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Aerial Spray Application of Plant Protection Products for Grapevine Downy Mildew Control: Efficacy and Canopy Deposit Evaluation in Semi-Field Trials

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Abstract

A growing interest in aerial drone applications has led to the European regulatory proposal 2022/0196/COD, which considers aerial spraying in steep-slope vineyards safer for human health and the environment. Nevertheless, disease control in perennial crops by aerial applications remains under-investigated. This study aims to identify suitable Plant Protection Products (PPPs) for aerial application in vineyards and analytical methods to quantify PPP deposits. A standardized protocol for controlling grapevine downy mildew was developed, testing Metalaxyl-M and copper-based fungicides' efficacy and foliar depositions. As Italian law prohibits aerial application, an Unmanned Aerial Spray System (UASS) constrained to the ground simulated aerial spray. Leaves were sampled on predetermined days after treatment application for both fungicides' efficacy evaluation and deposit quantification. Metalaxyl-M applied from UASS showed an efficacy comparable to ground sprays at pre- and post-flowering (≈70%), while copper efficacy from UASS was lower (≈47–63%) at each stage. Aerial sprayings resulted in higher deposits in the upper canopy, potentially explaining the lower efficacy of copper fungicides, while Metalaxyl-M's systemicity partially compensated for the uneven vertical distribution, improving disease control. This study established a methodology for aerial PPP testing in vineyards, further studies are needed to confirm these findings across different years and locations.

Keywords: simulated aerial spray; grapevine downy mildew; fungicide efficacy; fungicide deposits

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1. Introduction

One of the primary uses of Unmanned Aerial Vehicles (UAVs) in agriculture is crop monitoring and precision agriculture applications [1,2]. Precision agriculture is based on the principle of exploiting within-field variability and providing variable amounts of input, such as fertilizers, water, or pesticides, based on the real needs, thus adopting a site-specific field management [1–4]. UAVs are typically equipped with cameras to collect information about soil or crop status [1,4,5], and a GNSS system to provide georeferenced data. Information is collected in the form of images, which are then processed through image analysis systems to generate an output (i.e., a prescription map), on which farmers can make decisions [1,2,5]. For instance, different doses of input can be applied in different field sections.

Aerial spraying represents a more limited use of UAVs in agriculture but is a very interesting and promising solution [1,6]. UAVs are specifically defined as Unmanned Aerial Spray Systems (UASSs) when used for aerial applications. Currently, the European Directive on the Sustainable Use of Pesticides 2009/128/EC [7] prohibits aerial spray applications to prevent the dispersal of pesticides in the environment, which increases the risk posed to water basins, ecosystems, and human health. However, in recent years, interest has been rising in UASSs for the application of Plant Protection Products (PPPs), especially in steep-slope vineyards where PPPs are usually applied manually [8] with a high risk for both operators and the environment [8,9]. Indeed, in 2022, a new European regulatory proposal (2022/0196/COD) [10] considered the possibility of adopting UASSs (Art. 21) when aerial spraying represents a lower-risk solution for human health and the environment than a ground spraying system.

Some member states of the European Union already allow aerial spraying in specific circumstances [7]. For instance, in both Germany and France, PPPs can be applied from aircraft in steep-slope vineyards, when no other options are comparable in effectiveness and safety for ecosystems and human health [11,12]. In contrast, in Italy, UASS spraying application remains prohibited [13].

Several studies conducted in perennial plants have demonstrated that aerial applications generally result in a lower canopy coverage and more heterogeneous deposition compared to ground spraying [14–17]. Droplets have been observed to deposit more abundantly in the upper [14,18] and external parts [15] of the canopy. Fungicide applications require good canopy coverage to provide effective disease control [16]; therefore, uneven applications can pose a challenge, especially in vineyards where the bunches are located in the lower section of the canopy. Furthermore, several studies have found that canopy coverage and deposit density are affected by flight speed [18,19], flight height [18,20,21], nozzle type [15,19], and canopy density or shape [20,22]. In addition, most studies that compare aerial and ground spray have been conducted using, as a test liquid, tracers or only water [15,18,19] to evaluate deposit and coverage, rather than PPPs. As a result, most of them lack disease control evaluation, making it difficult to link actual UASS spray deposits and coverage to their effectiveness in controlling pests and diseases.

Poss et al. [23] and Jaquerod and Dubuis [24] conducted trials in steep-slope vineyards, comparing the control of downy and powdery mildew achieved by UASSs and ground sprayers, reporting similar results: in seasons with low disease pressure, UASSs can provide comparable disease control to ground sprayers [24], while in years characterized by high disease pressure, UASSs were found to be less effective, and additional ground spray application in UASS-treated plots might be required to ensure adequate bunch protection [23,24]. Furthermore, fungicides applied through a UASS struggle to reach the bunch zone. Jaquerod and Dubuis [24] reported that the amount of product reaching the bunches is seven times lower compared to ground sprayers. Poss et al. [23] found that

product penetration within dense canopies can be greatly limited. Interestingly, Anken et al. [25] reported a comprehensive study of trials carried out between 2018 and 2020 on the efficacy of UASS spray application to control fungal diseases (i.e., downy mildew and powdery mildew) in Swiss vineyards; in general, UASS fungicide treatments were found to be less effective than those performed with conventional ground spraying equipment.

However, the efficacy of UASS spray application in disease control remains poorly investigated in the scientific literature, particularly in perennial crops. To our knowledge, this is the first Italian study investigating the potential of UASSs, custom-made for canopy-targeted spray application in vineyards [26], in controlling grapevine downy mildew, caused by the oomycete *Plasmopara viticola* (Berk. & M.A. Curtis) Berlese & de Toni, and the first to compare their performance with that of ground sprayers traditionally used in vineyards. In particular, the study aims to (i) identify the most suitable commercial PPPs for aerial application; (ii) select the proper analytical methods to quantify PPP deposits through systematic literature research; (iii) define the methods for PPP efficacy evaluation; and (iv) implement semi-field trials to evaluate the PPPs' efficacy and deposits at three phenological stages of grapevine for both UASS and ground sprayer applications.

2. Materials and Methods

2.1. Selection of PPPs Suitable for Aerial Application

A literature review has been undertaken to establish a list of suitable PPPs for aerial applications. The research aimed to select two different active ingredients, based on previously published papers on this topic, and to cover different viticultural contexts, thus including both products allowed in organic [27] and in Integrated Pest Management (IPM) viticulture. Furthermore, fungicide selection was conducted to choose products characterized by different mobilities within the plant (contact vs. systemic), modes of action (broad-spectrum vs. single site), and chemical compositions (organic or inorganic active substance). These aspects were considered because UASSs are known to provide a lower spray coverage compared to ground sprayers [15]; to operate with low application volumes, thus resulting in a higher product concentration [15]; and to deposit primarily in the upper canopy portions [18].

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow diagram was applied (Figure S1). The research was conducted on SCOPUS, Web of Science, MDPI, and CABI and was based on the following combined query:

"Drone" OR "UAV" OR "aerial application" OR "Helicopter" AND "Vineyard" OR "grapevine" OR "grape" OR "*Vitis Vinifera*" AND "Plant Protection Products" OR "PPPs" OR "Fungicide" AND "downy mildew" OR "*Plasmopara viticola*".

Initially, the results were filtered to exclude duplicates or papers not available in English, Italian, and, eventually, French or German. Further refinement was carried out based on title and abstract, and a final list of articles was obtained by applying the following eligibility criteria: (i) the presence of an aerial spray application test and (ii) data concerning the evaluation of disease incidence or severity, product efficacy, or spray distribution.

Active ingredients, included in the final list of articles, were classified according to three criteria: (i) authorization in the European Union [28], and thus being listed in the European Pesticide Database [29] for their use and approval for the selected pathogen (i.e., *Plasmopara viticola*); (ii) mode of action and chemical class [30]; and (iii) efficacy of the active substance against downy mildew and its mobility within the plant [31]. The research was conducted among PPPs authorized for ground spray, since aerial applications are still prohibited in Italy [13].

