a significant role in canopy spray deposition, as demonstrated by Giles and Billing (2015) in vineyards and Meng et al. (2020) in peach orchards. Zhou and He (2016) conducted valuable simulations and experiments using UAVs equipped with WSPs on tea trees, highlighting that increased flight velocity improved droplet distribution uniformity but reduced droplet density and spray coverage. According to Wang et al. (2016), it has been proposed that small plant protection drones should operate at a flying altitude of 2.5 meters, maintain a flight speed of 4.0 m/s, and utilize a nozzle flow rate of 1.0 L/minute.

Kang et al. (2010) conducted an analysis of the flow and spraying characteristics of spray droplets generated by the primary rotor downwash, establishing optimal application conditions for aerial pesticide application. They determined that a boom with a 10° tilt angle and a spraying height of 3 meters represented the optimum setup, with the nozzle position positioned approximately 10 centimeters from the end of the main rotor to minimize scattering loss due to vortex phenomena.

Qin et al. (2016) examined the correlation between droplet deposition and distribution in the later stages of rice growth, as well as the operational height and velocity during crop spraying using a single-rotor unmanned aerial vehicle. In their study, Qin et al. (2016) employed drone spraying at varying altitudes (0.8m, 1.5 m) and speeds (3 m s-1, 5 m s-1) to assess the spray coverage on a rice crop. Optimal results were achieved at a flight height of 1.5 meters and a flight speed of 5 meters per second, maximizing droplet deposition in the lower layer with uniform distribution. However, the observed spray coverage consistently remained below 6%. In their study, Zhang et al. (2016) conducted experiments to evaluate the performance of a four-rotor UAV sprayer.

The UAV was operated at a constant forward speed of 1 m/s, while the flight altitude was varied at three levels: 0.5 m, 1 m, and 1.5 m. No statistically significant variations were seen in droplet coverage (%) and droplet deposition density (droplets per cm2) across the various flight positions. In a study conducted by Lou et al. (2018), experiments were carried out to assess the droplet dispersion and drift levels achieved through drone spraying on cotton crops. The tests were conducted at a flying altitude of 2 meters, and the results indicated satisfactory levels of droplet distribution and drift.

In their study, Qin et al. (2018) demonstrated the notable impact of spraying height on the distribution of droplets. They emphasized the efficacy of specific combinations, notably when the flight height was 5.0 meters and the flight speed was 4 meters per second. Qin et al. (2018) also unveiled the significant influence of spraying height on droplet distribution, highlighting the effectiveness of specific combinations, particularly when the flight height was 5.0 meters and the flight speed was 4 meters per second.

According to Shillin et al. (2017), the linear relationship model that attempts to modify the flow rate based on the spray quantity and fly speed at the flight altitude may not provide reliable results. This is because the environmental conditions and flight parameters tend to fluctuate in real time during plant protection operations. Hunter et al. (2020) conducted field experiments to investigate the impact of nozzle and speed selection on herbicide delivery utilizing drones, with a specific focus on coverage and drift potential. The findings of their study indicated that particular nozzle designs and application velocities provided sufficient coverage of intended areas while mitigating the risk for unintended drift.

In summary, the extensive amount of literature related to operational parameters for unmanned aerial vehicle spraying systems has yielded useful insights into the optimization of crop protection methods and the improvement of aerial spraying operations. The conducted assessments have conclusively shown the notable efficacy of drone technology in the application of pesticides to a diverse range of crops, frequently producing outcomes that are equivalent to or exceed those attained using conventional sprayers.

Nevertheless, it is crucial to recognize that although operational and delivery parameters have been carefully customized for particular crops or specific pests and diseases, there is still potential for further improvement to enhance effectiveness in diverse real-world situations.

2. AIM AND OBJECTIVES

This thesis endeavored to address a critical aspect of modern viticulture by comprehensively analyzing the spraying efficiency and deposition of UAVs within a vineyard in Spata, Greece. The overarching aim of this research was to contribute valuable insights into the optimization of UAV-based spraying practices in vineyard management, considering both over-row and inter-row spraying strategies.

The primary objective was to investigate the intricate interplay between operational parameters, specifically flight height and speed, and their impact on the deposition of spray liquid within the complex vineyard canopy. This study also aimed to explore the effects of over-row and inter-row spraying techniques on spray deposition, providing vineyard practitioners with essential knowledge for enhancing canopy coverage.

To achieve these objectives, an extensive series of field trials were conducted within an experimental vineyard setting. These tests involved the deployment of a UAV equipped with an 8-nozzle spraying system. Pre-located water-sensitive papers, positioned at various levels within the vineyard canopy, served as indicators for capturing the deposition patterns of the sprayed liquid during each flight.

The methodology adopted for this research enabled a systematic evaluation of the effects of varying operational parameters, including flight height and speed under a constant application rate, on spray deposition. The samples were analyzed using an image analysis software specifically designed for the analysis of WSPs, while rigorous statistical analyses were employed to interpret the deposition data, interpreting the performance of UAV-based spraying techniques in vineyard applications, considering the unique demands of over-row and inter-row sections.

The overall objective of this thesis revolved around conducting investigations into UAV spraying coverage and deposition in the setup similar to that of a commercial vineyard in Greece. This research aimed to uncover critical insights that would contribute to the optimization of UAV-based spraying practices in vineyard management. The anticipated outcomes held the potential to significantly enhance canopy deposition, ultimately promoting more efficient and sustainable vineyard operations across various vineyard systems.

3. MATERIAL METHODS

3.1 Experimental Area and Crop Characteristics

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 climate is warm and temperate, characterized by much rainier winter months compared to the summer months. Köppen and Geiger classify this climate as Csa. The average annual temperature is 17.3°C, and the region receives approximately 450 mm of precipitation annually[2] (Spata Climate (Greece), n.d.).

Figure 1. The experimental area in Spata, Greece.

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 Mesogeia-Atiki 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 vine height was about 1.3 m, with the leaves and grapes occupying the zone above ground between 0.3 and 1.4 m.

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[2] Spata Climate (Greece). (n.d.). Retrieved from https://en.climate-data.org/europe/greece/spata/spata-283043/ (Last accessed on September 17, 2023).

3.2 UAV Characterization

The unmanned aerial vehicle used in this study was a DJI Agras T16 (Figure 2). This UAV has a 16-liter capacity tank and an effective spray width of 6.5 meters. Its spraying system comprises four delivery pumps and eight sprinklers, capable of operating at a maximum spray rate of 4.8 liters per minute. In practical terms, the T16 can cover approximately 10 hectares of land in a single hour. Additionally, it features an electromagnetic flow meter, which provides enhanced precision and stability compared to traditional flow meters, ensuring accurate pesticide application[3].

Figure 2. The multi-rotor (hexacopter) UAV used in the spraying experiment, DJI Agras T16.

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[3] Agras T16 - DJI. (n.d.). DJI Official. https://www.dji.com/gr/t16 (Last accessed on November 3, 2023)

Table 1. DJI T16 UAV Specifications

Operating efficiency per hour	24.7 acres (10 hectares)
Number of rotors	6
Maximum operational flight speed	7 m/s
Maximum level flight speed	10 m/s (With strong GNSS signal)
Maximum bearable wind speed	8 m/s
Tank Capacity	16 L
Maximum effective spray width	6.5 m
Stationary flight duration	18 min (Takeoff weight of 24.5 kg with a 17500 mAh battery) 10 min (Takeoff weight of 39.5 kg with a 17500 mAh battery)
Maximum spraying flow	4.8 L/min
Number of nozzles	8

3.3 Environmental Monitoring

The environmental conditions were arranged in accordance with ISO 22866 and tailored for use with UAVs. Following this protocol, all experiments were conducted within a temperature range of 25 to 35 degrees Celsius, to mitigate any potential risks associated with temperature variations affecting the spraying deposition process.

Wind speed measurements were collected using a portable Ultrasonic Wind Instrument (as shown in Figure 3). The instrument's technical specifications are outlined in Table 2. To avoid any potential interference with the spraying process, the instrument was positioned at a distance of 20 meters from the application area, directly above the vineyard canopy, stabilized at 2 meters above ground. Data was collected at a rate of 1 recording per second (1 Hz), and the calculated average values are presented in Table 3.

Figure 3. Ultrasonic Portable Mini Wind Instrument and Data Logger used in the spraying experiment.

Table 2. Ultrasonic Portable Mini Wind Instrument and Data Logger Technical Data

Technical Data	**Specifications**
Sensors	Ultrasonic transducers (4x) Sample Rate: 1 Hz
Wind Speed	Range: 0.5-25 m/s Resolution: ± 0.1 m/s at 10 m/s
Wind Direction	Range: 0-359° Accuracy: ± 1°

Table 3. Average wind speed during the experiment

Treatment	**Application**	**Average Wind Speed (m s−1)**	**Wind Direction**
A	Over-row	1.0 m s−1	NW
B	Over-row	0.8 m s−1	NW
C	Over-row	1.5 m s−1	NW
D	Over-row	0.8 m s−1	NW
E	Inter-row	2.8 m s−1	SW
F	Inter-row	1.8 m s−1	SW
G	Inter-row	2.1 m s−1	SW
H	Inter-row	1.1 m s−1	SW

3.4 Experimental Design

The study investigated various combinations of the following parameters: spraying altitude (2 and 2.5 meters above ground level), flow rates per nozzle (1.4 and 1.8 liters per minute per active nozzle) directly connected to and represented as flight speed (1 m/s and 1.5 m/s), and spraying positioning (inter-row and over-row). All of these combinations were conducted with a constant deposition rate per hectare. This approach allowed for a comprehensive examination of how these operational parameters interrelated and responded within the context of the study's objectives.

Table 4. Experimental Parameters: Variations in Flight Speed and Altitude Across Treatment Conditions

Treatment	Factors	Factors 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

The experiment encompassed eight distinct treatment combinations, characterizing the interplay between flight height (H), flight speed (S), and row placement (OR for Over row and IR for Inter row). Table 4 provides precise values for flight altitude (in meters) and flight speed (in meters per second) associated with each treatment, and whether the treatment was over-row or inter-row application.

