82. Comparative analysis of aerial and ground-based spraying techniques: coverage efficiency in vineyards

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Abstract

This study reports the results of canopy spray coverage in vineyards using an uncrewed aerial spray system (UASS) which was customized for a targeted band application. Two application rates at two vine growth stages were compared. An airblast sprayer was also tested at the same growth stages and used as reference. Results showed that, increasing the UASS application rate, generally resulted in enhanced (+41.7% on average) canopy spray coverages. With respect to the UASS, the airblast sprayer resulted always in higher coverage values (about +70%). Despite this, the UASS achieved higher spray coverages in the uppermost canopy zones. Furthermore, suboptimal spray coverage values for fungal disease protection were obtained for the UASS.

Keywords: aerial application, customised spray system, low-volume, nozzle prototype, UASS

Introduction

In the evolution from Agriculture 2.0 to Agriculture 5.0, innovations are modifying traditional practices, with a particular focus on enhancing efficiency, sustainability, and precision. Uncrewed aerial vehicles (UAVs) have become a cornerstone of this transformation, and recently their role has expanded to include the application of plant protection products (PPPs). UAV spray systems (UASSs) have demonstrated their potential in addressing issues associated with manual spraying and mistblowers. Indeed, UASS are reported to offer notable benefits in reducing operator exposure to PPPs and minimising environmental contamination (Qin *et al.*, 2016; Sarri *et al.*, 2019). UASS applications are widespread in South-East Asia, and they account for a significant portion of agricultural spraying. However, its adoption in Europe is limited by regulatory constraints. Nonetheless, the ongoing efforts of organizations like the Organization for Economic Cooperation and Development (OECD), the technical groups like the European Precision Application Task Force (EUPAF), among others, suggest that a shift toward broader acceptance of UASSs may be imminent. Notably, in European countries outside the EU, such as Switzerland, the use of UASSs for crop protection has already become a well-established practice. Further highlighting this trend, an increasing number of commercial UASS models are being developed to meet the growing demand for advanced agricultural solutions. Typically, UASSs are designed for open field crops (e.g., cereals), where broadcast spray applications are standard practice. This spray application mode foresees adjacent flight paths with overlapping spray swath to achieve uniform spray coverage across the treated area. However, recent attention has shifted toward adapting UASS technology to 3D crops such as grapevines, which are cultivated in rows and feature discontinuous canopy structures that do not uniformly cover the ground surface (Biglia *et al.*, 2022; Sassu *et al.*, 2024). Unlike 2D crops, 3D crops require targeted application techniques that aim to deliver spray efficiently to the canopy while minimising off-target losses, especially to the ground. Unfortunately, UASS optimised for precise 3D crop spraying, targeting only the canopy, are currently lacking. Targeted application—delivering precise amounts of PPPs only when and where needed—must become the focus for future commercial UASSs dedicated to 3D crops. Therefore, precision spraying strategies, such as the band application fly mode that directly targets the vine rows, represent a promising alternative. Biglia *et al.* (2022) demonstrated that in vineyards a one-way band spray application fly mode approach significantly improved canopy deposition while minimizing off-target losses. Building further on this, Biglia *et al.* (2023) presented preliminary results from tests with customised narrow-spray pattern hollow-cone nozzles, aimed at further enhancing spray deposition on the canopy and reducing losses to the ground.

An important consideration in UASS is the determination of optimal spray application rates. Studies, such as Li *et al.* (2020), have shown the importance of testing different application rates to balance spray efficacy and UASS operational efficiency. However, UASS are technically limited by their payload capacity and pump capabilities, restricting the range of achievable application rates. The OECD (2021), reported that UASSs, due to their design and low flow rate capacity, cannot support high application volumes typical of ground-based systems.