2.2. Experimental Design

2.2.1. Study Areas Selection

Field experiments were conducted in two small-plot (about 30 m in length) experimental vineyards, located in the Università Cattolica del Sacro Cuore Campus (Piacenza, Italy) (45°02′9.78″ N, 9°43′36.735″ E) and at the University of Turin in the DiSAFA Campus (Grugliasco, TO, Italy) (45°3′54.6″ N, 7°35′28.9″ E) during the 2024 season. The vineyards were planted with *Vitis vinifera*, cvs 'Merlot' and 'Barbera', respectively, both highly susceptible to downy mildew. The Merlot and Barbera vineyards were 20 and 15 years old, respectively, trained with a spur-pruned cordon and guyot trellis system, with rows oriented north to south.

The vineyards were managed according to common grapevine management practices, except for the application of fungicides to control downy mildew. Temperature and precipitation were recorded every hour by weather stations (iMetos®, Pessl Instruments, Weiz, Austria) located in vineyards.

According to good experimental practice and gathering more consistent results, field trials were conducted in different locations [32,33], using varieties representative of the winegrowing area in which the trials are conducted.

2.2.2. Pesticide Application

Different combinations of fungicides and spray systems were tested to cover several possible real farm situations and strategies. The following treatments were considered: (i) inorganic-based fungicide applied from ground sprayer (Ground-Cu); (ii) inorganic-based fungicide applied from UASS (UASS-Cu); (iii) synthetic fungicide applied from ground sprayer (Ground-Met-M); (iv) synthetic fungicide applied from UASS (UASS-Met-M); and (v) UnTreated Control (UTC) plot. Treatments were applied during three critical phenological phases for the control of grapevine downy mildew, to cover the different conditions of intervention throughout the growing season [34]. The three phenological stages were defined according to the BBCH scale [35] and identified as follows: pre-flowering (BBCH 57), post-flowering (BBCH 67), and bunch-closure (BBCH 77). During the last two phenological stages, leaves from the higher (H) and lower (L) parts of the canopy were sampled separately to evaluate the efficacy and deposits of fungicides in both canopy areas (Figure 1). This distinction aimed to determine whether differences exist between canopy portions depending on the spray system used. UASSs, applying PPP from the top of the vine canopies, are known to provide better coverage in the upper part of the canopy (H, Figure 1) than in the lower part (L, Figure 1) [18]. During pre-flowering, no such distinction was considered, as canopy development was still limited [36]; indeed, growing shoots were still at the height of the second wire (Figure 1).

Irrespective of the spray application technique tested, the application of fungicides was always conducted at label doses.

Ground-based spray applications in the Grugliasco experimental vineyard were carried out using a tractor-mounted Dragone Athos airblast sprayer (Dragone S.r.l., Castagnole Lanze, AT, Italy) equipped with a 300 L polyethylene tank and a conventional mechanically driven axial fan, 700 mm in diameter, with eight blades that sucked air from the rear of a conventional round-shaped air conveyor. Two semi-circular booms held and supplied five nozzles per side at the airflow outlet. Depending on the canopy development at the growth stages and to match the application rates recommended by the Dosaviña decision support system [37], different rates were applied by varying the sprayer settings. As a result, at BBCH 57 and BBCH 67, 264 L ha^{-1} (four Solcera-Albuz®, Evreux Cedex, France, nozzles ATR80 orange in total—two per sprayer side—at 1.2 MPa operating spray pressure and 1.53 m s^{-1} forward speed, creating very fine droplets according to the technical information

provided by manufacturer) was applied, and at BBCH 77, 346 L ha^{-1} (eight Albuz® nozzles ATR80 orange in total—four per sprayer side—at 0.6 MPa operating spray pressure and 1.67 m s^{-1} forward speed) was applied. The ground sprayer was selected because it is representative of the equipment commonly used in vineyards in Italy and, more generally, in southern Europe. This choice reflects the prevailing farmer practice, as also highlighted in a recent scientific report by Azimonti et al. [38].

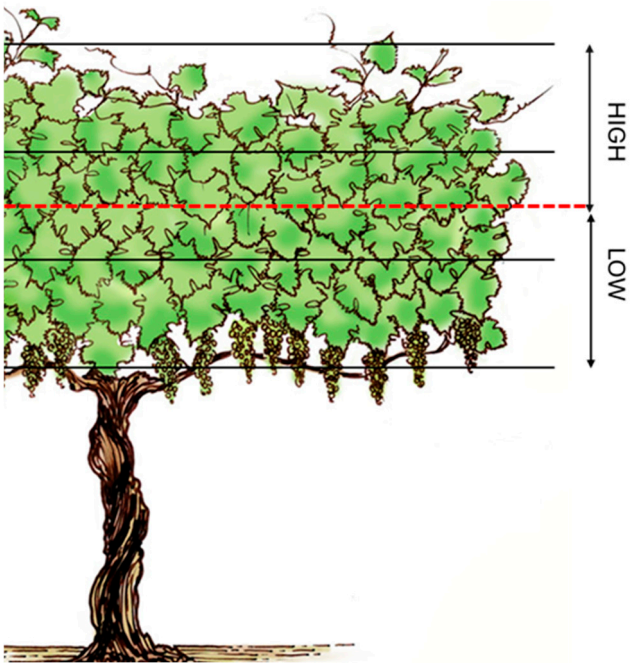


Figure 1. Schematic representation of how sampling was conducted, dividing the low (L) and high (H) canopy portions for the subsequent analysis during post-flowering and bunch-closure. The division (dotted red line) between the L and H canopy was considered to be between the second and third wire from the cordon.

In contrast, the ground-based spray application in the experimental vineyard of Piacenza was carried out using a battery-powered Volpi VITA 16 (Davide e Luigi Volpi S.p.a., Casalromano, MN, Italy). It is a backpack sprayer, manually operated by a walking operator, equipped with a 16 L polyethylene tank and a spray lance fitted with a single brass nozzle with an adjustable spray pattern. The sprayer was operated at 0.5 MPa spray pressure, delivering a flow rate of 1.16 L min^{-1}, with variable walking speed and operator behavior throughout the spray application. The intended spray application rate was 1000 L ha^{-1}, irrespective of canopy development at different growth stages and across the experimental vineyard plots.

This choice was due to the equipment availability in each experimental vineyard; however, both represent standard and authorized sprayers used by winegrowers [25]. Therefore, our results should be considered representative of multiple scenarios.

Concerning aerial application by a UASS, due to current regulatory limitations in Italy [13] and the constraints in obtaining the authorization for research purposes in 2024, a real application was not possible. Therefore, aerial applications were simulated by rigidly fixing the UASS to a metal frame attached to a ground vehicle to allow its advancement along the vineyard row (Figure 2A,B). In practice, the UASS was constrained to the ground, even if the metal frame was ad hoc designed to maintain the UASS suspended above the canopy at a height of 3.2 m from the ground (to maintain the nozzles approximately 0.5–0.7 m above the canopy) during spray application. Nonetheless, the simulation reproduced key flight parameters (UASS flight height, forward speed, and rotor throttle). To