Collectors: The data collection process involved the use of water-sensitive papers (WSP) measuring 0.76 mm x 26 mm. These collectors were chosen due to their ability to intercept spray droplets and undergo an instant color change upon contact with liquid.

This facilitated accurate detection and quantification of sprayed droplets across the various canopy sections.

Figure 4. WSP before exposure (a) and after exposure (b) to the spray.

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 1 meter (Upper), as illustrated in Figure 5 and 6. The water-sensitive papers were secured to the plant trellis with clothespins, replicating their positioning in the vine canopy as that of grape leaves (see Figure 6).

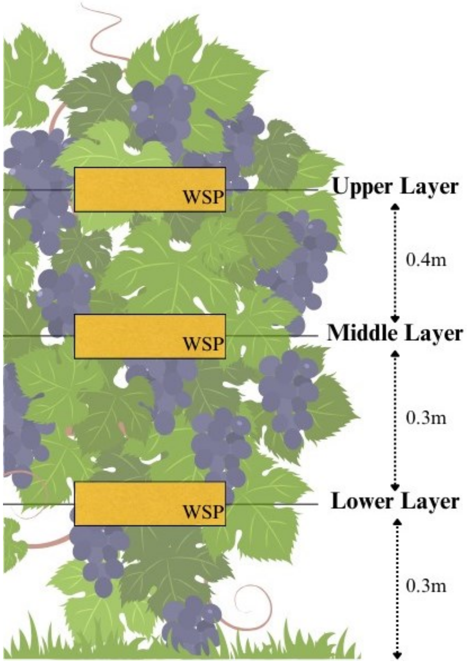

Figure 5. Sketch for the sampling collectors (WSPs) on the vineyard canopy.

Moreover, ground WSPs were placed on wooden supports to evaluate the dispersion of agrochemicals that did not reach the vegetation but instead came into contact with the soil. Figure 6 represents photos taken from the experiment. The first photo is how the WSPs were placed over the ground wood plate. These wooden plates were placed between the vineyard rows later on, in order to assess the spraying delivery on the ground.

Figure 6. Photos from the experiment showing Ground WSP, Canopy WSPs and zip lock bags used.

The collected WSPs that were sprayed were gathered immediately after the distribution process. To prevent any potential color changes due to moisture, these collected WSPs were carefully stored in zip lock bags (Figure 6). Furthermore, individual sampling bags were employed to ensure that there was no contact between the individual WSP samples, preserving the integrity of the data.

The visual representation provided below illustrates the experimental setup of this thesis (Figure 7). The objective of this setup is to evaluate the effectiveness of spraying UAVs in terms of their spraying coverage and deposition in a vineyard. The above diagram depicts two predominant methods employed for drone spraying, namely over-row and inter-row application approaches. The over-row application involves instructing the UAV to navigate directly over selected vine rows. On the other hand, the inter-row application concentrates on the areas between the selected rows, aiming to achieve a wider spray dispersion. Both systems employ strategically positioned WSPs in different parts of the vineyard canopy.

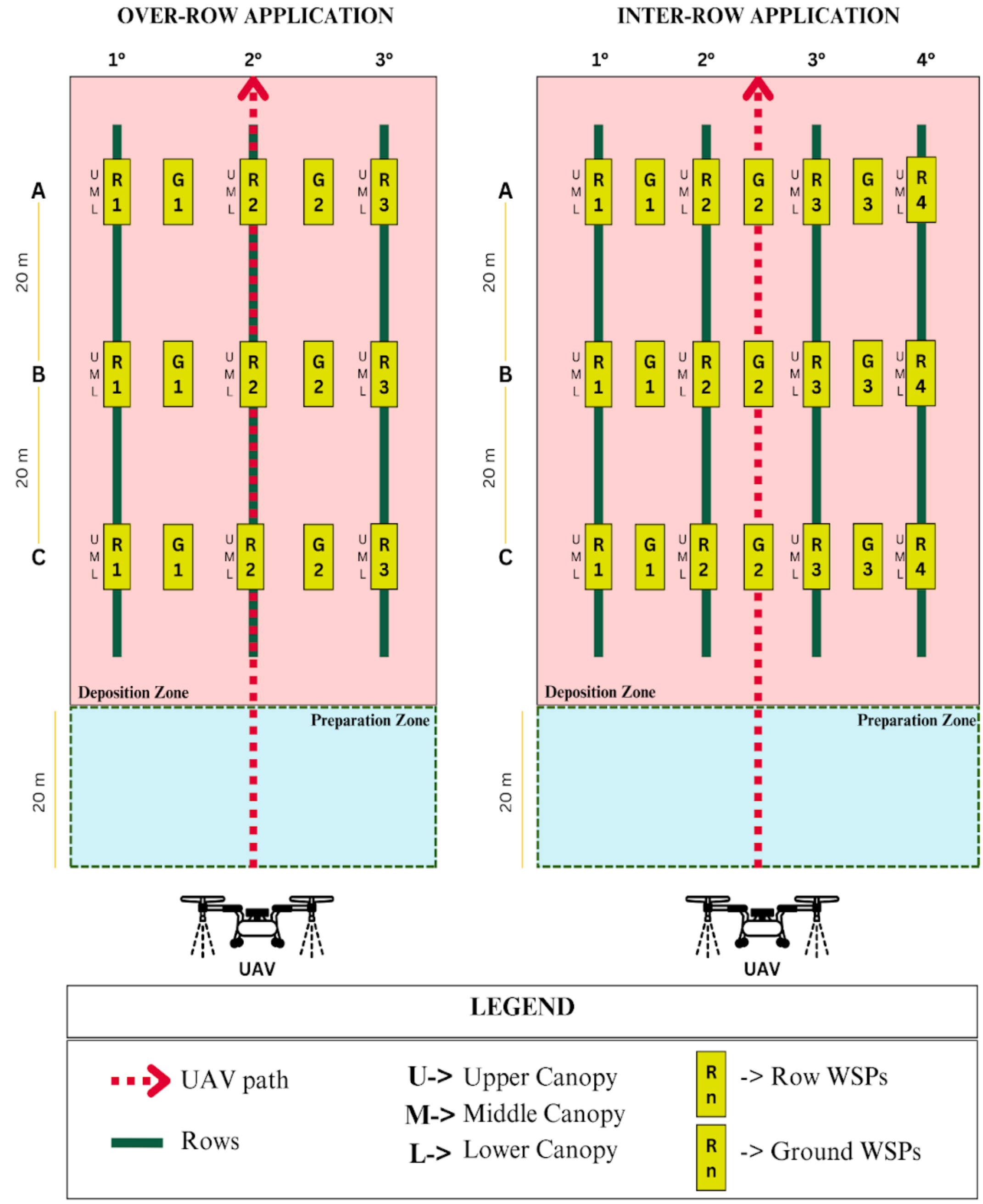

Figure 7. Experimental layout

In accordance with the research aims, this experimental methodology investigates the correlation between operational variables of the UAV, such as flying altitude and velocity, and their subsequent impact on the distribution of sprayed substances. The objective is to optimize the use of UAVs for spraying in order to achieve better coverage of the vineyard canopy and improve the management of vineyards, and to provide significant insights for vineyard practitioners by comparing the results of two spraying strategies.

Data Analysis

After collection, the WSP samples were stored in individual labeled sealed bags. Each label contained all associated information about the respective spray treatment, replication, and individual sample location details. These sealed bags were then promptly placed inside a container to prevent any potential color changes due to moisture. Subsequently, they were transported to the laboratory for further analysis. In the laboratory setting, the analysis of WSPs was conducted with the assistance of a high-resolution 600-dpi scanner. The scanner was utilized to create digital images of the WSPs, which were then subjected to image analysis using the DepositScan software (developed by the United States Department of Agriculture). The DepositScan software is specially designed to measure droplet deposits in digital images and analyze key parameters including droplet density, coverage percentage, and the Volume Median Diameter (VMD).

Upon initiating the software, the user is prompted to open the ImageJ window. The subsequent steps involve scanning the WSPs and converting the images into 8-bit grayscale format. The software then activates the "count black and white pixels" command and provides a means to select the area for analysis, utilizing the ANALYSIS feature within ImageJ. The Depositscan software provides results in the form of several key parameters, including DV 1 (µm), DV 5 (µm), DV 9 (µm), % Coverage, Image Area (cm^2), Deposits/cm^2, and Deposition (µL/cm^2). These parameters hold specific significance: DV1 signifies that 10% of the spray volume comprises droplets smaller than the specified size, while DV5 indicates that 50% of the spray volume encompasses droplets of varying sizes, both smaller and larger than the specified parameter. Meanwhile, DV9 reveals that 90% of the sprayed volume consists of droplets smaller than the specified size. % Coverage represents the vital percentage of the target area covered by the spray, offering a critical measure of spraying efficiency in vineyards. Image Area (cm^2) represents the total assessed area in square centimeters, providing the spatial context for understanding spray coverage and deposition. Deposits/cm^2 quantifies the number of deposited droplets per square centimeter, providing insights into droplet density on the target surface. Deposition (µL/cm^2) quantifies the amount of liquid, measured in microliters, deposited per square centimeter of the target area. It serves as a measure of the quantity of spray material applied to the surface.

Statistical Analysis

In this study, the primary focus was on the analysis of two critical factors: Coverage % and Deposition (µL/cm²), with the ultimate goal of evaluating spray coverage and deposition in the context of UAV-based vineyard spraying operations. All the results from the DepositScan software will be analyzed through two-way ANOVA using R-Studio. Following the two-way ANOVA, a post-hoc test will be conducted. The analysis will help us understand which treatments worked best both in over-row and inter-row applications, as well as which flight speed and height result in higher coverage and deposition rates. This comprehensive approach will provide valuable insights into enhancing the efficiency and effectiveness of vineyard spraying practices.

