BRIEF OVERVIEW OF UNMANNED AERIAL VEHICLE (UAV) SPRAY APPLICATIONS: OPPORTUNITIES AND CHALLENGES

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Abstract. The use of Unmanned Aerial Vehicles (UAVs) for pesticide spraying is a promising technology; however, it is a controversial issue in the European Union. Currently, the aerial application of pesticides is generally banned by EU member states according to Article 9.1 of Directive 2009/128/EC on the sustainable use of pesticides, which equates UAVs with traditional aerial vehicles. UAVs sprayers are relatively new, and the associated technologies are in the early stages of development. Therefore, this area is in a state of scientific uncertainty. Fortunately, waivers are being granted for spraying tests that improve application accuracy and increase knowledge of these technologies. This study reviews recent scientific contributions from 2021 to the present, , evaluating the performance of UAVs in relation to key technical parameters (flight height, droplet size, coverage, and drift), and comparing the experimental methodologies used to assess treatment coverage and penetration as well as soil and drift losses. This overview provides a discussion of the performance and effectiveness of this equipment to understand the limitations that hinder its development and provides information to operators who wish to test this equipment to increase scientific evidence on the potential benefits and risks of UAVs use. Experimental results show that, when properly calibrated, UAVs can provide even coverage, significant drift reduction, and less dispersion in the soil than conventional methods, thus helping to ensure sustainable agriculture. However, for this technology to be effectively integrated into European agricultural practices, further field research and standardization of assessment methodologies are needed. Only then will it be possible to fully exploit the potential of UAVs in the European agroecological transition.

Keywords: UAV, spraying test, methodology, sustainability, safety.

Introduction

In recent years, UAVs have gained increasing attention in agriculture, becoming the focus of numerous studies. This is demonstrated by the goals achieved during the studies, which have enabled these devices to be used for multiple activities. From monitoring to sowing, UAVs are now used as a viable alternative to conventional machinery. The reasons for preferring these vehicles are amply documented in scientific articles validating their use and emphasising their potential. Despite considerable developments, the EU is not yet ready to authorise the sprayer use of UAVs due to risks related to safety, health, environmental impact, and data protection [1]. While this hinders technological development, it also fosters research to ensure proper and efficient application. It is necessary to balance the desire to promote their positive potential with preventing the risks of their use.

The EU prohibits UAV spraying under Directive 2009/128/EC, though waivers may be granted if benefits are demonstrated. Spain has set specific requirements, and France, despite banning drones after trials (2018-2021), is reconsidering authorization due to reduced operator exposure and drift [1]. Italy is exploring UAV spraying in its National Action Plan. Internationally, ISO 23117 regulates aerial spraying, with Part 1 (2023) outlining environmental requirements. Part 2 defines methods for assessing spray distribution but does not yet address drift or deposition within crop canopies. Future standards are expected to be developed to cover these aspects of UASS performance.

In this evolving regulatory landscape, research into the opportunities and challenges of UAV spray application is essential to assess its benefits in terms of reducing impacts on human health and the environment. This requires understanding the appropriate flight height, speed, droplet size, and optimal spray volume to maximise effectiveness while minimising associated risks.

The spray distribution of UAV is known to be significantly influenced by the behaviour of the airflow generated by the propellers, known as “downwash effect of UAV” so the performance of the spray depends on performance of UAV. Nozzle arrangement in UAV and application methods of UAV are different from that of the ground vehicle mounted horizontal boom sprayers for field crops. Maximizing the utilization of downwash airflow while preventing lateral air movement beyond the target crop area is a crucial challenge in UAV sprayer applications, especially given the growing consensus on the need for enhanced environmental protection during chemical application processes

[2]. This downward airflow follows a spiral motion and exhibits variations known as “contraction and expansion”, where air accelerates or decelerates in different zones. As the drone approaches the ground, the airflow expands vertically (along the z-axis), covering a larger area. The pressure distribution becomes more uniform, improving the deposition of the sprayed liquid. A phenomenon known as “upwash” occurs due to the ground effect: after hitting the ground, the air is deflected laterally and then rises. This effect can be beneficial, as it enhances the penetration of the solution between leaves, but it can also be detrimental, as it may lift chemical particles and reduce application precision, increasing the risk of drift [3]. For this reason, it is essential to study and optimize these phenomena by adjusting flight and spraying parameters to achieve maximum coverage and efficiency while minimizing waste and environmental impact. This review aims to clarify these aspects by analysing the current challenges and future perspectives of UAV sprayer applications.