simulate real flight conditions, the rotor speed was adjusted until the thrust measured by the CB C4 200 kg TR load cell (Società Cooperativa Bilanciai Campogalliano, Campogalliano, MO, Italy), placed between the UASS and its support frame, approached zero (Figure 2A). This indicated that the rotors were operating close to the rotational speed they would reach in free hovering, thus reproducing the actual downwash and airflow conditions (Figure 3). This tuning procedure also allowed for adjusting the rotor speed during the trials when necessary to compensate for changes in total weight due to the spray application during trials. In addition, key UASS spray application parameters (nozzle type, spray pressure, forward speed) were considered during the simulation of aerial PPP applications. Indeed, the UASS was equipped with the customized kit spray engineered and developed by DiSAFA and already detailed by Mozzanini et al. [26]. The customized UASS kit spray was equipped with two ISO 02 size 30° hollow cone nozzles (ASJ S.r.l., Centallo, CN, Italy) [26,39–41] operated at 0.3 MPa spray pressure. The nozzles were mounted on separate holders, one on each UASS arm, spaced 910 mm apart, oriented vertically downward, and positioned 175 mm below the horizontal plane of the rotor and 110 mm from the vertical axis of the rotor. A one-way band application mode was selected, as previously suggested and detailed by Biglia et al. [19], to perform a targeted canopy spray application. Briefly, the selected application mode consists of aligning the nozzles along the central axis of the vine row and delivering the liquid following (and moving along) the row orientation. A forward speed of 1.38 m s^{-1} was adjusted through the ground-based platform to which the UASS was affixed. The UASS setting was defined to achieve a spray application rate of 70 L ha^{-1}, irrespective of canopy development at the different growth stages and across the experimental vineyard plots. The application volume for the simulated UASS was defined according to preliminary tests and calibration trials previously conducted [41]. The spray was activated through a remote controller by an operator to exactly match the intended area to be applied, always keeping a safe distance as the UASS approached the plot.

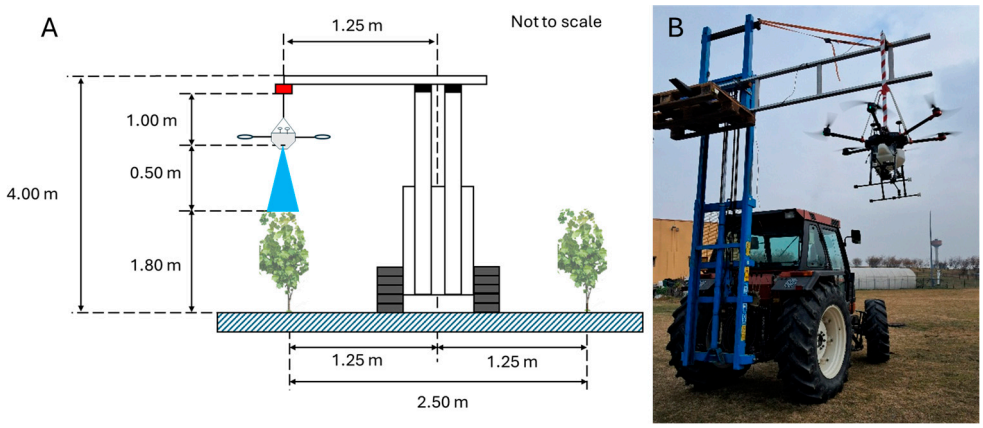


Figure 2. (**A**) The schematic (front view) of the UASS constrained to the ground through a metal frame affixed to a ground vehicle to simulate aerial spray application. The red shape indicates the position of the load cell used to set the rotors' throttle during the PPP aerial application simulation, and the distances between the UASS and the vine canopies were set to simulate PPP application under realistic conditions. The blue triangular shape stands for the two spray jets (patterns), which are not both visible because one is in front of the other, delivered by the nozzles during the one-way band applications adopted. (**B**) Photograph of the UASS constrained to the ground, corresponding to the schematic configuration illustrated in (**A**).

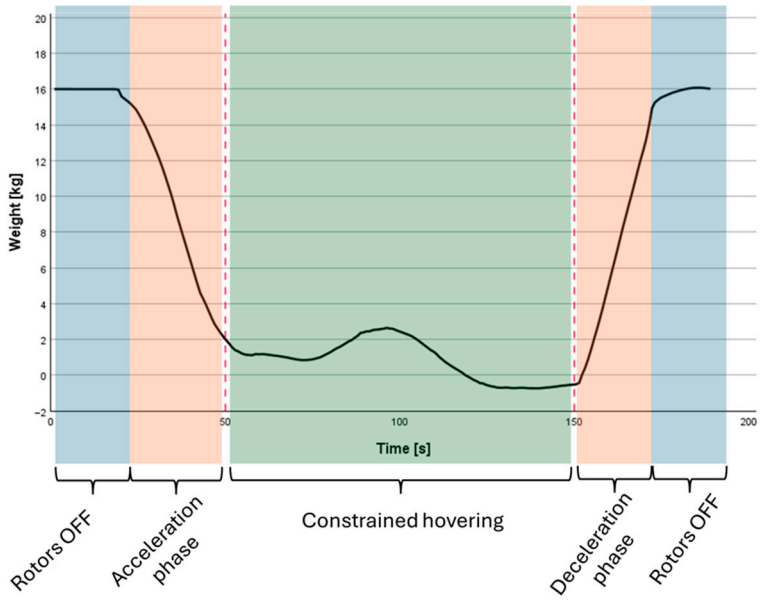


Figure 3. The weight trend recorded by the load cell during the tuning test for rotor speed adjustment. The colored areas indicate the main operating phases: rotors OFF, acceleration, control for constrained hovering, deceleration, and final shutdown. The near-zero-weight region corresponds to the condition in which the rotor thrust replicates the hovering state of the UAV.

2.2.3. Leaf Sample Collection

The vineyards were divided into plots according to the treatment applied, with three replicates per treatment [32]. After applying PPPs, leaf samples were collected from each plot at predetermined days after treatment (DAT) at 1, 3, 5, and 7 DAT, and maintained separately for each treatment. At each DAT, five leaves were collected from each replicate for artificial inoculation with *P. viticola* sporangia, and approximately 20 g of leaves for the determination of product deposit. An example of PPP deposit on leaves is reported in Figure S2. In the pre-flowering stage, leaves were randomly collected from the canopy, while in the following phenological stages (post-flowering and bunch-closure), leaves from the H and L parts of the canopy were sampled separately (Figure 1). In the Piacenza vineyard, the application of PPPs was conducted only at pre-flowering, due to technical problems with the UASS kit spray (pump clogged), which prevented the trials from being repeated during later stages.

2.2.4. Evaluation of PPPs Efficacy

Artificial inoculation followed the method described by Bove and Rossi [42] and Taibi et al. [43]. At each predetermined DAT, the most susceptible leaves to downy mildew, located at the 3rd or 4th position from the shoot apex [44], were collected and placed in Petri dishes previously prepared with two filter papers and a metallic net, and watered with 3 mL of bi-distilled water. Leaves were artificially inoculated with a suspension of *P. viticola* sporangia (5×10^4 sporangia mL^{-1}) on the abaxial leaf page using a manual nebulizer, spraying about 1 mL per leaf.

Sporangia suspension for artificial inoculation was prepared from fresh sporulating lesions from naturally infected leaves. Sporangia were gently collected with a sterile cotton swab and put in distilled sterile water. Sporangia concentration was determined by a hemocytometer (BLAUBRAND Bürker-Türk, BRAND GMBH, Wertheim, Germany) under an optical microscope (40× magnification). Once inoculated, the leaves were incubated in a thermostat at 20 °C, with a 12 h photoperiod, until symptoms appeared in the UnTreated Control (UTC), approximately 7–10 days later.

Downy mildew symptoms were evaluated as incidence and severity (%), as defined by Madden et al. [45]. Severity (%) was assessed using the EPPO reference scales for leaves [46], while disease control was expressed as efficacy (%), calculated as follows [33]:

$$\text{Efficacy}(\%) = \frac{(\text{Severity}(\%)\ \text{UTC} - \text{Severity}(\%)\ \text{Treated})}{\text{Severity}(\%)\ \text{UTC}}$$

2.2.5. Evaluation of PPP Deposits

The analytical methods for quantifying PPP deposits were defined through a comprehensive literature search (Figure S3). The results of this review (Table S2), the selected methods, and their optimization and validation are described in detail in Sections S2 and S3 of the Supplementary Materials.