4. RESULTS

4.1 Canopy Coverage by UAV Spraying

Notably, the results obtained from the DepositScan software underwent a comprehensive statistical analysis utilizing R Studio. Through two-way ANOVA and posthoc tests, the objective was to investigate the treatments that resulted in the most advantageous outcomes in both over-row and inter-row applications. Furthermore, the aim was to investigate the impact of different flight speeds and heights on the rates of coverage and deposition.

Over-row Applications

Statistical analysis was performed to evaluate the impact of different variables on spray coverage during over-row UAV spraying in vineyards. The dataset was imported and explored using RStudio, with a summary showing key statistics for the variables under investigation, including 'Speed,' 'Height,' 'Site,' and 'Coverage.' A two-way ANOVA was conducted to assess the significance of these variables. The analysis revealed several findings. Specifically, the factors 'Speed', 'Height' and 'Site' did not yield statistically significant differences in spray coverage ($p > 0.05$) as indicated by the results of the two-way ANOVA.

In order to further investigate the variations in canopy coverage, a Tukey post hoc test was conducted to compare ‘Site’ factor within the vineyard. The 'Site' factor represents both the location of the water-sensitive paper (WSP) collector in the field (1°, 2°, or 3° row) and its position within the plant canopy ('Lower,' 'Middle,' or 'Upper'). The outcomes of the Tukey post hoc test showed distinctions in spray coverage across various categories. Specifically, '2° row / Upper WSP' was grouped into category 'a' due to its notably higher coverage rate (19.93%), while the remaining categories were grouped into 'b' with varying coverage levels. Figure 8 represents a scatter chart illustrating the mean coverage values for each vineyard row, and how the canopy coverage differed between different locations through the vineyard canopy.

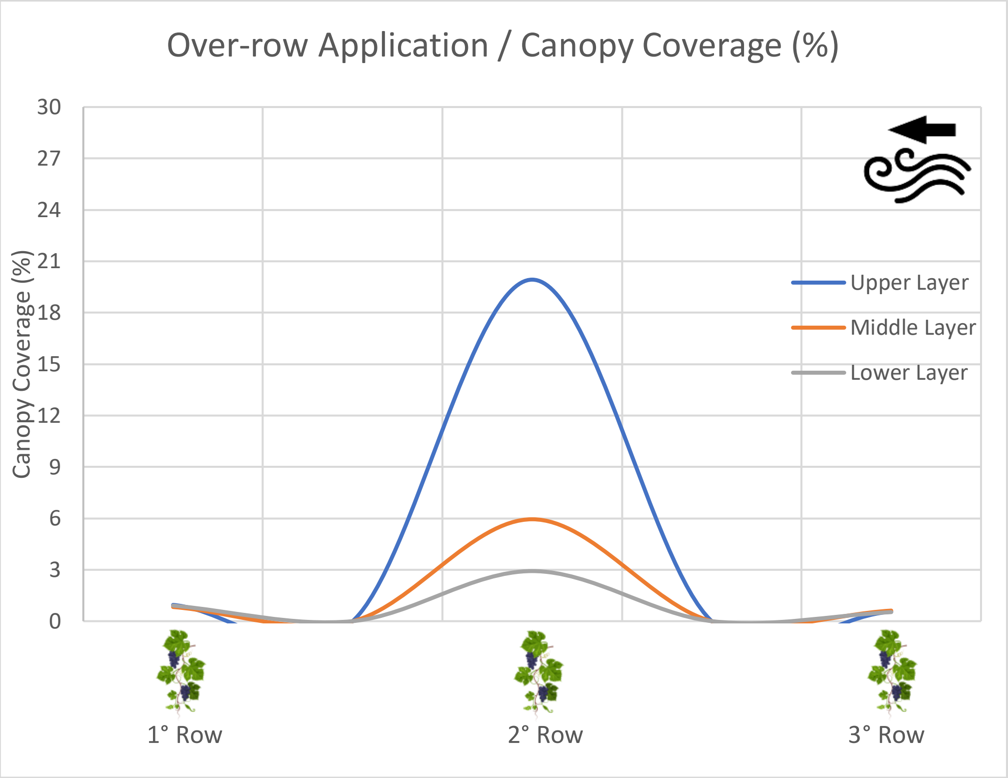

Figure 8. Scatter chart illustrating the mean coverage percentages for over-row applications across all the sites.

By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 9. X-axis labels indicate the location of WSP paper. First letter indicates the row of the WSP (L for Left therefore the 11° Row, M for Middle therefore the 2° row and R for Right therefore the 3° row), and second letter indicates the location of the WSP over the canopy (L for lower canopy, M for middle canopy and H for the higher canopy).

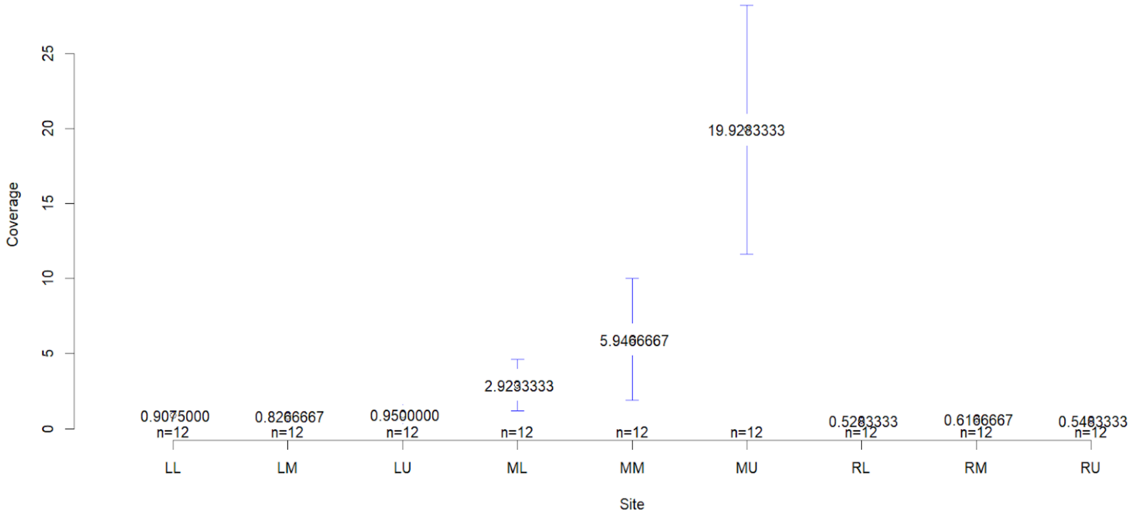

Figure 9. A plot showing the mean coverage rate for different WSP locations as a mean of over-row applications.

Further 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 with a mean of 4.38%, surpassing the 3.0% coverage rate observed at a 2-meter flight altitude.

After separately analyzing the effects of speed and height, the study proceeded to investigate the impacts of treatments A, B, C, and D. These treatments represented various combinations of speed and height, with the aim of determining which combination achieved the optimal coverage.

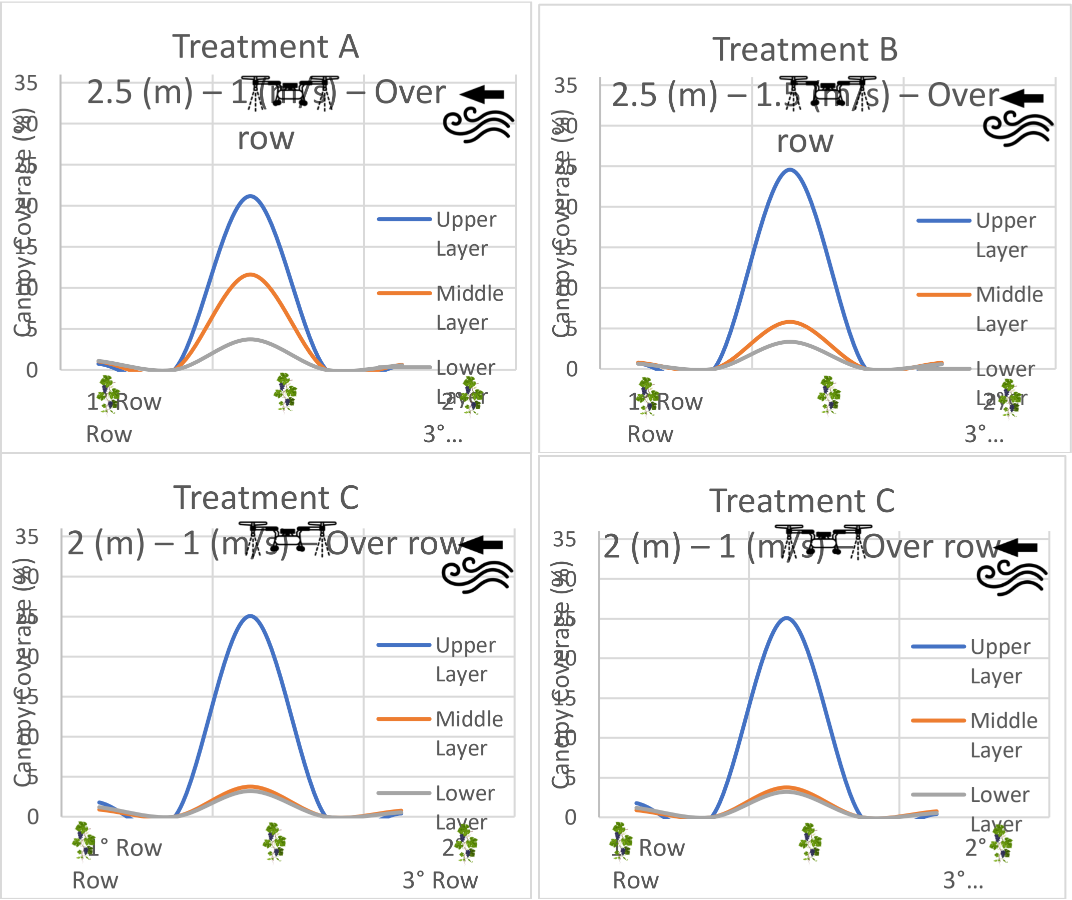

Figure 10. Charts showing the effect of different treatments over the canopy coverage in different layers of the canopy.