Materials and methods

For the study of the state of the art on UAV spraying applications, several documents were identified using the following keywords: “Unmanned aerial vehicle”, “sprayer”, and “agriculture”. For the data range the articles published from 2021 to present were used because it was important to explore the recent activity on the focus of interest. The Boolean operator AND was used to limit the search to drones employed in agricultural spraying. The database used for the search was Scopus. During the initial phase of the search, 100 articles considered relevant to the focus of the study were analysed. Then, in the second phase, to refine the search, studies focusing on the efficacy of pesticides were excluded, as the focus was on the use of drones and associated parameters. It is noted that most of the articles came from Chinese studies, and in the authors’ opinion it is a real trend in international scientific production in this area. Indeed, China is one of the world leaders in UAV research due to more permissive testing regulations, which allow large-scale data collection. However, this does not imply a lag in technological capability by other countries, but rather a difference in research and development strategies.

Many factors may influence the coverage, droplet size, and drift potential of UAV spraying, such as the selection of appropriate meteorological conditions, flight altitude and flight speed. This research aims to investigate the methods used to analyse the effectiveness of UAV sprayers. Specifically, it focuses on determining the optimal flight height and speed. Additionally, it examines the materials used to assess treatment coverage and penetration, as well as ground and drift losses. The following are the results of the research.

Operational parameters

During UAV spraying, many factors influence coverage, droplet size and drift potential. Speed and flight height, nozzle type and droplet size are crucial. A lower flight height reduces drift but can compromise uniformity of coverage. Similarly, the droplet size must be balanced: smaller drops improve canopy penetration but are more susceptible to off-target dispersion, while larger drops minimise drift but can lead to uneven distribution.

The structure and density of the crop also affect droplet deposition. Tall, dense plants hinder the penetration of smaller droplets, while larger droplets tend to fall to the ground. Recent studies have highlighted the need to optimise flight parameters according to plant morphology. For example, a study on coconut palms showed that a spray height of 2 m and a spray time of 8 s ensured a maximum penetration efficiency of 34.41% [4]. However, these parameters are not universally applicable. For small and medium-sized plants, a flight height of 1.5 m, a spray volume of 180 L/hm² and a speed of 2 $m \cdot s^{-1}$ provided optimum results [5]. For cotton crops, a height of 1 m and a speed of 3 $m \cdot s^{-1}$ improved droplet deposition, minimising drift and increasing spray efficiency. In particular, the volume median diameter (VMD) at 1 m and 3 $m \cdot s^{-1}$ was 361 μm, with a numerical median diameter of 392 μm, ensuring a more uniform distribution [6].

Application volumes and flight patterns also affect spraying performance. In an apple orchard with small, sparse trees, the drone downwash airflow promoted good spray penetration. However, in tall, closely spaced trees the effectiveness was lower. To improve coverage, it was observed that flying along the rows and increasing the spray volume to 63.5 L/ha produced better results [7]. Spraying performance therefore depends on factors such as the tree shape, planting layout, UAV payload, application volume, droplet size and the downward airflow range.

Weather conditions, such as the wind speed and temperature, can greatly influence the drift. Since drones are an emerging technology, current guidelines for pesticide use often do not specifically mention them. In a study conducted on Areca catechu fields, deposition quality, drift and ground loss were evaluated. The results showed that at a flight speed of 1.5 $m \cdot s^{-1}$ the droplets penetrated the vegetation better, while the ground loss was greater. At a speed of 2.5 $m \cdot s^{-1}$, the drift increased to double that measured at 1.5 $m \cdot s^{-1}$, demonstrating the importance of adjusting the flight speed [8].