The deposits of organic and inorganic PPPs in the vine leaves of the Grugliasco vineyard were analyzed for the three selected phenological phases, differentiating between leaves from the H and L parts of the canopy during the last two phenological stages. In the Piacenza vineyard, leaves were analyzed only during pre-flowering.

Validation Method and Analysis of Organic PPPs

The extraction method was based on the AOAC Official Method 2007.01 (QuEChERS), discussed in detail by Lehotay et al. [47], and on the analytical protocol developed by Balkan and Kara [48] specifically for grapevine leaves, with minor modifications, including the addition of filtration and dilution steps to improve chromatographic detection (Figure S4).

Methanol, water, and acetonitrile (HPLC grade) were obtained from Carlo Erba Reagents (Milan, Italy), while formic acid, Supel™ QuE Acetate (AC), and PSA (AC) tubes were purchased from Sigma-Aldrich (Milan, Italy). The pesticide standard was supplied by VWR International (Milan, Italy). A stock standard solution of (100 mg L^{-1}) was prepared in methanol, followed by serial dilutions for calibration.

Vine leaf samples (10 g) were homogenized, spiked (only for recovery), and extracted with 15 mL of acetonitrile containing 1% acetic acid. After homogenization and vortex mixing with the Supel QuE Acetate (AC) tube contents, the samples were centrifuged (10 min, 4500 rpm, 21 °C). The acetonitrile layer (5 mL) was transferred to a Supel™ QuE PSA (AC) tube for further cleanup, followed by vortex mixing and a second centrifugation (same parameters). Extracts were filtered (0.22 µm PTFE membrane) and diluted (1:5) in 70% HPLC-grade water and 30% acetonitrile to reduce color interference in the LC-MS/MS analysis. Moisture content was determined to express concentration on a dry matter basis.

LC-MS/MS analysis was performed with a Vanquish pump and autosampler coupled to a TSQ Fortis triple-quadrupole mass spectrometer (Thermo-Fisher Scientific, San Jose, CA, USA). Separation was achieved on an EC-C18 column (2.1 × 50 mm, 5 µm, Agilent Technologies, Milan, Italy) with a 10 µL injection volume, 20 min runtime, and 0.2 mL min^{-1} flow rate. The mobile phases were 0.2% formic acid in ultra-pure water (A) and 0.2% formic acid in acetonitrile (B), with a gradient from 30% to 90% B over 13 min, followed by equilibration at 45% B until 20 min. The pesticide identification and quantification were based on precursor/product ions from the literature [49], with retention time established via standard solutions (Table S3).

The mean recovery from vine leaves spiked with two standard solutions of 1 mg L^{-1} and 0.1 mg L^{-1} ranged between 96.6% and 124.2% (Table S4). The linearity was evaluated through the coefficient of determination (R^2) of the analytical curves at concentration levels between 0.0001 and 10 mg L^{-1} (Figure S5). The limit of detection (LOD) was equal to 0.025 µg kg^{-1}, and the limit of quantification was 0.075 µg kg^{-1} (Table S5).

Analysis of Inorganic PPPs

The vine leaves were oven-dried at 50 °C for 72 h and weighed. The dried samples were ground into a fine powder in a planetary ball mill (Pulverisette 7, Fritsch, Idar-Oberstein, Germany). For digestion, 500 mg of dried powder was mixed with 5 mL of purified HNO_3 (sub-boiling distillation system subPUR, Milestone, Sorisole, Italy) and 1 mL of H_2O_2 (Carlo Erba, Milan, Italy) in a 50 mL Teflon® tube and placed in a graphite digestion block (DigiPREP MS, SCP Science, Baie-D'Urfé, QC, Canada) at 95 °C for 90 min. After cooling, the final volume was adjusted to 50 mL with ultrapure water (18.2 MΩ cm, ELGA PURELAB flex; VeoliaWater Solutions and Technologies, ON, Canada). The extracts were filtered using a 0.45 µm Teflon filter (DigiFILTER, SCP Science), and the total pesticide concentrations were measured by ICP-OES (ICP-OES 5800; Agilent Technologies) according to EPA 6010D. The validity and accuracy of the digestion process were verified using a Certified Reference Sample of olive leaves—*Olea europaea* (BCR 62), achieving a recovery of 98% for the selected inorganic PPP.

2.3. Data and Statistical Analysis

Statistical analysis of the efficacy and deposits of PPPs was carried out employing the IBM SPSS statistics package (version 27, SPSS Inc., Chicago, IL, USA). The homogeneity of the variance was checked. One-way analysis of variance (ANOVA) was applied to detect significant differences in the efficacy and deposits of the selected PPPs between the different treatments (UASS vs. ground spray vs. UTC). Tukey's post hoc test was applied ($p = 0.05$).

3. Results

3.1. PPP Selection for Aerial Application

The results of the literature review were used to select PPPs suitable for UASS applications targeting *P. viticola*. The search query yielded 261 papers, which were refined to 82 after filtering by language and excluding duplicates and non-pertinent studies. Applying the eligibility criteria, only 3 papers, out of the 82, concerned fungicide application in vineyards. Therefore, the search was then extended to all types of PPPs and crops, resulting in 34 articles (Figure S1) from 1996 to 2023 across eight countries, with China contributing the most (19 publications).

From these articles, 29 active ingredients were identified, but only 16 showed activity against grapevine downy mildew. Table S1 reports only fungicides approved for grapevine in the European Union [28]. The active ingredients included were classified according to their mode of action and chemical group [30], their activity against downy mildew, and their physical mode of action [31]. The most frequently used fungicides were inorganic products, such as copper. Based on the fungicides' characteristics listed in Table S1, Copper (Cu) and Metalaxyl-M (Met-M) active ingredients were selected for field trials.

Active Ingredients

Cu has been selected because it is an inorganic, contact, broad-spectrum fungicide and represents the most widely used product to control downy mildew in both organic and IPM vineyards [31,50]. While Met-M is a synthetic, site-specific fungicide that cannot be applied in organic vineyards, it is among the most widely used in IPM vineyards for the control of downy mildew [31]. The selection of these two active ingredients allowed the comparison of different vineyard management systems (organic vs. IPM) and fungicides with different mobility (contact vs. systemic). Both commercial fungicides, Cu-based, Airone Liquido® (Gowan, Faenza, Italy) and Met-M-based, Flare® Gold R liquido (Syngenta, Milan, Italy), were applied at label dose (2.5 L ha^{-1} and 4.0 L ha^{-1} for Cu-based and Met-M-based fungicides, respectively), using the spray application volume most appropriate for the

phenological stage/canopy development and according to the spray application technique tested (Section 2.2.2).

3.2. Treatment Efficacy

The four treatments (Cu-based fungicide from simulated aerial spray (UASS-Cu); Met-M based fungicide from simulated aerial spray (UASS-Met-M); Cu-based fungicide from ground spray (Ground-Cu); and Met-M based fungicide from ground spray (Ground-Met-M)) were evaluated in terms of fungicide efficacy (%) in the three phenological stages for the control of grapevine downy mildew as an average over the 7 DAT in the two vineyards (Figure 4). Treatment application dates and meteorological conditions during trials are reported in Table 1. During pre-flowering in both vineyards, heavy precipitation occurred, while during the post-flowering and bunch-closure stages, rainfall was more limited (Table 1).