Figure 10 represents the scatter charts illustrating the effects of each treatment on canopy coverage, showcasing the Upper layer, Middle layer, and Lower layer of the vineyard canopy separately in over-row applications.

In order to statistically analyze which treatment achieved the most optimal performance, another 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, 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 in this study. By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 11.

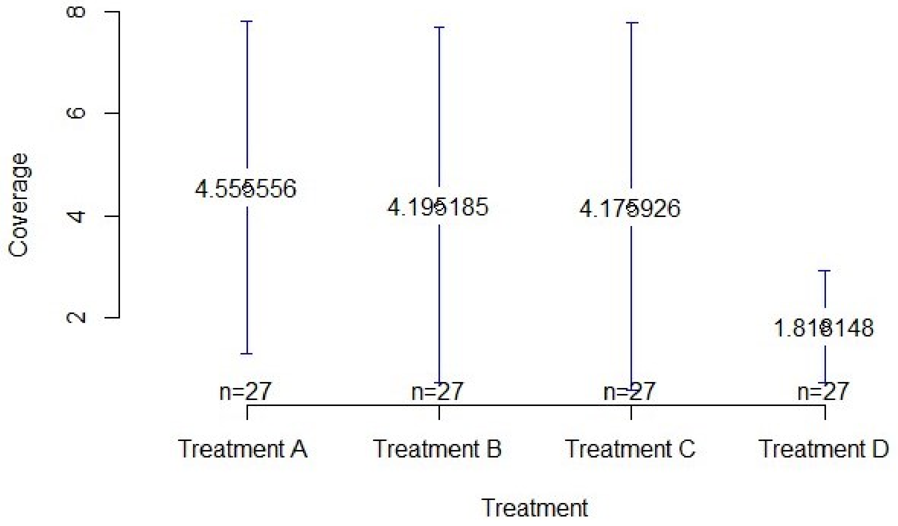

Figure 11. A plot showcasing the mean coverage rate for each treatment.

Figure 12 highlights the performance of various treatments in the study based on the vineyard row. Notably, Treatment A, with a flight altitude of 2.5 meters and a flight speed of 1 m/s, emerged as the most successful in terms of overall canopy coverage throughout the experiment.

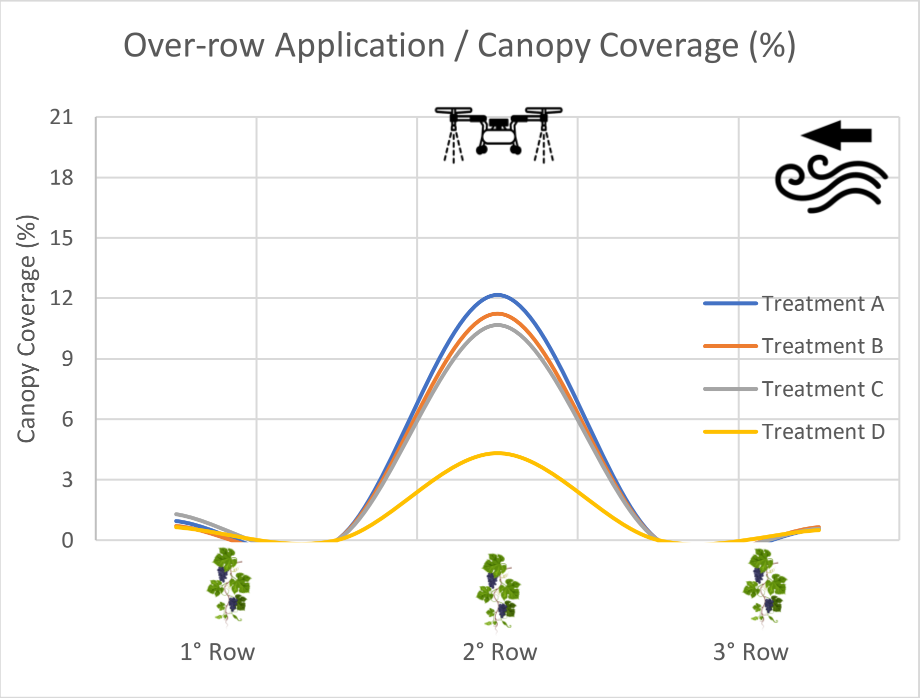

Figure 12. Chart showing the canopy coverage for over-row treatments in spesific vineyard rows

Refined statistical analysis was later conducted, with a specific focus on canopy coverage values obtained from water-sensitive paper results only in the middle row and upper canopy. This tailored approach was employed to exclude potential outliers, allowing for a more precise examination of the impact of various flight speeds and altitudes on canopy coverage within the upper canopy.

Two-way ANOVA was performed to investigate the influence of various factors on the "coverage" variable in the middle row upper canopy. The factors included were "speed," "Height," and repetition variables (Line A, B, and C) identified as "block." The results of the ANOVA revealed 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.

When comparing the mean coverage of treatments specifically, it was observed that Treatment C was the best performing treatment, with 25.1% canopy coverage in the middle row upper canopy, followed by slightly lower treatments B and A, respectively. Treatment D was the least performing among the treatments (Figure 13).

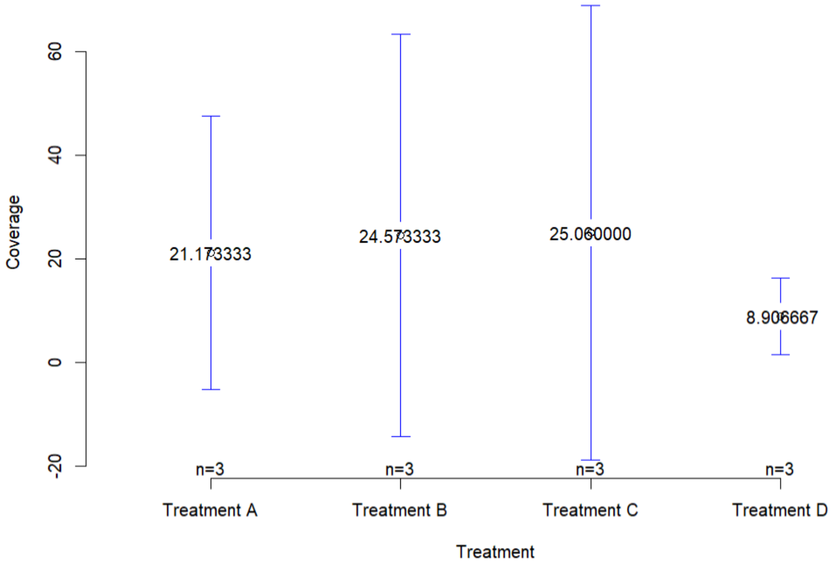

Figure 13. Plot showing the canopy coverage percentage of over-row applications over the middle-row upper canopy.

Inter-row Applications

A statistical analysis was performed to evaluate the impact of different operating variables on spray coverage during inter-row UAV spraying in vineyards. The dataset prepared using the results from DepositScan with the WSPs was imported and explored using RStudio. A two-way ANOVA was conducted to assess the significance of the variables "block", "row", "WSP location", "speed", "height" and "coverage".

Later on, the Tukey post hoc test was used to compare the means of the variables to have a better understanding. It was observed that the main effects of "Row," "Speed," "Height," and "Block" were not statistically significant ($p > 0.05$), indicating that these factors did not show a statistically significant impact on the "Coverage" variable in this study. The main effect of "WSP Location," however, showed a p-value of 0.0875, which is slightly above the conventional significance level of 0.05. Figure 14 represents the canopy coverage rate in inter-row applications based on WSP locations.

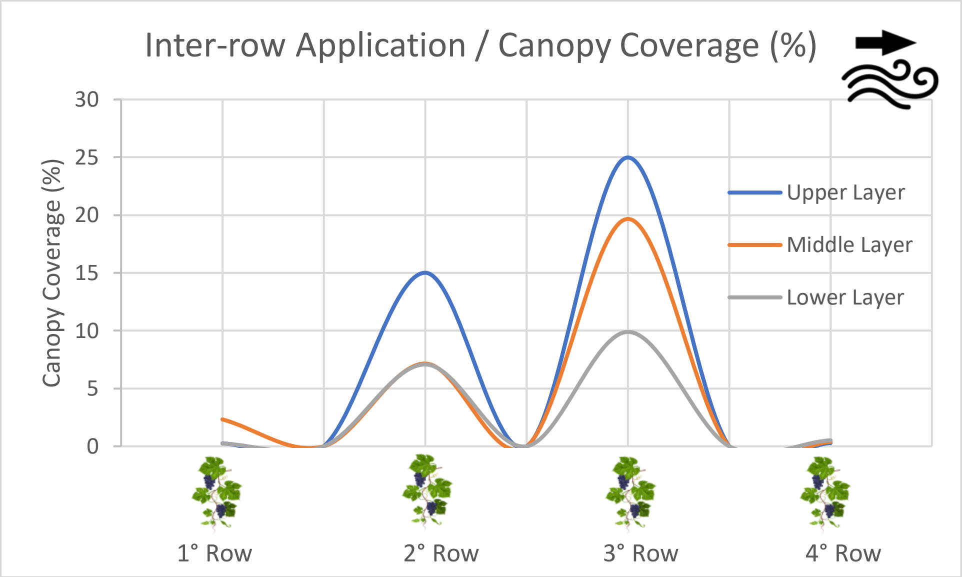

Figure 14. Chart representing the canopy coverage rate in inter-row applications based on WSP locations.