The choice of the nozzle also affects spraying performance. In a study conducted at an altitude of 3 m and a speed of 2 $m \cdot s^{-1}$, air induction nozzles improved crop coverage by 130% compared to flat fan nozzles. The lower drift of the air induction nozzles increased droplet coverage, although the difference in penetration ratios was not significant. Furthermore, there were no significant differences in crop yield or pest control effectiveness. However, given the reduction in drift, air induction nozzles are recommended for aerial control [9].

Drift and soil contamination remain critical issues in aerial pesticide applications. Due to their small size and manoeuvrability, drones can reduce inadvertent drift compared to conventional aerial spraying. The downwash airflow and limited spray flap width can mitigate drift in hedge crops. In high-density olive fields, UAVs showed a substantial reduction in aerial drift, while soil depositions did not differ significantly from those of a conventional sprayer. However, deposition on crops was lower, suggesting that UAV technology can reduce environmental impact in specific scenarios [10]. Environmental conditions, such as wind and thermal inversion, influence drift patterns, but studies suggest that the use of improved adjuvants and nozzles can mitigate these effects. For example, experiments on rice fields showed that adding adjuvants to UAV sprayers improved droplet deposition and insect control even with a 30% reduced pesticide dosage [11]. Similar results were obtained in Nanguo pear orchards, where adjuvants increased the droplet size (Dv50 by 469 μm), improving spray technology [12].

Methodology for analysing spray deposition

In the scientific community, various techniques are employed to analyse spray deposition, which can be categorized into intrusive and non-intrusive methods. Droplet collectors, including natural and artificial collectors, Water Sensitive Papers (WSP), and polyethylene collectors, are commonly used. Additionally, researchers utilize fluorometric analysis, spectrophotometry, image analysis, and laser-based techniques to evaluate deposition patterns and efficiency. Intrusive methods include the liquid immersion technique and the use of WSP, while non-intrusive approaches encompass laser-based systems – such as laser diffraction and phase Doppler particle analysis – along with high-speed imaging techniques like shadowgraphy.

Most studies have evaluated spray deposition and penetration using WSP, tracer dyes and fluorescent agents. Typically, WSP samples are placed at different canopy levels (top, middle, bottom) to assess the droplet size, deposition rate, droplet density and coverage in both target and non-target areas using software such as DepositScan [8; 13]. Similar approaches were used to assess droplet distribution in cotton canopy where droplet deposition obtained from water-sensitive papers (WSP) clipped onto cotton leaves was considered as an observational metric. The canopy was divided into three layers and further segmented into eight directions to analyse the deposition from different angles [14]. The software DepositScan is a leading programme for determining deposition, number of droplets in unit area, coverage, droplet diameters and volumetric diameters (Dv10,50,90) [4; 7; 8; 12; 15-19]. It is used for scanning both PWS and petri dishes used in the liquid immersion method, which are also useful for measuring droplet size by providing an alternative method for evaluating spray characteristics. To assess drift, additional collectors are placed under selected trees and at several downwind distances, forming three collection strips perpendicular to the flight path of UAV for detailed drift analysis [16-19].

Effectiveness and challenges of UAV spraying

Several studies indicate that UAVs can achieve comparable or superior coverage than conventional sprayers. In high-density olive groves in Greece, UAVs required up to 45 times less pesticides and six times less operating time than ground-based systems. These findings highlight drones' potential to improve efficiency and precision in agrochemical applications [20]. Another comparison between the knapsack sprayer and UAV sprayer showed that the droplets produced by the drone were significantly smaller (200.34 to 253.01 μm) than those produced by the knapsack sprayer (463.88 to 738.80 μm). The greatest reduction in *Bemisia tabaci* incidence observed three days after UAV spraying (36.84% and 42.72%), outperforming the conventional sprayer (28.71% and 29.70%). The UAV proved more effective in producing smaller droplets, increasing droplet density per unit area, and controlling *B. tabaci* in green bean crops [21]. Additionally, the rotor-generated downwash airflow enhances pesticide distribution, improving droplet deposition across all leaf layers, including the lower ones [13].

Despite positive results, including minimal off-target deposition [15], some critical issues remain. Studies on cotton canopies showed uneven droplet distribution, with higher deposition in the upper layers than in the middle and lower ones. Centrally located plants also received more droplets than peripheral ones [14]. A similar pattern was observed in apple orchards, underscoring the need for improved spray performance in lower canopy layers. Insufficient underside coverage remains a key limitation of UAV spraying in orchards, particularly given the small droplet size (<200 μm) [7].