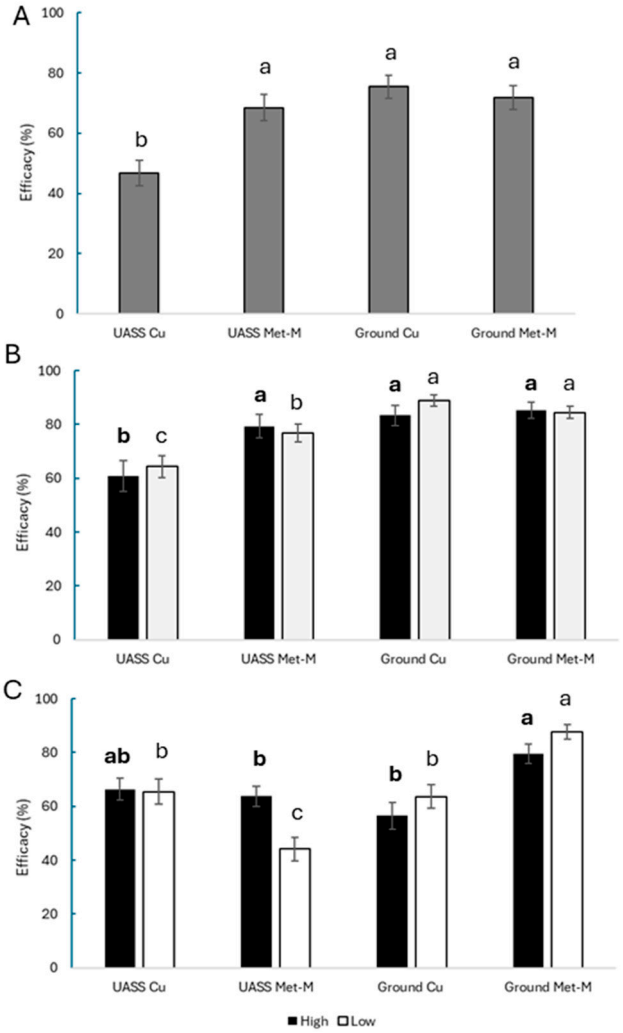


Figure 4. Average efficacy (%) over 7 DAT in the two experimental vineyards in controlling grapevine downy mildew of the four treatments: Cu-based fungicide from simulated aerial spray (UASS-Cu); Met-M-based fungicide from simulated aerial spray (UASS-Met-M); Cu-based fungicide from ground spray (Ground-Cu); and Met-M-based fungicide from ground spray (Ground-Met-M) at pre-flowering (**A**) (BBCH 57), post-flowering (**B**) (BBCH 67), and bunch-closure (**C**) (BBCH 77). During post-flowering (**B**) and bunch-closure (**C**), efficacy was evaluated and analyzed separately for leaves collected in the H (black column) and the L (white column) canopy portions, only in the Grugliasco

vineyard. A technical problem with the UASS kit spray (pump clogged) prevented the trials from being repeated in the Piacenza vineyard. The bars are averages, and the whiskers are standard errors; letters above the bars show a significant difference at $p = 0.05$.

Table 1. Experimental vineyard locations, grapevine phenological stages (BBCH), PPP application date during 2024 season, precipitation amount (mm), and average temperature (°C) recorded by the weather stations during each trial in the 7 DAT.

Vineyard Location	Phenological Stage	PPP Application Date	Cumulative Precipitation (mm) over 7 DAT	Average Daily Temperature (°C) over 7 DAT
Piacenza	BBCH 57	22 May	101.2	18.8
Grugliasco	BBCH 57	21 May	45.6	17.1
Grugliasco	BBCH 67	13 June	11.0	21.4
Grugliasco	BBCH 77	16 July	1.2	27.0

During pre-flowering (Figure 4A), the highest efficacy was achieved by products applied from the ground, between 70% and 75%; however, UASS-Met-M resulted in comparable efficacy (≈68%), whereas the UASS-Cu treatment showed significantly lower efficacy (≈47%). At BBCH 67 and BBCH 77, fungicide efficacy was evaluated separately for leaves from the upper and lower canopy portions. During post-flowering (Figure 4B), in both the H and L canopy portions, ground applications were the most effective, exceeding 80%. The efficacy of UASS-Met-M in the H canopy portion (≈78%) was not significantly different from ground applications. On the other hand, in the L canopy portions, both simulated aerial sprays were significantly less effective than ground sprays, but UASS-Met-M's efficacy remained above 75%. At bunch-closure (Figure 4C), the highest efficacy was achieved by Ground-Met-M treatment, in both the H (≈80%) and L (>85%) canopy portions. The two simulated aerial applications were significantly less effective, ranging between 63% and 67% in the H and between 45% and 60% in the L canopy parts.

3.3. Fungicide Canopy Deposits

The vine leaves were analyzed to evaluate the deposits of Cu and Met-M after conventional ground spraying and simulated aerial spraying with UASS. The UTC was maintained for comparison. The analyses were conducted concurrently with the efficacy assessments at three phenological stages: pre-flowering (BBCH 57), post-flowering (BBCH 67), and bunch-closure (BBCH 77).

During pre-flowering (Figure 5A), Cu deposits were also detected in the untreated control vines in both experimental vineyards, indicating the presence of this active substance from previous treatments. In Piacenza, Cu applied by UASS decreased from 229.6 to 75.9 mg kg^{-1} d.w. between DAT 1 and 3, then increased to 128.5 mg kg^{-1} d.w. at DAT 5. Similarly, in Grugliasco, the UASS application resulted in an initial concentration of 232.3 mg kg^{-1} d.w., which almost doubled at DAT 5. The ground application in Piacenza exhibited a similar trend: a decrease from 249.2 mg kg^{-1} d.w. to 128.5 mg kg^{-1} d.w. (DAT 1 to 3), then a non-significant ($p = 0.476$) slight increase to 132.8 mg kg^{-1} d.w. at DAT 5. In contrast, Ground-Cu in Grugliasco steadily declined from 346.3 mg kg^{-1} d.w. to 227.5 mg kg^{-1} d.w. from DAT 1 to 5.