In order to further investigate the variations in canopy coverage, a Tukey post hoc test was conducted. In the post-hoc analysis, the differences were examined between levels of the factors "row," "WSP location," "speed," and "height" to gain a deeper understanding of their effects on the "coverage" variable. The Tukey HSD test was conducted for each factor in order to examine the mean coverage rates, and the following results were obtained:

For the factor "row," four levels were considered. The mean coverage values for these levels were as follows: Row 1° (0.93), Row 2° (9.75), Row 3° (18.18), and Row 4° (0.39). By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 15.

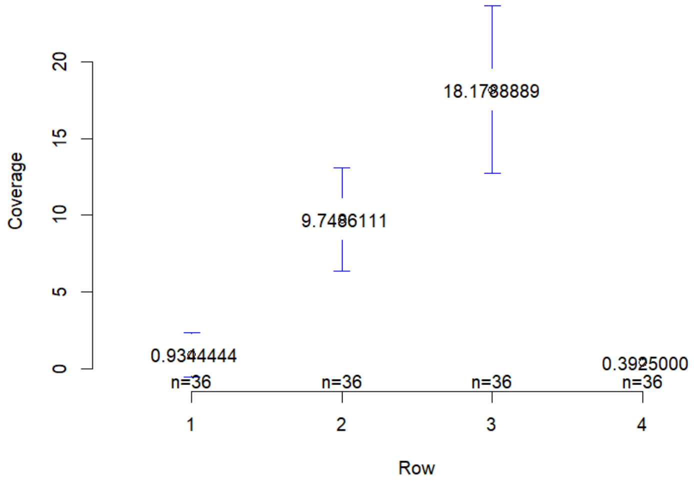

Figure 15. Plot showing the mean coverage rates of the vineyard rows

Moving on to the factor "WSP Location," which had three levels, the mean coverage values were: lower (4.43), middle (7.38), and upper (10.13). "upper" canopy had the highest mean coverage, followed by "middle" and "lower" canopies. By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 16.

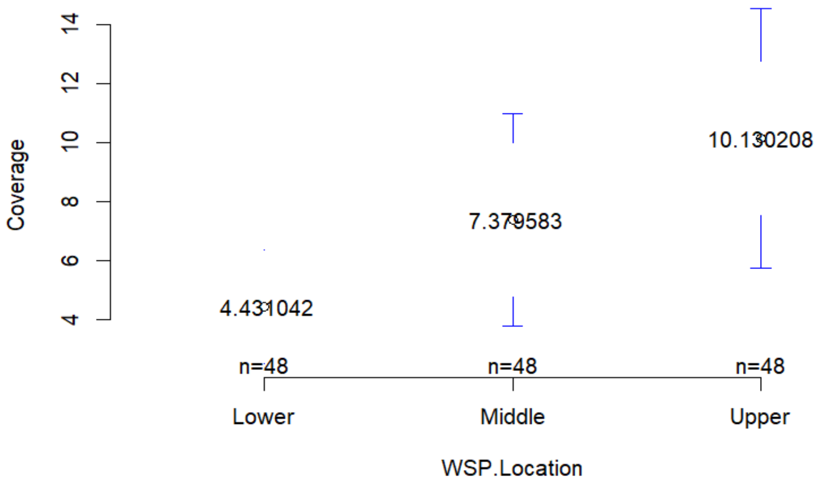

Figure 16. Plot showing the mean coverage rates for the WSP locations

Regarding the factor "Height," which had two levels, the mean coverage values were: 2 m flight altitude (5.94) and 2.5 m flight altitude (8.68). The results indicated that 2.5 m flight altitude had higher mean coverage compared to 2m flight altitude. By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 17.

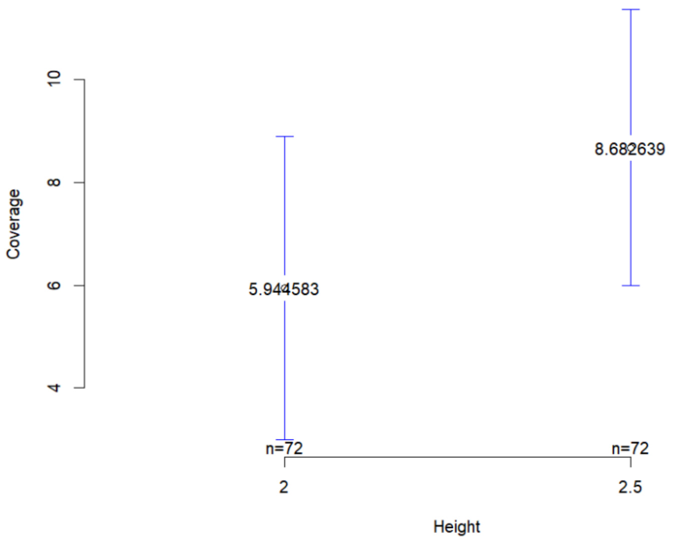

Figure 17. Plot showing the mean coverage rate of flight altitudes (2m and 2.5m, respectively)

Finally, for the factor "speed," which also had two levels, the mean coverage values were: 1 m/s (7.43) and 1.5 m/s (7.20). The Tukey HSD test showed no significant difference between these two levels in overall canopy coverage. By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 18.

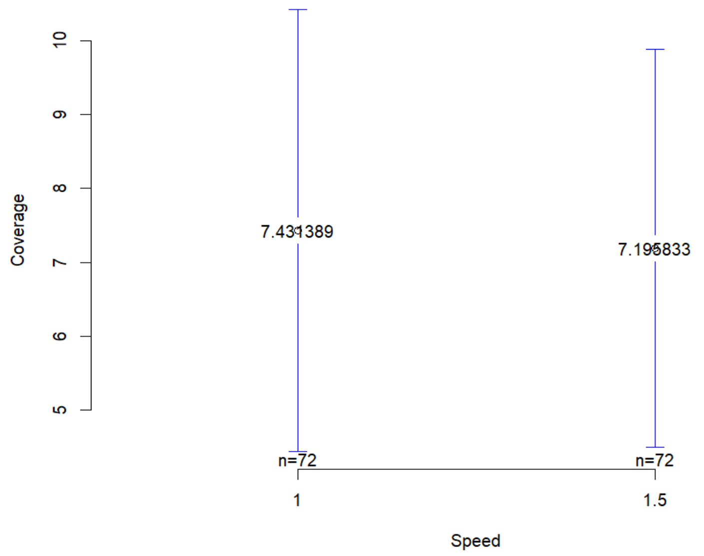

Figure 18. Plot showing the mean coverage rate of flight speeds (1m/s and 1.5m/s, respectively).

Having the knowledge related to speed and height factors and their effects on the canopy coverage, further analysis was conducted in order to evaluate the effect of different treatments, which involve the interaction of different speed and height factors.

The Tukey HSD test for "Treatment" revealed the following means: "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. 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.

By using the ‘gplots’ library in RStudio, means were plotted and represented in Figure 19.

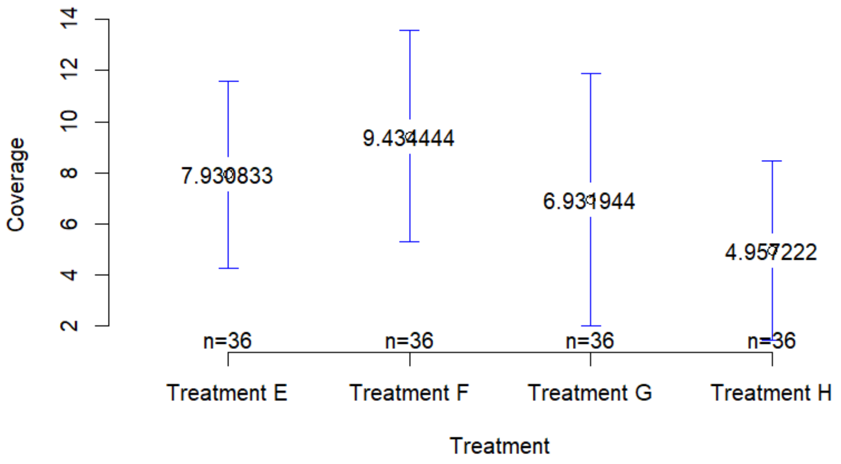

Figure 19. Plot showing the mean coverage rate of different inter-row treatments

In the context of inter-row applications, Figure 20 illustrates the average canopy coverage percentages in relation to different treatments and vineyard rows. Row 3° exhibited consistently higher canopy coverage, regardless of the treatment applied. On the other hand, Row 2° displayed varying coverage levels, with Treatment F showing the highest coverage, followed by Treatments E, G, and H in descending order.

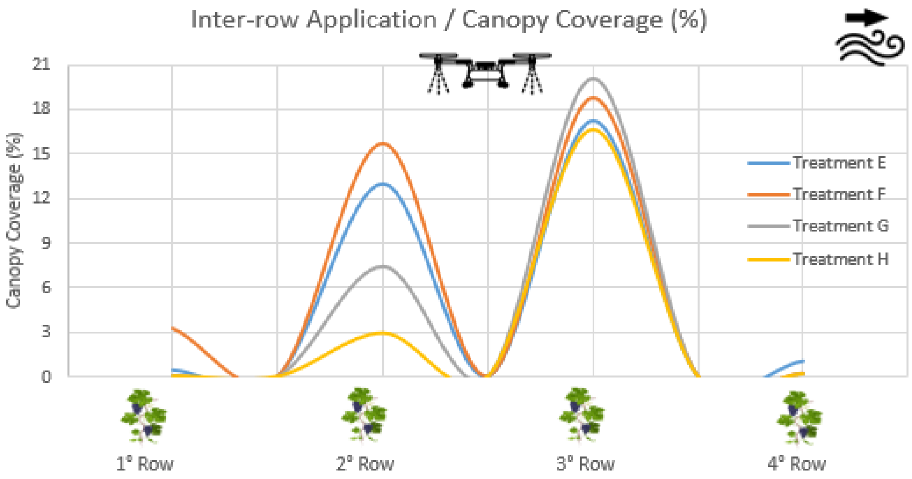

Figure 20. Graph illustrating the mean canopy coverage percentages for inter-row applications

Figure 21 contains four different charts, each focusing specifically on different treatments. The scatter charts depict the effects of each treatment on canopy coverage, showcasing the Upper layer, Middle layer, and Lower layer of the vineyard canopy separately in inter-row applications. The charts clearly illustrate the differentiation in canopy coverage based on various treatments, particularly with regard to speed and altitude.