Concerns also arise regarding pesticide residues, which were 2.44 to 20 times higher with UAVs compared to knapsack sprayers. Although UAVs produced finer droplets and higher droplet density, their distribution was less uniform. While pest control effectiveness was similar between UAVs and knapsack sprayers, reduced pesticide dosages led to lower efficacy, raising concerns about UAV use in tea cultivation [22]. Furthermore, UAVs reduced droplet losses to the ground but increased spray drift, reaching distances 3 meters farther than conventional sprayers [23]. Contrary to expectations, droplet deposition does not increase exponentially with canopy volume. More droplets accumulate in the upper foliage, while lower layers receive significantly fewer. Droplet size plays a crucial role, with fine droplets achieving 2.5 times better coverage at the canopy base compared to coarse droplets [24]. Finally, UAV use presents a higher risk of operator exposure, particularly affecting the legs and chest. Contrary to expectations, as canopy volume increases, droplet deposition does not show exponential growth. More drops are deposited in the upper part of the foliage than in the lower part. The change in the droplet size significantly influences droplet deposition and distribution within the canopy. In particular, the coverage effect of fine drops at the base of the canopy is 2.5 times greater than that of coarse drops [24]. Of concern was the finding of a higher risk of exposure with the use of UAV. The parts of the body that present a high risk of exposure for operators are legs and chest.

Results and discussion

Recent developments in aerial spraying with UAVs offer new and unique application possibilities [16]. However, comparative studies on spraying systems remain very limited, as do investigations into optimal requirements based on environmental conditions, soil slope, crop density and specific crop characteristics. The lack of solid scientific evidence and the presence of controversial results contribute to regulatory uncertainty. Widespread adoption of these technologies in Europe is unlikely without first ensuring their reliability. To use them correctly, it is crucial to adapt operational strategies to different scenarios and crop types. In specific situations, unique requirements must be established regarding nozzle atomisation, flight parameters, adjuvants and UAV types [2]. This technology is still developing and requires further improvements to compete with traditional spraying methods. Economically, UAV adoption involves high initial costs for equipment, but long-term benefits could include reduced pesticide use, increased efficiency, and lower labour dependency, especially in steep or hard-to-reach areas. Assessing economic viability on a case-by-case basis is essential. From an environmental perspective, UAVs can minimize soil compaction compared to conventional tractors, reducing erosion and preserving soil structure. Enhanced spray precision may also limit overspray and groundwater contamination. However, technical challenges persist, including limited battery autonomy, stability in windy conditions, and the need for advanced systems to optimize pesticide application. Another critical aspect is the limited payload capacity of UAVs, which requires frequent refilling at designated points.

With careful evaluation, these critical aspects can be addressed. The key factors influencing liquid deposition on plants include droplet size, flight height, and speed. The latter influences downwash dynamics, as UAV propellers alter the dispersion of sprayed liquid. Determining the ideal flight height and speed for each crop enhances uniform canopy coverage by leveraging the downwash effect. Droplet size can be adjusted by nozzle selection, with air induction nozzles proving effective but requiring higher pressures, which demand more powerful, heavier pumps – potentially limiting for some UAVs. A possible solution for uniform canopy coverage is to integrate multiple devices to optimize pesticide distribution [25]. One study found that conventional tracked sprayers concentrated deposition in the middle and lower canopy (61.1%), whereas UAVs focused more on the upper canopy (43%). While total canopy deposition was higher with the sprayer (48.6%), its ability to reach the upper canopy was limited (17%). Consequently, tracked mist sprayers are more suited for lower and middle canopy pest control due to their high droplet density, particularly beneficial for fungicide applications, whereas UAVs are more effective for upper canopy treatments against external pests like thrips.

A more sustainable future with UAVs is achievable, but further improvements are needed to address existing challenges. The ISO 23117 standard and the scientific literature on spray distribution assessment methods provide valuable support for advancing research in this area.