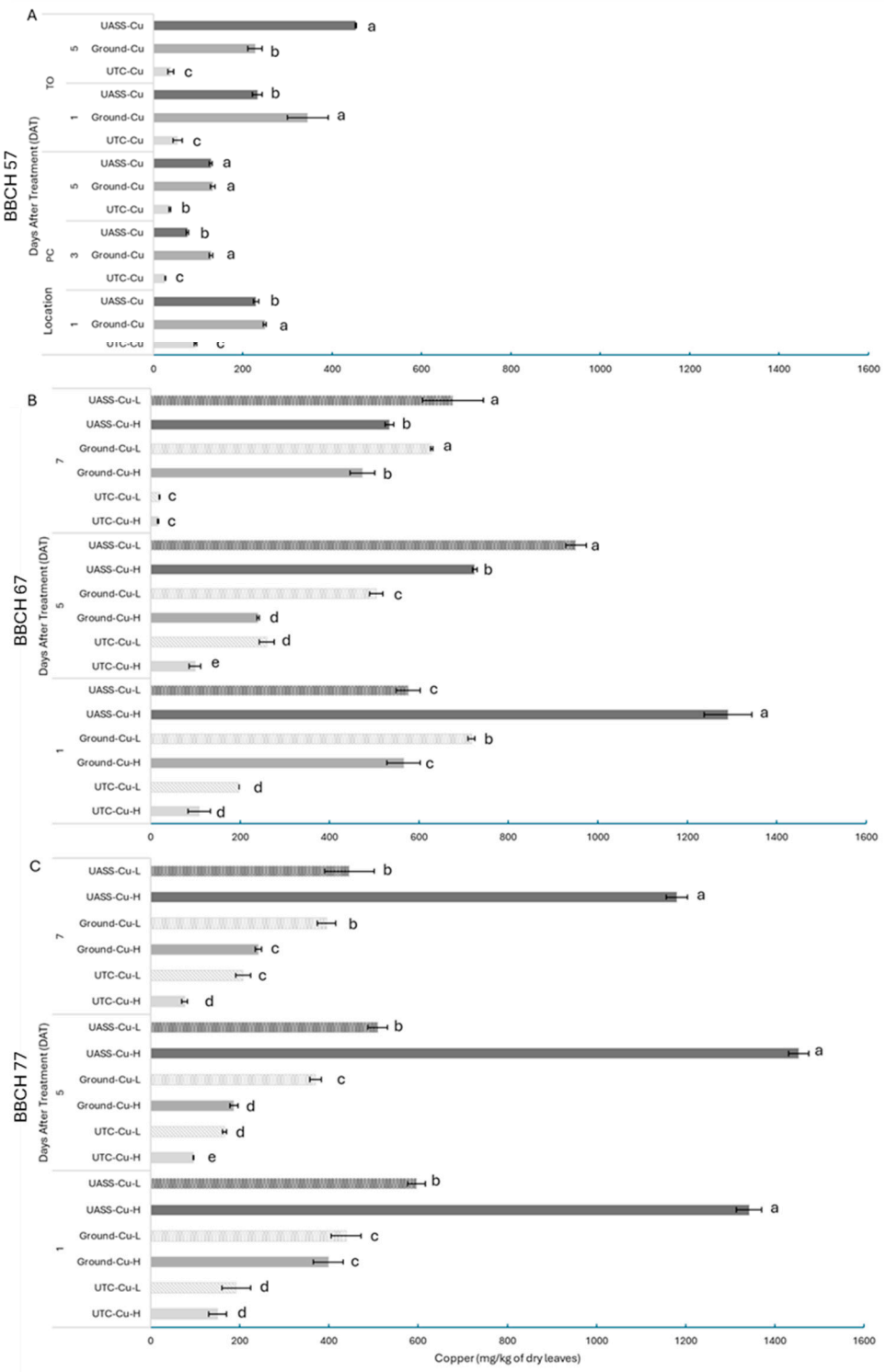


Figure 5. Average Cu concentration (mg kg^{-1} d.w. of dry leaves) over different DAT in the two vineyards (Piacenza (PC) and Grugliasco (TO), Italy) for the untreated control (UTC-Cu) and for the conventional (Ground-Cu) and simulated aerial (UASS-Cu) treatments at pre-flowering (**A**) (BBCH 57, treatments applied on 22 May in PC, and 21 May in TO); post-flowering (**B**) (BBCH 67, treatments applied on 13 June); and bunch-closure (**C**) (BBCH 77, treatments applied on 16 July). During post-flowering (**B**) and bunch-closure (**C**), the concentration was evaluated separately for leaves collected in the high (H) and the low (L) canopy portions only in the Grugliasco vineyard. The bars are averages, and the whiskers are ± standard deviation; letters above the bars show a significant difference between the treatments within each DAT (p = 0.05; Tukey post hoc test).

At post-flowering (Figure 5B), the UASS-Cu-H (higher part of the canopy) resulted in about double the initial concentration of Cu compared to the UASS-Cu-L (lower part of the canopy) (1290.6 mg kg^{-1} d.w. and 576.1 mg kg^{-1} d.w., respectively) on DAT 1, highlighting more direct deposition on the upper foliage. Over the subsequent days, lower canopy deposits increased, while upper canopy concentrations decreased, indicating a redistribution of Cu. The ground application, in contrast, initially showed a higher deposition in the L part of the canopy (717.1 mg kg^{-1} d.w. and 565.6 mg kg^{-1} d.w. in the L and H parts, respectively). By DAT 5, the deposits declined at both canopy heights, followed by an increase at DAT 7, reaching a concentration of 628.5 mg kg^{-1} d.w. and of 474.0 mg kg^{-1} d.w in the H and L canopy portions, respectively.

At bunch-closure (Figure 5C), UASS applications consistently resulted in significantly higher Cu deposits in the H canopy in all sampling data. In contrast, ground treatments—except at DAT 1—showed significantly greater deposition in the L canopy. No statistically significant differences were observed between canopy levels throughout the entire sampling period for ground applications. Similarly to post-flowering, Cu concentration in the L canopy decreased at DAT 5 (from 438.8 mg kg^{-1} d.w. at DAT 1 to 369.9 mg kg^{-1} d.w.), followed by a non-significant increase ($p = 0.513$) at DAT 7 (395.1 mg kg^{-1} d.w.).

During the first Met-M application (Figure 6A), performed at pre-flowering, both the UASS and the ground application methods exhibited a general decline in active substance concentrations over time. UASS treatments resulted in a consistent dissipation pattern: in Piacenza, deposits decreased from 987.7 μg kg^{-1} d.w. (DAT 1) to 93.6 μg kg^{-1} d.w. (DAT 5), and in Grugliasco, from the initial deposition of 1568.0 μg kg^{-1} d.w. to 239.1 μg kg^{-1} d.w. over the same period. In contrast, the ground application demonstrated a more variable pattern, while maintaining a general decreasing trend. In Piacenza, Ground-Met-M decreased from 620.4 μg kg^{-1} d.w. (DAT 1) to 43.3 μg kg^{-1} d.w. (DAT 3), followed by an increase to 84.3 μg kg^{-1} d.w. (DAT 5). In Grugliasco, ground application resulted in higher initial concentrations (3457.8 μg kg^{-1} d.w. on DAT 1), which gradually decreased to 1223.0 μg kg^{-1} d.w. by DAT 5. Divergent deposition patterns were observed between the two application methods: the UASS deposition exceeded the ground application in Piacenza at DAT 1 and 3, whereas the opposite occurred in Grugliasco at DAT 1 and 5.

In the second trial (Figure 6B), the UASS application demonstrated a clear pattern of deposit distribution and reduction over time at both canopy heights. The initial concentration of UASS-Met-M-H in DAT 1 was 5064.9 μg kg^{-1} d.w., decreasing to 909.4 μg kg^{-1} d.w. by DAT 5 and reaching undetectable levels (<LOD) by DAT 7. Similarly, in the L canopy, the deposits decreased from 3766.7 μg kg^{-1} d.w. to 33.9 μg kg^{-1} d.w. over the same period, also becoming undetectable by DAT 7. The ground application showed similar patterns, with initial concentrations of 3849.0 μg kg^{-1} d.w. (Ground-Met-M-H) and 3783.4 μg kg^{-1} d.w. (Ground-Met-M-L) by DAT 1, dropping to 137.4 μg kg^{-1} d.w. and 144.2 μg kg^{-1} d.w., respectively, by DAT 5, and becoming undetectable (<LOD) by DAT 7. The deposits at each of the two canopy heights under the conventional sprayer were not statistically different during the trial period and were comparable to the UASS values in the L canopy.

The third treatment, performed during bunch-closure (Figure 6C), showed a consistent decline of this active substance in leaves. At DAT 1, Ground-Met-M-L resulted in a significantly higher concentration (972.0 μg kg^{-1} d.w.) compared with Ground-Met-M-H (428.3 μg kg^{-1} d.w.), which was not statistically different from the UASS application at either canopy height (890.3 μg kg^{-1} d.w. and 868.0 μg kg^{-1} d.w. in the H and L canopy, respectively). By DAT 5, the only detectable concentrations were observed for Ground-Met-M-L (29.0 μg kg^{-1} d.w.) and in UASS-Met-M-H (105.0 μg kg^{-1} d.w.).