Nonetheless, knowledge gaps remain, particularly regarding the optimization of UASS spray application rates for grapevines. This leaves unanswered questions about UASS performance in vineyards, where canopy shape and density vary significantly throughout the growing season. To address this, the PRIN 2022 PNRR 3E-UAVspray project (https://www.3e-uavspray.unito.it/home-page/en-copy-of-home-page) is conducting comprehensive assessments. The consortium has been comparing the spray coverage achieved by a UASS carrying out canopy targeted band application (aerial-based spray application technique) with that reached by a conventional airblast sprayer (ground-based spray application technique) in vineyards.

The present research aims to evaluate the potential of a UASS, equipped with a customised spray system, as a viable alternative to ground-based techniques for vineyard crop protection. Different spray application rates were compared in vineyard to determine their effect on canopy spray coverage. This preliminary research is intended to provide valuable insights to balance efficacy and operational efficiency toward the development of spraying strategies tailored to espalier-trained vineyards.

Materials and methods

Aerial-based application technique characteristics

The aerial-based application technique (hereafter named as UASS) used in this study consisted of a UAV hexacopter DJI Matrice 600 Pro (DJI) equipped with a 3.0 kg (tare weight) customised spray system and a RTK antenna (DJI). The customised spray system was *ad hoc* designed and implemented as part of the 3E-UAVspray project activities. This system featured a 10-litre diamond-shaped polyethylene tank, two nozzle holders, and, for each nozzle, a diaphragm pump (Shenzhen GC Electronics).

To maintain a constant operating pressure of 0.30 MPa, an active pressure regulator was integrated. This system included a pressure transducer that converted pressure values into voltage signals, an Arduino controller to process these signals, and an electronic speed control (ESC) unit. The ESC modulated the pump speed via pulse-width modulation to adjust the pump outlet pressure and ensure it remained constant. Both pumps and electronic parts were powered by the UASS platform batteries. The two nozzle holders were installed on a UASS arm each, spaced 910 mm apart, positioned straight-down, 175 mm below the rotor plane, and 110 mm from the propeller axis (Figure 1).

Vineyard characteristics

Field trials were carried out in Piedmont Region (north of Italy) in a vertical shoot positioning-trained commercial vineyard. The vineyard (*cv.* Ruché) was characterised by a 5000 vines/ha density

Figure 1. The UASS used for experimental purposes. The UASS consisted in the UAV Matrice 600 Pro equipped with a customized spray system.

with a row and plant spacing equal to 2.5 m and 0.8 m, respectively. Two vine growth stages were selected for experimental purposes: BBCH 55 (hereafter named as early growth stage) and BBCH 81 (hereafter named as late growth stage). As previously done by other authors (Biglia *et al.*, 2023), for each vine growth stage, the canopy characterization was conducted using the inclined point quadrat technique. The leaf area index was 0.29 and 1.22 at early and late growth stages.

Spray application techniques settings

According to Biglia *et al.* (2022, 2023), a one-way band canopy targeted spray application was adopted in these trials for the UASS. The flight mode was set using the UgCS software (SPH Engineering) to follow the vine row at 2.70 m above the ground level (about 0.7–1.0 m over the top of the vine row), with the nozzles aligned along the central axis of vine rows. The UASS was equipped with two 30° narrow-spray pattern hollow-cone conventional nozzle (ASJ). These nozzles were modified from their standard 60° design (ASJ), to achieve a nominal flow rate suitable for the target spray pressure (0.30 MPa, based on pump characteristics) while concurrently reducing the spray angle to 30° with the main aim to convey the spray jet as much as possible into the canopy when spraying from their top. To evaluate the effect of the spray application rate on canopy spray coverage, per growth stage, the nozzle size was changed while keeping the flight speed constant at 1.5 m/s. Therefore, an application rate equal to 53 l/ha and 133 l/ha were tested by installing an ISO 015 and ISO 04 nozzle size, respectively. Spray operating pressure was kept at 0.30 MPa through the active pressure regulator above described.