Conclusions

UAV spraying represents a great opportunity for the agricultural sector, because it can offer advantages such as increased efficiency, reduced chemical use, and increased accessibility in all soil types. Some studies analyzed indicate that, if well calibrated in terms of flight height and speed, they can achieve more than 70% leaf coverage while ensuring even penetration in the lower levels of the canopy. However, efficacy is strongly influenced by weather conditions and droplet size: for example, droplets with a diameter of < 200 µm showed increased drift. Despite these promising results, large-scale adoption still requires overcoming regulatory and scientific issues. Knowledge gaps need to be filled through more extensive comparative studies that include different crop types, topographies and climatic conditions. Establishing standardized protocols and acceptable threshold limits of drift will be crucial to ensure safe and effective use of UAVs. With appropriate technological developments, UAV spraying could become part of sustainable agriculture, balancing productivity and environmental responsibility.

Author contributions

Conceptualization, A.F.; methodology, A.F.; investigation, A.F., S.P., F.P. and T.Q.; writing – original draft preparation, A.F.; writing – review and editing, A.F. and S.P..; visualization, S.P; project administration, A.F.; All authors have read and agreed to the published version of the manuscript.

References

[1] Lattanzi P., Mariani S. The aerial application of pesticides by drones: challenges and regulatory issues. Proceedings of the 14th European conference on precision agriculture – Unleashing the potential of precision agriculture, July 2-6, 2023, Bologna, Italy. Book of abstracts; pp. 27-28.

[2] Zhang R., Hewitt A.J., Chen L., Li L., Tang Q. Challenges and opportunities of unmanned aerial vehicles as a new tool for crop pest control. Pest Management Science, vol. 79(11), 2023, pp. 4123-4131.

[3] Guo Q., Zhu Y., Tang Y., Hou C., He Y., Zhuang J., Zheng Y., Luo S. CFD simulation and experimental verification of the spatial and temporal distributions of the downwash airflow of a quad-rotor agricultural UAV in hover. Computers and Electronics in Agriculture, vol. 172, 2020, Article 105323.

[4] Pandiselvam R., Daliyamol S., Imran S., Hegde V., Sujithra M., Prathibha P.S., Prathibha V.H., Hebbar K.B. Evaluation of unmanned aerial vehicle for effective spraying application in coconut plantations. Heliyon, vol. 10(19), 2024, Article e38569.

[5] Gao J., Bo P., Lan Y., Sun L., Liu H., Li X., Wang G., Wang H. Study on droplet deposition characteristics and application of small and medium crown garden plants sprayed by UAV sprayer. Frontiers in Plant Science, vol. 15, 2024, Article 1343793.

[6] Rajesh P., Mohankumar A.P., Kavitha R., Suthakar B., Ganesan K. Optimizing the impact of spray characteristics of hybrid drone on spray deposition in cotton crops. Philippine Agricultural Scientist, vol. 106(1), 2023, pp. 39-46.

[7] Wang C., Liu Y., Zhang Z., Han L., Li Y., Zhang H., Wongsuk S., Li Y., Wu X., He X. Spray performance evaluation of a six-rotor unmanned aerial vehicle sprayer for pesticide application using an orchard operation mode in apple orchards. Pest Management Science, vol. 78(6), 2022, pp. 2449-2466.

[8] Wang J., Ma C., Chen P., Yao W., Yan Y., Zeng T., Chen S., Lan Y. Evaluation of aerial spraying application of multi-rotor unmanned aerial vehicle for Areca catechu protection. Frontiers in Plant Science, 2023, Article 1093912.

[9] Yu S.-H., Kang Y., Lee C.-G. Comparison of the spray effects of air induction nozzles and flat fan nozzles installed on agricultural drones. Applied Sciences (Switzerland), vol. 13(20), 2023, Article 11552.

[10] Sánchez-Fernández L., Barrera-Báez M., Martínez-Guanter J., Pérez-Ruiz M. Reducing environmental exposure to PPPs in super-high density olive orchards using UAV sprayers. Frontiers in Plant Science, vol. 14, 2023, Article 1272372.

[11] Wang X., Zhang Y., Hu H., Liu B., Wang F., Zhang Y., Wang W., Li X., Xu W. Evaluation of the droplet deposition and control effect of a special adjuvant for unmanned aerial vehicle (UAV) sprayers. Journal of Pesticide Science, vol. 48(3), 2023, pp. 78-85.