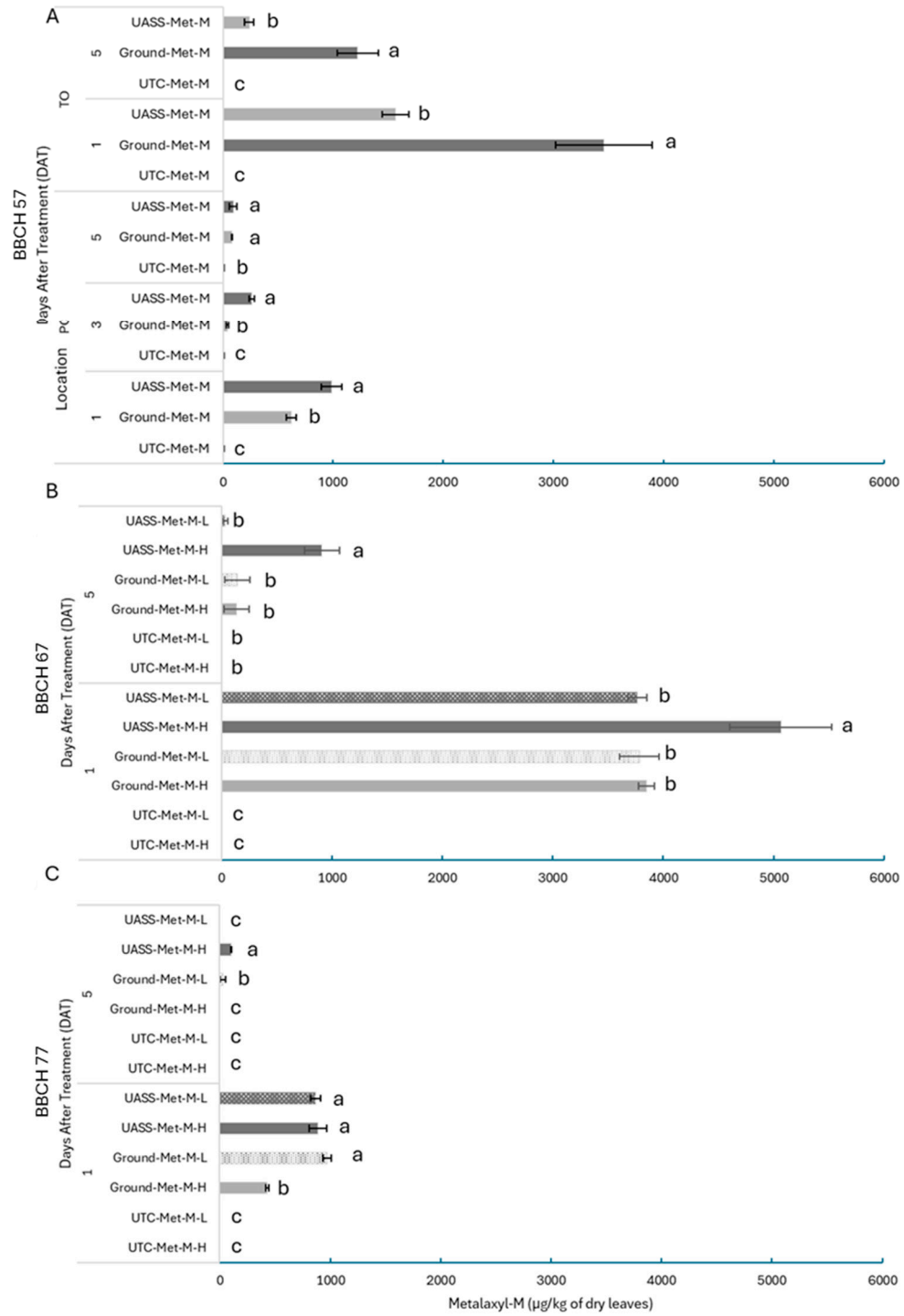


Figure 6. Average Met-M concentration (µg kg^{-1} d.w. of dry leaves) over different DAT in the two vineyards (Piacenza (PC) and Grugliasco (TO), Italy) for the untreated control (UTC-Met-M) and for the conventional (Ground-Met-M) and simulated aerial (UASS-Met-M) applications during at pre-flowering (**A**) (BBCH 57, treatments applied on 22 May in PC, and 21 May in TO); post-flowering (**B**) (BBCH 67, treatments applied on 13 June); and bunch-closure (**C**) (BBCH 77, treatments applied on 16 July). During post-flowering (**B**) and bunch-closure (**C**), the concentration was evaluated separately for leaves collected in the high (H) and low (L) canopy portions only in the Grugliasco vineyard; at DAT 7, concentrations were always <LOD (not reported in the graphs). The bars are averages, and the whiskers are ± standard deviation; letters above the bars show significant difference ($p = 0.05$; Tukey post hoc test).

4. Discussion

4.1. State of the Art

The current literature on UASS-based plant protection is quite limited and variable, with only a few studies testing UASSs spray systems in perennial crops, and even fewer applying commercial products, preferring tracers instead [51] and testing different operational parameters [19,21,52–55]. Most of the articles were from Asia, where aerial pesticide applications represent the main use of drones in agriculture, rather than remote sensing or precision agriculture [14,56,57]. However, most of the studies are about arable crops [58–64], which cannot be compared with orchards or vineyards, due to the completely different canopy architecture, characterized by an expanded and tridimensional shape [14].

4.2. Treatment Efficacy and Deposits

Although our study adopted different ground sprayers, the airblast sprayer and the backpack sprayer were selected as reference technologies because they represent the most commonly used equipment for the application of Plant Protection Products in European vineyards, with airblast sprayers widely adopted in flat and hilly areas and backpack sprayers being the only feasible option in steep-slope "heroic viticulture" contexts [8]. This choice is consistent with current commercial practice and with recent experimental studies, such as Anken et al. [25]. Therefore, our results represent multiple real scenarios. In addition, both ground sprayers applied the same fungicide dose per hectare; therefore, the disease control efficacy should not be affected by the type of ground sprayer adopted.

Based on the results obtained in the early stages of the season, when the grapevine canopy is not fully developed [65], Metalaxyl-M applied by UASS provided efficacy comparable to ground spraying, indicating satisfactory disease control and coverage. These findings are consistent with Viret et al. [66], who highlighted that in the early season, the lower canopy portion is more easily reached due to the reduced vegetation density, facilitating the penetration of the spray by the UASS downwash. Furthermore, the uniform dissipation pattern of Metalaxyl-M deposits observed in both vineyards after the first treatment indicated that the UASS spraying may promote a more controlled and gradual degradation of systemic fungicides. Since Metalaxyl-M is absorbed by plant tissues, it maintains effective control of downy mildew even under limited canopy development [67,68]. However, the reduced efficacy of copper in aerial applications may be attributed to wash-off caused by intense precipitation occurring after the product application. This was especially the case for the pre-flowering stage, where severe rainfall was measured in the Piacenza vineyard (101.2 mm, Table 1), potentially contributing to explaining the redistribution and increased concentration at DAT 5. Meanwhile, at the post-flowering and bunch-closure stages, the rainfall occurred with a lower intensity. Copper showed a higher susceptibility to environmental factors, such as wind and rainfall [69], with wash-off depending on both the intensity and energy of rain [70]. Therefore, adverse weather conditions can redistribute the product, potentially increasing concentrations in the lower canopy while depleting the upper. Furthermore, sampling inconsistencies between canopy heights, particularly in underdeveloped canopies, may have contributed to the apparent variations in deposit distribution.

In the later stages of the season, when the canopy foliage is denser, the UASS sprays struggled to penetrate the foliage from the top canopy to the bunch zone (lower canopy portion) [23], as confirmed by our results. This limitation was not observed with the ground sprayer, which sprays the canopy from the sides, and therefore, the foliage mass to penetrate is lower. In addition, the air volume used by the ground sprayer is much higher, allowing greater penetration. Furthermore, UASS relies only on the downwash generated by the rotors during the advancement, whereas the airblast sprayer is equipped with an

axial fan specifically designed to drive droplets into the canopy, ensuring a homogeneous distribution of PPP [26,71]. As a result, ground-based sprays maintained high efficacy in disease control. Metalaxyl-M applied by aerial spray was highly effective in both canopy heights, while the efficacy of UASS-distributed copper was reduced. As reported by previous studies, aerial applications generally provide lower or less uniform canopy coverage, especially in the lower canopy portions [23,24,66,72]. However, the systemicity of Metalaxyl-M can compensate for reduced canopy coverage, as it is translocated to younger growing tissue [67,68], while copper remains on the leaf surface [50,73]. This can explain the higher efficacy of Metalaxyl-M compared with copper in UASS applications. Indeed, Viret et al. [66] suggested adopting systemic products to ensure better disease control, especially under high disease pressure. Nevertheless, in the late phenological stages, the evaluation of copper efficacy and deposits remains complex, as residual copper detected in untreated control samples suggested cumulative deposition from previous applications, potentially biasing the deposits analysis.