To provide a broad comparison between the customised UASS and a traditional ground-based spray application technique, the Dragone TAV2006 airblast sprayer (Dragone) was used as reference. This sprayer model was equipped with a radial fan and three air spouts per side, each holding two nozzles. Across the growth stages the Dragone TAV2006 was configured based on regional farmer's routine practices. For the early growth stage, three ATR orange nozzles per sprayer side (Albuz) were used, with the sprayer passing through alternate alleys, resulting in an application rate of 143 l/ha. For the late growth stage, four ATR yellow nozzles per sprayer side were selected, with the sprayer passing through every alley, achieving an application rate of 283 l/ha. In both growth stages, the forward speed and the operating pressure were maintained at 7 km/h and 1.00 MPa, respectively.

Canopy spray coverage evaluation

Measurements were carried out at three equally spaced sampling location along the vine row. At each location, canopy spray coverage was measured across four (two depths and two heights above the ground per depth) and nine canopy zones (three depths and three heights above the ground per

depth) for the early and late growth stages, respectively. Similarly to the sampling strategy used in previous studies (Mozzanini *et al.*, 2023a; Salas *et al.*, 2022), at each canopy zone, a water sensitive paper (WSP; 26×76 mm, Syngenta) was directly stapled on the adaxial and abaxial leaf sides.
After spray application the WSPs were left drying before collection. WSPs were then picked up and stapled on a labelled sheet for scanning at 600-dpi resolution with a CanoScan LiDE 300 scanner (Canon) to produce RGB images. Three temporal replicates were, in all cases, carried out. The WSP images were analysed using ImageJ software (https://imagej.net/ij/index.html; version: 1.54g). Canopy spray coverage (%) was then calculated as the ratio between the spray deposits area (area covered by impacts) and the total area analysed on the WSP. Density of impacts (No. impacts/cm^2), calculated as the total number of impacts per WSP surface unit, was also determined.
Throughout the trials, environmental conditions (wind speed and direction, air temperature, and relative humidity) were monitored at 1 Hz sampling rate using the same weather station (Campbell Scientific) detailed in Mozzanini *et al.* (2023b).

Statistical analysis and data processing
Statistical analyses were carried out using IBM SPSS Statistic (Version 29) predictive analytical software for Windows. A two-way ANOVA was used to establish the effects of the tested UASS application rate (53 and 133 l/ha) and vine growth stage (early and late) on the dependent variable canopy spray coverage. Means were compared using a Duncan *post-hoc* test for multiple comparison (p<0.05).
The potential efficiency of the UASS, with respect to the ground-based application technique, was then further analysed. To this extent, the UASS configuration that performed the best across both growth stages was selected. The analysis aimed to classify, with respect to the total WSPs (separately for the UASS and the ground-based technique), the percentage of WSPs over-, effectively-, and under-sprayed. In line with previous studies the covered surface (%) and the density of impacts (No. of impacts cm^{-2}) data were used for the classification (Biglia *et al.*, 2022; Grella *et al.*, 2022). To this extent, WSPs with a spray coverage >30% were classified as over-sprayed. Furthermore, since fungicide treatments optimization is the focus of the 3E-UAVspray project, as done by other authors (Biglia *et al.*, 2022; Grella *et al.*, 2022), the threshold of 70 impacts/cm^2 was used to evaluate the density of impacts for effective fungicide applications that rely on contact-based mechanisms of action. Therefore, spray coverage <30% with density of impacts >70 impacts/cm^2 were classified as effectively-sprayed. On the other side, <30% with density of impacts <70 impacts/cm^2, were classified as under-sprayed.