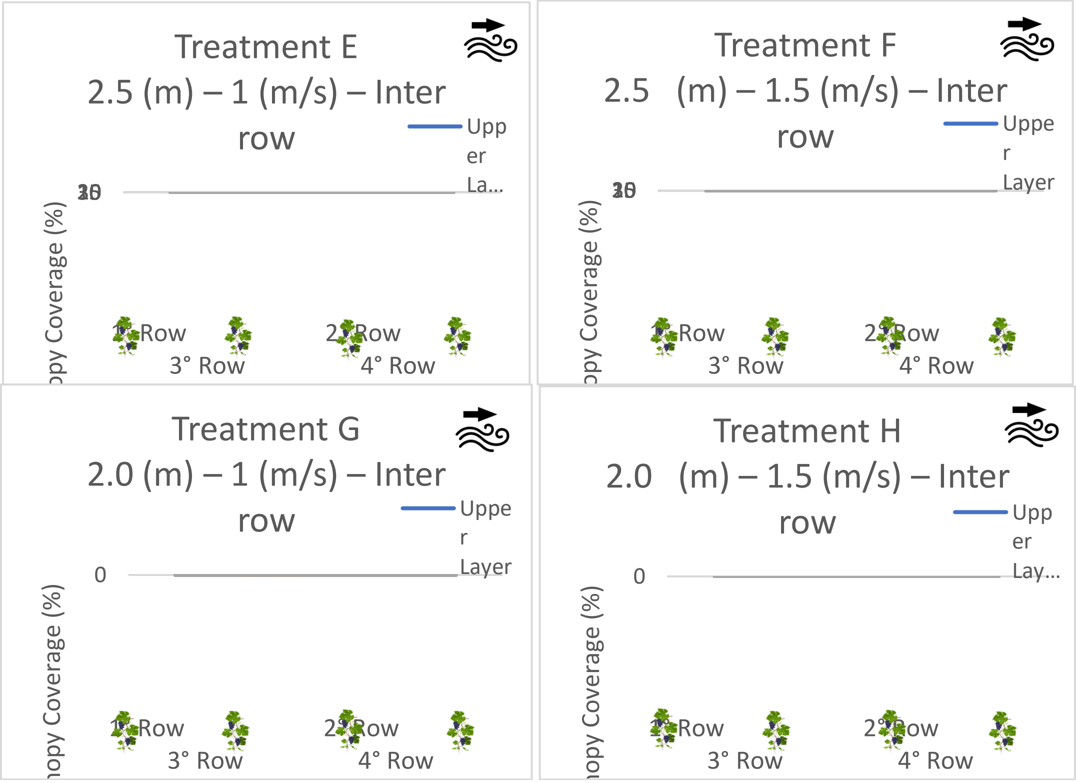

Figure 21. Graphs representing different inter-row applications and their canopy coverage rates

Figure 22 portrays the mean canopy coverage values specifically for the 2° and 3° rows, focusing on the upper canopy. This tailored methodology was utilized to eliminate potential outliers, facilitating a more precise assessment of how different flight speeds and altitudes affect canopy coverage within the upper canopy of the UAV flights conducted between these rows.

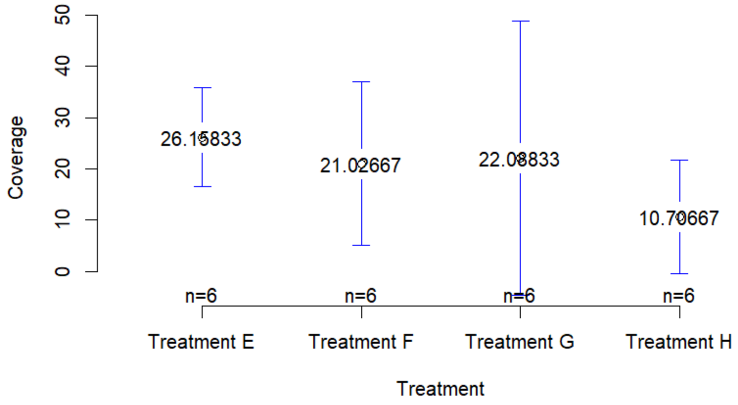

Figure 22. Plot showing the canopy coverage rates for specifically for the 2° and 3° rows for different inter-row treatments

Ground WSPs

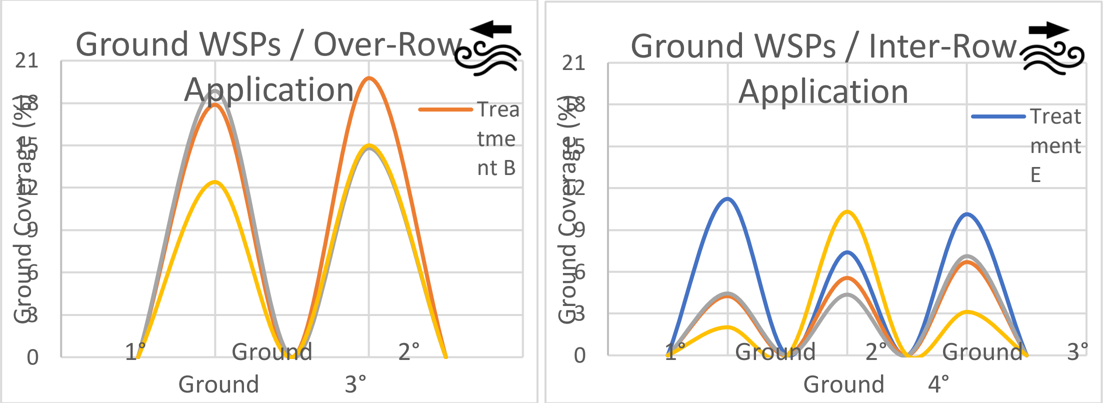

Figure 23. Charts showcasing the ground coverage rates for over-row and inter-row applications

Two graphs are presented above (Figure 22), illustrating the ground coverage percentage of the WSPs adhered to wooden plates placed between vineyard rows. The left graph represents over-row applications, while the right graph depicts inter-row applications, both within various treatment scenarios. For over-row applications, ground measurements were only conducted for Treatment B, C, and D, as conclusive data for Treatment A was not available. In general, the ground deposition was observed to be consistent and not significantly affected by wind conditions.

4.2 Deposition by UAV Spraying

The deposition (µL/cm²) results obtained from the DepositScan Software reflects the amount of liquid or substance deposited on the WSP surface in microliters per square centimeter (µL/cm²). It serves as a vital indicator of the effectiveness and efficiency of various treatments applied in the experiment. Notably, the deposition factor is often in correlation with the coverage percentage, as an increase in coverage percentage typically results in a corresponding increase in deposition.

In all treatments conducted within the experiment, Pearson correlation coefficients above 0.9 were observed between the coverage percentage and deposition (µL/cm²) for the WSPs. These high correlation values signify a very strong and positive linear relationship. Such correlations indicate that, as the coverage percentage increases, the deposition is strongly and consistently influenced.

Consequently, the results of the graphs and statistical analyses pertaining to deposition (µL/cm²) were omitted from the results section, considering the predictability and strength of the identified relationships.

5. DISCUSSION

The successful adoption of UAVs in agricultural practices, particularly in vineyard management, has been a subject of growing interest due to their potential to revolutionize the precision and efficiency of crop spraying. The effect of operational parameters on spray canopy coverage and deposition was investigated through the utilization of a DJI Agras T16 UAV spraying drone on an experimental vineyard. Given that all treatments exhibited a Pearson correlation exceeding 0.9 between canopy coverage and deposition, canopy coverage was selected as the primary metric for evaluating the effects, considering the robustness of the identified relationships.

In this study, the choice of a two-way ANOVA and subsequent Tukey post hoc test was considered to address the research objectives and evaluate the impact of different variables on spray coverage during UAV spraying in vineyards. The use of a two-way ANOVA was justified as it allowed for the simultaneous examination of the effects of multiple independent variables. This was important as it facilitated a comprehensive analysis of the interactions and main effects of these variables on spray coverage, considering the potential combined influence of multiple factors.

Furthermore, a two-way ANOVA is well-suited for identifying any significant differences between the groups, which was essential for determining which variables had a statistically significant impact on spray coverage. The utilization of a Tukey post hoc test following the ANOVA was also rationalized as it enabled a more in-depth exploration of the means, helping to indicate specific differences and providing a deeper understanding of the relationships between the variables.

Over-row Applications

In this study, four distinct over-row applications, identified as Treatments A, B, C, and D (Table 3), were executed, featuring variations in flight speed (1 m/s and 1.5 m/s) and flight altitude (2 m and 2.5 m). The drone was primarily operated over the middle row of the three vineyard rows, with a specific emphasis on analyzing its impact on the main row as well as the adjacent rows (see the experimental layout in Figure 7).

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 location of the WSP, particularly in the middle row of the upper canopy, where a notably higher mean coverage of 19.93% was consistently recorded across the different treatments. This location was categorized as 'a' by the Tukey post hoc test, while other locations were grouped into category 'b' with varying coverage levels (Figure 9). This observation is in accordance with the fact that the UAV in the over-row application predominantly flew over the middle row of the vineyard, and it was not the primary focus of the analysis.