[12] Guo S., Yao W., Xu T., Ma H., Sun M., Chen C., Lan Y. Assessing the application of spot spray in Nanguo pear orchards: Effect of nozzle type, spray volume rate, and adjuvant. Pest Management Science, vol. 78(8), 2022, pp. 3564-3575.

[13] Dengeru Y., Ramasamy K., Allimuthu S., Balakrishnan S., Kumar A.P.M., Kannan B., Karuppasami K.M. Study on spray deposition and drift characteristics of UAV agricultural sprayer for application of insecticide in redgram crop (Cajanus cajan L. Millsp.). Smart Agricultural Technology, vol. 2, 2022, Article 100047.

[14] Meng Y., Ma Y., Wang Z., Hu H. Droplet distribution in cotton canopy using single-rotor and four-rotor unmanned aerial vehicles. PeerJ, vol. 10, 2022, Article e13572.

[15] Ahmad F., Baijing Q., Xiaoya D., Jing M., Xin H., Ahmed S., Chandio F.A. Effect of operational parameters of UAV sprayer on spray deposition pattern in target and off-target zones during outer field weed control application. Journal of Chinese Agricultural Mechanization, vol. 42(8), 2021, pp. 74-82.

[16] Shan C., Xue C., Zhang L., Song C., Kaousar R., Wang G. Effects of different spray parameters of plant protection UAV on the deposition characteristics of droplets in apple trees. Crop Protection, vol. 184, 2024, Article 106835.

[17] Shan C., Wang G., Wang H., Wu L., Song C., Hussain M., Wang H., Lan Y. Assessing the efficiency of UAV for pesticide application in disease management of peanut crop. Pest Management Science, vol. 80(9), 2024, pp. 4505–4515.

[18] Guo S., Chen C., Du G., Yu F., Yao W., Lan Y. Evaluating the use of unmanned aerial vehicles for spray applications in mountain Nanguo pear orchards. Pest Management Science, vol. 80(7), 2024, pp. 3590–3602.

[19] Yallappa D., Kavitha R., Surendrakumar A., Suthakar B., Mohan Kumar A.P., Kalarani M.K., Kannan B. Effect of downwash airflow distribution of multi-rotor unmanned aerial vehicle on spray droplet deposition characteristics in rice crop. International Journal of Agricultural Sustainability, vol. 21(1), 2023, Article 2247803.

[20] Gertsis A., Karampekos L. Evaluation of spray coverage and other spraying characteristics from ground and aerial sprayers (drones: UAVs) used in a high-density planting olive grove in Greece. In Springer Optimization and Its Applications, Vol. 185, 2021, pp. 255-268.

[21] Parmar R.P., Singh S.K., Singh M., Verma A. On-farm assessment of unmanned aerial vehicle (UAV) based spraying technology in green gram. Indian Journal of Entomology, vol. 84(2), 2022, pp. 286-289.

[22] Chu B., Luo F., Luo Z., Liu Y., Lou Z., Chen H., Cai X. Feasibility evaluation of the application of unmanned aerial vehicle for tea plant protection. Nongye Jixie Xuebao/Transactions of the Chinese Society for Agricultural Machinery, vol. 52(3), 2021, pp. 1-16.

[23] Punyawattoe P., Sutjaritthammajariyangkun W., Thirawut S., Chaiyasing N., Supornsin S., Sampaothong S., Nagura T. Comparison of the physical spray efficacy between unmanned helicopter and motorized knapsack sprayer in Thai paddy field. Asian Journal of Agriculture and Biology, vol. 2021(4), 2021.

[24] Wang J., Lan X., Chen P., Liang Q., Liao J., Ma C. Field evaluation of spray quality and environmental risks of unmanned aerial spray systems in mango orchards. Crop Protection, vol. 182, 2024, Article 106718.

[25] Li Y., He X., Han L., Huang Z., He M. Comparison of droplet deposition performance between caterpillar mist sprayer and six-rotor unmanned aerial vehicle in mango canopy. Journal of Agricultural Engineering, vol. 49(6), 2022, pp. 117-130.