Results and discussion

Aerial-based application technique spray coverage
Higher coverage was achieved with the 04 nozzle size (i.e., 133 l/ha), reaching 3.79±0.44% and 4.07±0.50% for the early and late growth stages, respectively (Figure 2). In contrast, the 015 nozzle size (i.e., 53 l/ha) allows a mean coverage of 2.75±0.51% in the early stage to be obtained. However, with the increased canopy density in the late stage, the average coverage decreased to 1.80±0.34%. According to the statistical analysis, the vine growth stage was not a significant factor (F(1,459)=0.436; p=0.509). In contrast, the application rate was a significant factor (F(1,459)=10.637; p=1.2E-03) affecting spray coverage; this is in line with literature (Sassu *et al.*, 2024). No significant interaction was observed between the two factors (F(1,459)=1.472; p=0.226). By increasing the spray application rate using the 04 nozzle, the spray coverage increased proportionally up to 27.5% and 55.9% in early and late growth stage, respectively. Therefore, improvements with the 04 nozzle size were generally better than the 015 one.

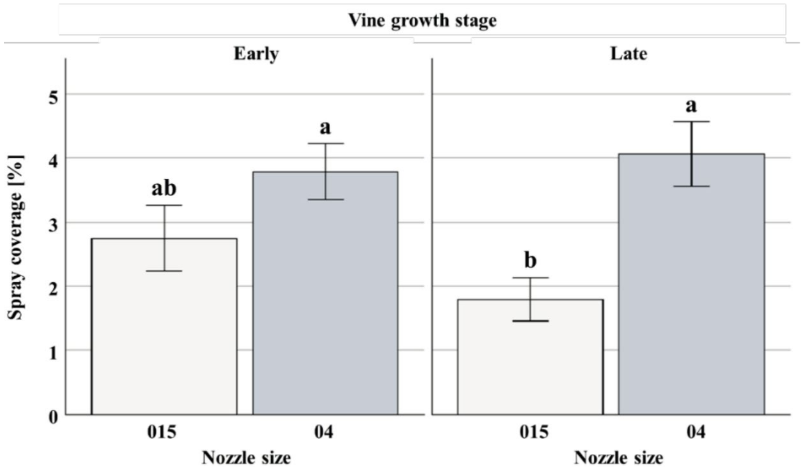

Figure 2. Spray coverage (mean±SE of the mean) achieved by the UASS, per each vine growth stage, while testing the 015 and 04 nozzle sizes. Different letters denote significant difference among the spray coverage achieved ($p<0.05$).

UASS and ground-based application technique comparison

Based on the results of Figure 2, the configuration with the 04 nozzle size was selected for comparison with the ground-based technique. The UASS achieved, even in the best-case scenario, poor spray coverage (below 5%) indicating potential limitation in ensuring biological efficacy. In contrast, the ground-based technique achieved high spray coverage, with values of 25.68±0.44% and 20.19±2.9% at the early and late growth stages, respectively. This outcome, especially the one achieved in the early growth stage where similar application rates were tested (approx. 140 l/ha), highlighted the limits of the UASS. Overall, the ground-based technique obtained substantially higher coverage performance with values, compared to the UASS, higher than 85.25% (early growth stage) and 79.84% (late growth stage).

At the late growth stage, the UASS resulted in higher mean spray coverages in the uppermost canopy area (approx. 60% of the total spray coverages), followed by the medium and bottommost canopy ones (approx. 30% and 10% of the total spray coverages, respectively). In contrast, the ground-based technique achieved a more uniform spray coverage all over the three canopy heights sampled. In this case, values as 44%, 24% and 32% of the total spray coverages were measured in the uppermost, medium and bottommost canopy areas, respectively. The same trend, even if two canopy heights were sampled instead of three, was observed for both application techniques in the early growth stage. These outcomes were perfectly in line with those obtained by other authors while testing similar application techniques and settings (Biglia *et al.*, 2022, 2023; Sassu *et al.*, 2024).