As illustrated in Figure 9, while there was no statistical significance found in differentiating between the left and right rows, a consistent pattern arose where the left rows regularly exhibited slightly larger canopy coverage in comparison to the right rows. The observed phenomena can be attributed to the substantial effect of the wind direction, which plays a crucial role when assessing the distribution characteristics of droplet deposition in the setting of aerial spraying. Wind direction in over-row applications was 'NW', which complemented the canopy coverage in row 1° to be slightly higher than the coverage in row 3°. Even when considering the established "safe" environmental standards, the impact of wind direction remained detectable.

The results indicate that, with regard to the "speed" factor, a 1 m/s flight speed yielded superior mean coverage percentages, averaging 4.37% across all experimental sites, compared to the 1.5 m/s speed, which exhibited a mean coverage of 3.0% across the sites under examination. For a more comprehensive understanding of this phenomenon, refer to Figure 10, which comprises four charts illustrating the impact of each over-row application treatment (A, B, C, and D) individually on canopy coverage within various layers of the canopy. When comparing treatment A and treatment B, both of which maintained the same flight altitude of 2.5 meters but differed in flight speeds, it becomes evident that the slower flight speed (1 m/s) resulted in greater canopy coverage across various canopy areas, leading to an increased mean coverage. Furthermore, in the case of the comparison between Treatment C and Treatment D, where both treatments maintained a consistent flight altitude of 2 meters while employing different flight speeds, the selection of a 1 m/s flight speed also demonstrated a notable advantage, showing a higher level of canopy coverage. These findings underscore the intricate relationship between flight speed and canopy coverage, with slower flight speeds leading to enhanced coverage in this specific context. This effect can be directly attributed to the correlation between flight speed and flow rates per nozzle, which were 1.4 and 1.8 liters per minute per active nozzle.

Regarding flight altitude, the mean canopy coverage results indicate that the 2.5-meter flight altitude exhibited a higher coverage rate, with a mean of 4.38%, surpassing the

3.0% coverage rate observed at a 2-meter flight altitude as a mean coverage rate across all over-row applications. For a more comprehensive understanding of this pattern, please refer to Figure 10. When comparing Treatment A and Treatment C, both sharing the same flight speed but differing in flight altitudes, a distinct pattern becomes apparent. Despite the higher altitude leading to reduced deposition in the upper canopy, it ultimately results in higher deposition and improved coverage in the middle and lower canopy regions, contributing to an enhanced overall mean coverage. In the comparison between Treatment B and Treatment D, where both treatments maintain the same flight speed of 1.5 m/s but differ in flight altitudes, a clear trend emerges as the lower altitude corresponds to a notable reduction in canopy coverage, mirroring the observation made in the comparison between Treatment A and C. These findings underscore the substantial impact of flight altitude on the distribution of sprayed material within the canopy. Notably, a 2.5-meter flight altitude yields higher coverage compared to a 2-meter flight altitude in this context. This can be attributed to the fact that the elevated flight altitude over the middle row enhances the spraying coverage in the adjacent rows, ultimately resulting in greater mean coverage.

The results revealed that the primary effect of "treatment" did not exert a statistically significant influence on "coverage" ($p > 0.05$). When examining the mean coverage values, Treatment A exhibited the highest mean coverage, registering at 4.56%, followed closely by Treatments B and C, both demonstrating similar mean coverages of 4.20% and 4.18%, respectively (Figure 11). 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. It is worth noting that Treatment D employed a 2-meter flight altitude and a flight speed of 1.5 m/s, which aligns with our earlier discussion highlighting the trend of 2-m flight altitudes resulting in lower coverage compared to 2.5 m and 1.5 m/s speed leading to reduced canopy coverage in contrast to the 1 m/s flight speed.

Figure 12, which provides a visual summary of the over-row application performance trends across different vineyard rows, offers insights into which location yielded the highest canopy coverage for each treatment. In Figure 12, a significantly lower coverage for Treatment D is prominently evident. While the variations between Treatments A, B, and C over the second row were not substantial, it is apparent that Treatment A achieved the best results. This underscores the earlier discussion concerning the influence of speed and altitude, where a speed of 1 m/s and an altitude of 2.5 meters proved to be the best performing factors. Treatment A incorporated these advantageous parameters, which contributed to its increased performance in terms of canopy coverage.

Subsequently, a more refined statistical analysis was undertaken, focusing on the middle row upper canopy, with the aim of eliminating potential outliers from the analysis. This approach allowed for a more precise examination of the influence of flight speed and altitude on canopy coverage within the upper canopy. The results of this analysis revealed that neither the "speed" factor nor the "height" factor exhibited statistically significant correlations with "coverage" in the middle row upper canopy. Regarding the "Speed" factor, the analysis indicated that a flight speed of 1 m/s yielded a higher mean coverage of 23.12%, in contrast to the mean coverage of 16.7% associated with a speed of 1.5 m/s in the middle row upper canopy. As for the "height" factor, it was observed that a flight altitude of 2.5 meters resulted in a superior mean coverage of 22.87%, in contrast to the mean coverage of 16.98% observed at a 2-meter flight altitude.

However, when an analysis was conducted to determine which treatment yielded the highest canopy coverage over the middle row upper canopy, it became evident that Treatment C emerged as the top-performing treatment, achieving a remarkable 25.1% canopy coverage in the middle row upper canopy. It was closely followed by Treatment B, with Treatment A slightly trailing behind. In contrast, Treatment D stood as the least effective among the treatments (as shown in Figure 13). Notably, Treatment A, despite having the highest mean average, only differed from Treatment C in terms of flight altitude. Treatment C, with its higher canopy coverage in the middle row upper canopy but lower overall average, provides further support for the earlier observation regarding the influence of higher flight altitude, which results in relatively greater coverage in the middle row and adjacent rows, contributing to a higher overall mean canopy coverage.

Inter-row Applications

In this study, four inter-row applications, labeled as Treatments E, F, G, and H (Table 3), were conducted, encompassing differences in flight speed (1 m/s and 1.5 m/s) and flight altitude (2 m and 2.5 m). The drone was predominantly operated over the middle section of the four vineyard rows, specifically positioned between the 2nd and 3rd rows. The primary focus of the analysis was to assess the drone's impact on both the main rows it traversed and the outer adjacent rows, resulting in a total of four rows under investigation (see the experimental layout in Figure 7).

A two-way ANOVA analysis followed by a Tukey post hoc test did not reveal statistically significant differences between flight speed and altitude. Regarding the factor "Row," four levels were considered, with mean coverage values as follows: Row 1° (0.93%), Row 2° (9.75%), Row 3° (18.18%), and Row 4° (0.39%) (refer to Figure 15). The wind direction for the inter-row applications was from the "NW," which resulted in Row 1° (0.93%) having slightly higher coverage than Row 4° (0.14%). It was evident that the wind's effect was more pronounced, resulting a higher coverage rate in Row 3° (18.18%). This indicates that, even with the safe environmental conditions, the effect of the wind in spraying cannot be ignored.

In relation to the 'WSP Location' factor, which had three levels, the mean coverage values were as follows: lower (4.43), middle (7.38), and upper (10.13). The mean coverage rate for the upper canopy was 10.1%, followed by the middle canopy at 7.4%, and the lower canopy with a mean of 4.4% (refer to Figure 16). Given that WSPs were positioned within the trellis structure as they were the grapevine leaves, understanding the coverage rates of WSPs also provides insights into the coverage rates achieved by the drone spraying in each crop region. The 'Height' factor displayed similar mean coverage results to those of over-row applications. The findings revealed that a flight altitude of 2.5 meters had a higher mean coverage rate (8.7%) in comparison to a 2-meter flight altitude (6.0%) (Figure 17). This phenomenon, as previously discussed, is attributed to the fact that a greater flight altitude results in increased canopy coverage in adjacent rows, ultimately benefiting the overall mean coverage rate. The results from the 'speed' factor also paralleled the outcomes of over-row applications. The mean coverage values for this factor were 1 m/s (7.43) and 1.5 m/s (7.20) (Figure 18). However, in this case, the mean canopy coverage rate at 1 m/s was only slightly higher than that at 1.5 m/s.

For a more comprehensive understanding of this pattern, please refer to Figure 21, which comprises four charts illustrating the impact of each inter-row application treatment (E, F, G, and H) on canopy coverage within various canopy layers individually. When comparing Treatment E and Treatment G, both sharing the same flight speed (1 m/s) but differing in flight altitudes, a distinct pattern emerges. While the lower canopy coverage remained almost consistent between the treatments with different flight altitudes, a lower flight altitude resulted in increased deposition in Row 3 and decreased deposition in Row 2. This shift in deposition could be attributed to the fact that lower flight altitudes may make the drone more susceptible to wind effects compared to higher flight altitudes. When comparing Treatment E and Treatment F, which share the same flight altitude value

(2.5m) but differ in flight speed, a higher flight speed results in a more symmetrical deposition within each part of the crop canopy. It is evident that the lower canopy layer obtains significantly higher coverage with a higher flight speed. In the comparison between Treatments G and H, which share the same flight altitude (2m) but differ in flight speed, the higher flight speed appears to reduce overall canopy coverage. This phenomenon can be attributed to the relationship between speed and pump pressure, where higher speed requires higher pump pressure to maintain a constant deposition rate. Consequently, the nozzle pushes the droplets faster, resulting in a finer mist with smaller droplets that can penetrate more easily into the lower canopy levels. This, in turn, leads to a more homogenous spraying pattern in the lower canopy. It's worth noting, however, that the increased speed and finer mist also contribute to an elevated risk of drift. When comparing Treatment F and H, which share the same flight speed but differ in flight altitude, a lower altitude results in lower canopy coverage, especially reducing the coverage in the 2nd row compared to Treatment F.

As clearly shown in Figure 22, which portrays the mean canopy coverage values specifically for the 2° and 3° rows, focusing only on the upper canopy, Treatment E was the best-performing treatment, which consisted of 2.5m flight altitude and 1 m/s flight speed within the inter-row applications. This figure was tailored to eliminate any potential outliers and give a precise assessment of how different speeds and altitudes affected the upper canopy coverage in rows in which UAVs flied in between. The highest courage in Treatment E (26.2%) was followed by Treatment G (22.1%), Treatment F (21%), and finally, with the lowest coverage, Treatment H (10.7%).