Figure 3 shows the relationship between covered surface (%) and density of impacts (No. of impacts cm^{-2}). It should be noted that measurement made on WSPs (Grella *et al.*, 2022) are unlikely to be standardised. The overlapping or touching of impacts make it impossible to determine weather a mark results from a single or multiple overlapping impacts; thus, any attempt at standardisation would lead to meaningless and uncorrelated values. Despite this, in the early growth stage, similar application rates for the UASS (133 l/ha) and ground-based technique (143 l/ha) were tested. Compared to the ground-based technique, the UASS exhibited over three times (98.6% *vs.* 30%) and six times (94.4% *vs.* 15.7%) as many under-sprayed WSPs during the early and late growth stages, respectively. While no over-sprayed WSPs were observed for the UASS during the early stage, and only 1.2% in the late stage, the ground-based technique resulted in an average of 29.4% of over-sprayed WSPs across both stages. Furthermore, only 1.4% and 3.7% of the UASS WSPs were classified as effectively sprayed during the early and late stages, respectively, compared to 38.6% and 56.9% for the ground-based technique. Similar trends were noted by Biglia *et al.* (2022) while comparing UASS equipped with 60° hollow cone nozzle performing targeted canopy band application and an airblast-sprayer. While increasing the application rate for UASS might improve spray coverage, such an increase is constrained by the payload capacity of UASS. Achieving a higher application rate requires the use of high-capacity pumps, which in turn necessitate larger tanks to avoid frequent UASS refilling. However, the additional weight of these components would exceed the maximum payload limits permitted for UASS, making this solution impractical (OECD, 2021). Therefore, an holistic approach need to be adopted to address this issue. A possible solution is enhancing the efficacy of UASS by integrating agrochemicals with alternative modes of action beyond contact mechanisms, such as those with acropetal or basipetal systemicity.

Conclusions

This study highlighted significant challenges of UASS in achieving effective spray coverage and canopy penetration in vineyard compared to a ground-based technique. While increasing application rate (by increasing nozzle size) improved UASS spray coverage (up to 4.07% coverage at the late growth stage), it remained significantly lower than the ground-based technique (almost 5 times less). Additionally, UASS exhibited uneven spray distribution across the canopy. Payload constraints further limit UASS efficiency, restricting the use of larger tanks and high-capacity pumps to further increase the application rate. To address the UASS canopy coverage challenges, considering the UASS technical limitations, it is suggested to enhance the UASS efficacy by integrating agrochemicals with alternative modes of action beyond contact mechanism. Further step, in the ambit of the 3E-UAVspray project, is to field validate this proposed strategy through biological efficacy trials in 2025 growing season.

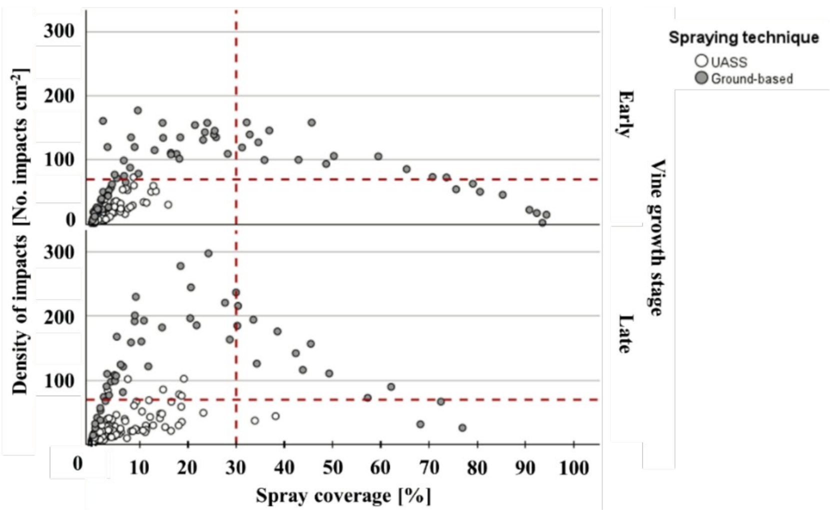

Figure 3. Scatter graph showing relationship between covered surface and the density of impacts for the two spray applications across both growth stages. The horizontal dashed line is the density of impacts threshold for effective fungicide applications (70 impacts/cm^2). The vertical dashed line indicates the spray coverage threshold above which WSPs are considered over-sprayed (30%).