Over-row vs Inter-row

Figures 8 and 14 present the average values for all treatments in each application. These charts clearly depict that, in the primary rows where the UAV operated, inter-row applications outperformed over-row applications by achieving higher canopy coverage. Furthermore, inter-row applications resulted in better coverage in different parts of the canopy layer, especially in the lower portions of the vineyard canopy. This enhanced coverage suggests better penetration, which is advantageous for effective spraying operations.

Treatment A (see Figure 10) and Treatment E (see Figure 21) share identical operational parameters, both maintaining a flight altitude of 2.5 meters and a flight speed of 1 m/s. The key distinction between the two lies in their respective application methods:

Treatment A employs an over-row application approach, while Treatment E employs an inter-row application technique. When comparing the effectiveness of these treatments, it becomes evident that one of the primary rows in the inter-row application method achieved similar coverage rates on par with the over-row approach, but the other primary row surpassed it by achieving higher coverage levels. Notably, it's important to mention that both Treatment A and Treatment E were the best-performing treatments within their respective application methods. However, Treatment E, by achieving higher coverage than Treatment A, emerged as the best-performing treatment in this study, signifying its effectiveness.

Treatment B (see Figure 10) and Treatment F (see Figure 21) are conducted under identical operational parameters, maintaining a consistent flight altitude of 2.5 meters and a flight speed of 1.5 meters per second. The pivotal difference between these two treatments lies in their chosen application methods, over-row and inter-row application. A comparative analysis of these treatments underscores the distinctive advantage of the inter-row application method, which consistently yields superior canopy coverage when contrasted with the over-row approach. Notably, inter-row application excels in covering the middle and lower regions of the canopy, a particularly valuable attribute when evaluating the effectiveness of drone spraying within vineyards. Furthermore, in Treatment F, it's noteworthy that canopy coverage rates remained almost consistent across various WSP (Wind-Sensitive Pattern) locations. In contrast, Treatment B showed a different pattern, with the upper canopy WSP achieving the highest coverage, while the middle and lower canopy regions obtained notably lower coverage levels. This discrepancy underscores the effectiveness of inter-row applications, especially in uniformly covering the entire canopy.

Similar findings were replicated in Treatment C (see Figure 10) and Treatment G (see Figure 21). This parallel approach reveals a consistent trend where inter-row application consistently outperforms over-row application, notably in achieving greater canopy coverage in the middle and lower canopy sections. However, it's worth noting that in the case of Treatment G, the application process did not uniformly distribute the spray across the main rows. Instead, the UAV application led to significantly higher deposition in Row 3, underscoring the importance of achieving more even distribution in this specific scenario. These results also emphasize that, even under favorable environmental conditions, the influence of wind on spraying delivery cannot be underestimated.

Evidence of higher canopy coverage rates achieved through inter-row applications over over-row applications was also apparent when comparing Treatment D (see Figure 10) and Treatment H (see Figure 21). Notably, these treatments exhibited lower performance levels within their respective application methods. This observation aligns with the previously discussed understanding that, in this study, the operational parameters of a 2-meter flight height and a 1.5-meter-per-second flight speed were less effective. Remarkably, Treatment D and Treatment H were the only ones that shared both of these suboptimal operational parameters. Yet, even in this scenario, inter-row applications consistently outperformed over-row applications in terms of achieving higher canopy coverage rates. It's important to recognize that the influence of wind cannot be overlooked in this context. For the inter-row applications, Row 3 yielded significantly higher coverage rates than Row 2, indicating the impact of wind even in the inter-row application method.

Ground Applications

Ground WSPs play a pivotal role in assessing the effectiveness of spraying operations. Within this context, Figure 23 provides important insights. It notably highlights that over-row applications consistently achieved higher ground coverage rates when compared to inter-row applications. This observation complements the earlier discussion emphasizing the association of inter-row applications with enhanced canopy coverage. Furthermore, the disparity in ground coverage between over-row and inter-row applications offers a compelling explanation for the lower canopy coverage achieved by over-row methods.

Over-row applications consistently exhibited lower canopy coverage compared to the mean coverage achieved with inter-row applications. However, in the case of the ground wood plate, it is observed that a larger portion of the over-row applications reached the ground rather than the canopy. This observation underscores a critical factor in UAV spraying experiments, the drone size itself. Size of the drone was one of the most important parameters obtaining the results of this study. Due to the relatively large size of the UAV, which is nearly as wide as the vineyard canopy trellis, and also based on the Agras t16 nozzle positioning, when flying over-rows, nozzles were positioned over the ground layer instead of vineyard canopy, which resulted in higher ground coverage with the over-row applications. In the context of inter-row applications, the UAV's size enabled the nozzles to align closely with the canopy trellis as the drone maneuvered between the rows. This alignment proved advantageous, leading to a notable increase in the canopy coverage rate and achieving a higher coverage percentage. However, in this scenario, the ground WSPs received significantly less spray, as clearly depicted in Figure 23.

Challenges

In the course of this study, it must be acknowledged that challenges were encountered in achieving homogeneity of variances within the dataset. This non-homogeneity is a notable limitation of the analysis and merits open discussion. The presence of non-homogeneous variances, as observed in the dataset, can potentially impact the results of the statistical analysis, particularly in the context of ANOVA tests. It should be noted that this non-homogeneity can render the detection of statistically significant differences among the groups under investigation more challenging. This limitation may have implications for the interpretation of the findings. Specifically, it could have made the identification of statistically significant effects within the data more difficult. Additionally, the precision of the estimates may have been influenced, resulting in wider confidence intervals and potential impacts on the overall reliability of the conclusions.

It must be crucially emphasized that, despite the presence of this limitation, valuable insights have still been provided by the study, trends have been identified, and meaningful patterns within the data have been highlighted. These findings can guide further research and practical decision-making in the field of interest. While statistical significance may not have been achieved by our results in some instances, a foundation for future investigations and a broader understanding of the subject matter are offered.

It is essential to caution against the overinterpretation of non-significant results. As noted, the absence of statistical significance in certain cases does not necessarily imply the absence of a real effect. It signifies that, based on the data collected and the statistical methods employed, the establishment of statistical significance was not possible. Future research should explore these aspects more comprehensively to unveil potential effects that may have been masked by the limitations encountered.

6. CONCLUSIONS

In summary, this research has effectively achieved the predefined research objectives. This research underscores the importance of tailoring operational parameters for UAV spraying to suit different crop types, thus optimizing the effectiveness of canopy coverage and deposition. The study's findings reveal that inter-row application methods have demonstrated superior canopy coverage compared to over-row techniques. This outcome can be attributed to the inter-row applications' ability to penetrate the canopy more effectively, resulting in higher deposition within the middle and lower canopy regions when compared to over-row applications. While over-row applications effectively cover the upper canopy layers, they struggle to reach the lower sections.

Furthermore, the experiments revealed that a flight altitude of 2.5 meters outperformed the 2-meter flight altitude, exhibiting better coverage in adjacent rows. Additionally, a flight speed of 1 m/s proved to be more efficient than 1.5 meters per second. Notably, Treatment A for over-row applications and Treatment E for inter-row applications yielded the most promising results. This correlation can be attributed to both treatments sharing similar operational parameters, with a flight altitude of 2.5 meters and a flight speed of 1 m/s.

Significant implications arise from these findings regarding the potential integration of UAVs into agricultural practices, with a specific focus on vineyard management. As emphasized by Mangado et al. (2013), to achieve the desired biological efficacy on plants, it is imperative to maintain optimal spray coverage within the range of 20% to 50%. In this context, the results from Treatment E are particularly noteworthy, with canopy coverage reaching 21% and 32% in the main canopy rows of Row 2 and Row 3, respectively. These findings suggest that Treatment E holds promise as an effective treatment for achieving biological efficacy in vineyard management.

In conclusion, this thesis has significantly contributed to our understanding of various operational parameters and their impact on canopy coverage and deposition, paving the way for further research in this field.

7. FUTURE RESEARCH

Future research in the realm of UAV-based spraying in vineyards should build upon the foundation laid by this thesis and explore several critical avenues. Since adequate and homogeneous spray deposition throughout the canopy volume represents, to date, the best strategy to contain both pests and diseases in each type of crop, the UAV spraying performance needs detailed evaluations, and the effects of the UAV operational parameters have to be characterized.

First and foremost, there is a need for continued investigations into the optimization of operational parameters. Further studies should delve deeper into the relationships between flight height, speed, and their combined effects on spray deposition within the vineyard canopy. Furthermore, different types of nozzles and their effects on spraying delivery should be investigated. Different drone types and sizes should be used to test different wingspans and nozzle positioning in row crops. Fine-tuning these parameters to achieve the most efficient and uniform canopy coverage is essential for enhancing the overall effectiveness of UAV spraying in viticulture.

Moreover, there is a pressing need to delve deeper into the integration of real-time monitoring and data analysis tools into UAV systems. By harnessing the potential of artificial intelligence and machine learning algorithms, UAVs can dynamically adapt to the ever-changing conditions within vineyards. This adaptation involves the use of dynamic modeling, which simulates the overall process with precision and flexibility, enabling UAVs to make on-the-fly decisions concerning spray application, optimizing resource utilization, and maximizing the effectiveness of the spray. Research in this field should prioritize the development of intelligent UAV systems capable of seamlessly incorporating dynamic modeling, ultimately enhancing their efficiency and decision-making capabilities.

In conclusion, the future of UAV-based spraying in vineyards holds immense promise, but it also presents numerous challenges and opportunities for further exploration. Future research should focus on optimizing operational parameters, advancing spraying technologies, integrating intelligent systems, promoting sustainability, expanding UAV applications, and fostering interdisciplinary collaboration. By addressing these critical areas, researchers can contribute to the ongoing evolution of vineyard management practices and ensure the industry's long-term success.

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