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References

Biglia, A., Grella, M., Bloise, N., Comba, L., Mozzanini, E., Sopegno, A., …, & Gay, P. (2022). UAV-spray application in vineyards: Flight modes and spray system adjustment effects on canopy deposit, coverage, and off-target losses. Science of the Total Environment 845, 157292. https://doi.org/10.1016/j.scitotenv.2022.157292

Biglia, A., Comba, L., Eloi Alcatrao, L., Sopegno, A., Messina, C., Mozzanini, E., Bloise, N., Guglieri, G., & Grella, M. (2023). Comparison between 60° and 30° hollow cone nozzles for targeted UAV-spray applications in vineyards. In J.V. Stafford (Ed.) Proceedings of the 14th European Conference on Precision Agriculture. Wageningen Academic Publishers, Wageningen, pp. 67–73. https://doi.org/10.3920/978-90-8686-947-3

Grella, M., Gioelli, F., Marucco, P., Zwertvaegher, I., Mozzanini, E., Mylonas, Nuyttens, D., & Balsari, P. (2022). Field assessment of a pulse width modulation (PWM) spray system applying different spray volumes: duty cycle and forward speed effects on vines spray coverage. Precision Agriculture, 23, 219–252. https://doi.org/10.1007/s11119-021-09835-6

Li, X., Giles, D.K., Niederholzer, F.J., Andaloro, J.T., Lang, E.B., & Watson, L.J. (2020). Evaluation of an unmanned aerial vehicle as a new method of pesticide application for almond crop protection. Pest Management Science, 77, 527–537. https://doi.org/10.1002/ps.6052

Mozzanini, E., Grella, M., Bondesan, D., Marucco, P., Rizzi, C., Ioriatti, C., Balsari, P., & Gioelli, F. (2023a). Preliminary evaluation of irrigator emitters for pesticides application through solid set canopy delivering system in apple orchard and vineyard. Angers (FR): ISHS Acta Horticulturae, 13778, 227–236. https://doi.org/10.17660/ActaHortic.2023.1378.30

Mozzanini, E., Grella, M., Marucco, P., Balsari, P., & Gioelli, F. (2023b). Characterization of irrigator emitter to be used as solid set canopy delivery system: which is best for which role in the vineyard? Pest Management Science, 79, 584–597. https://onlinelibrary.wiley.com/doi/abs/10.1002/ps.7228

OECD (2021). Report on the state of the knowledge – literature review on unmanned aerial spray systems in agriculture, series on pesticides and biocides, OECD, Paris. Available online at https://doi.org/10.1787/9240f8eb-en

Qin, W.-C., Qiu, B.-J., Xue, X.-Y., Chen, C., Xu, Z.-F., & Zhou, Q.-Q. (2016). Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. Crop Protection, 85, 79–88. https://doi.org/10.1016/j.cropro.2016.03.018

Salas, B., Salcedo, R., Ortega, P., Grella, M., & Gil, E. (2022). Use of ultrasound anemometers to study the influence of air currents generated by a sprayer with an electronic control airflow system on foliar coverage. Effect of droplet size. Computers and Electronics in Agriculture 202, 107381. https://doi.org/10.1016/j.compag.2022.107381

Sarri, D., Martelloni, L., Rimediotti, M., Lisci, R., Lombardo, S., & Vieri, M. (2019). Testing a multi-rotor unmanned aerial vehicle for spray application in high slope terraced vineyard. Journal of Agricultural Engineering 50, 38–47. https://doi.org/10.4081/jae.2019.853

Sassu, A., Psiroukis, V., Bettucci, F., Ghiani, L., Fountas, S., & Gambella, F. (2024). Unmanned aerial system plant protection products spraying performance evaluation on a vineyard. Precision Agriculture, 25, 2082–2112. https://doi.org/10.1007/s11119-024-10155-8