During bunch-closure, Metalaxyl-M applied by ground was the most effective, while both products applied by simulated aerial spray partially lost their effect. The higher persistence of copper on UASS-treated upper leaves did not translate into improved efficacy, suggesting that deposit quantity alone may not guarantee disease control if the distribution is uneven or the penetration into the canopy is limited. This aligns with Poss et al. [23], who indicated significantly higher coverage of the external leaf layer and a limited penetration in the lower and inner canopy layer and the bunch areas, suggesting agronomical interventions, such as leaf removal in the bunch area, to improve the efficacy of UASS by enhancing the penetration into the canopy.

Therefore, the present study agrees with previous studies about the greater efficacy of ground spray compared to UASS [23,24]. However, in some cases, UASS spray reached a comparable or slightly lower efficacy, particularly at the beginning of the season. The adoption of a systemic fungicide appears to partially compensate for the lower canopy coverage of the aerial spraying system. Further studies should also investigate systemic fungicides with basipetal mobility (e.g., phosphonates), to verify whether their redistribution can further compensate for the higher deposit on the upper leaf layers. Furthermore, the relatively low efficacy of copper can be attributed to the very high disease pressure in Northern Italy during the study period, characterized by high humidity and precipitation [74,75]. Under such conditions, grapevine downy mildew is particularly difficult to manage with aerial applications [23,24,66], and the integration of ground spray in the bunch area may be required [23–25]. Another limitation of aerial spraying concerns the rotor downwash created by UASS that may be insufficient to move leaves and reach the lower and internal leaf layers and the abaxial leaf surface, which is crucial for the control of grapevine downy mildew [76]. Indeed, Schmidt [72] and Viret et al. [66] observed a reduced deposit on the abaxial leaf surface compared to the adaxial surface. Biglia et al. [19] confirmed that with the UASS, the deposit on the abaxial leaf side is at least halved compared to the adaxial leaf side. Systemic fungicides may partly overcome these limitations by redistributing within plant tissues, ensuring disease protection even with suboptimal deposition.

4.3. Limitations and Recommendations

This study presents some limitations. First, aerial application was performed under simulated conditions, as UASS was constrained to the ground due to the impossibility of obtaining legal authorizations for UASS flight, while other studies conducted application from flying aerial sprayers in vineyards [23–25,66]. This is the reason why the trials are defined as "simulated" and, therefore, labeled as "semi-field". Nevertheless, the simulation was carefully designed to reproduce real flight conditions: the downwash effect was

measured, calculated, and calibrated prior to the experiments, ensuring that the airflow and spray dynamics reproduce those of the UASS under real operations. For this reason, the results can be considered reliable and representative of real scenarios. However, full field validation under unconstrained flight conditions is planned to confirm and strengthen these findings over longer-term studies. Second, the trials were conducted in two experimental vineyards; therefore, additional years and locations are required to support the consistency of these findings under different meteorological and disease pressure scenarios. To our knowledge, this is the first Italian study investigating commercial fungicide applications in vineyards. Few studies were conducted in the European context; Viret et al. [66] and Schmidt [72] tested aerial fungicide application from a helicopter rather than a UASS. Poss et al. [23], Jaquerod and Dubuis [24], and Anken et al. [25] conducted trials with a UASS applying commercial fungicides, but disease control was evaluated only based on naturally occurring disease infections. Our study conducted artificial inoculation with *Plasmopara viticola* in three different stages of grapevine growth. This allowed us to be sure of the pathogen presence during each fungicide application, potentially causing disease; indeed, an untreated control was always included. This can reduce the variability of field conditions, where epidemics occur only when environmental conditions are favorable and pathogens are able to cause infection [77]. Furthermore, we investigated the deposit of commercial fungicides on grapevine leaves from both UASS and ground sprayers. Previously published studies quantify only tracers' deposition or analyze different matrices, such as WSP or filter papers [15,18,19]. Indeed, during our study, a protocol for the quantification of fungicide deposits on grapevine leaves was developed. Nevertheless, application by UASSs still represents an interesting solution for steep-slope vineyards, where mechanization is not possible [24], offering time and labor savings [66] or allowing for operation in inaccessible fields [78]. The aerial spray could also be tested for the application of alternative products, such as biocontrol agents or natural enemies, as reported by Ivezić et al. [78] and Resecco et al. [79], highlighting the prompt application permitted by drones.

Currently, the most realistic use scenario for UASS spray systems appears to be the substitution of manual applications in steep-slope vineyards, where operator safety is a key concern. However, UASS use should be combined with periodic field inspections to monitor disease development and, if necessary, intervene with ground treatment in the bunch area, to ensure disease control and grape production. Studies are ongoing to design more advanced UASSs to improve spray application performance, including a specific PPP formulation for UASSs to increase tenacity on leaves, aiming to increase efficacy and persistence [80].

5. Conclusions

These preliminary trials highlighted both the potential and limitations of aerial fungicide applications in vineyards. Metalaxyl-M applied by a UASS achieved a disease control efficacy comparable to that of ground spraying, and it is likely that the product's systemic properties compensate for the lower deposition, especially in the lower canopy portions. In contrast, the copper-based fungicide showed a reduced efficacy when applied by UASS, highlighting the difficulties of achieving sufficient coverage, especially in dense canopies at later growth stages. These findings reveal the importance of carefully selecting suitable Plant Protection Products for aerial applications, as well as developing customized sprayer systems for UASSs. Although the current regulatory framework in Italy (D. Lgs. 150/2012) still prohibits UASS spray applications, our findings may contribute to risk–benefit assessments for future regulatory revision, as envisioned in Regulation 2022/0196/COD. In this perspective, UASSs could represent a valuable option for steep-slope vineyards, where mechanization is unfeasible and operator safety and environmental losses are a

concern. In addition to reducing human exposure, UASS generates less spray drift than airblast sprayers, making them a promising alternative for Italy, as well as in several other countries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15122703/s1, Figure S1: PRISMA flow diagram of papers selection process for UASS-spray application to identify the most suitable active ingredients for grapevine downy mildew control in vineyards; Figure S2: Examples of grapevine leaves sampled for analytical deposit quantification. (A) Leaves collected from UASS-treated plot and (B) leaves from ground sprayer-treated plot. Figure S3: PRISMA flow diagram of papers selection process used for analytical method identification; Figure S4: Schematic representation of the steps for QuEChERS extraction (A) and dispersive-SPE cleanup (B) for both leaf and water sensitive papers (WSPs); Figure S5: Examples of calibration curves produced for the quantification of Metalaxyl-M. Table S1: List of identified relevant active ingredients and their characteristics. The table reports the active ingredient name, the mode of action (MOA) and the chemical group to which they belong based of FRAC [30] classification; the activity against grapevine downy mildew (DM) [31] and the physical mode of action (PhMOA) [31] and the number of selected papers, through PRISMA flow diagram method, in which the active ingredient is mentioned; Table S2: The table lists the active ingredients or tracers used, the extraction methods employed, the analytical methods, the plant materials employed for the extraction (extraction material), the deposit concentrations (mg/kg) and the reference papers from which the information was retrieved; Table S3: Multiple reaction monitoring conditions for Metalaxyl-M employing LC-MS/MS. The table reports the precursor ion, the product ions, the collision energy (V), and the retention time (RT) (min) for Metalaxyl-M; Table S4: Recovery concentrations for method validation for vine leaves. The table reports the concentration (mg/L) of the spiked Metalaxyl-M and the mean concentration recovery (%) ± standard deviation after analysis with LC-MS/MS; Table S5: Limit of detection (LOD) and limit of quantification (LOQ) for fresh vine leaf samples [81–103].

Author Contributions: M.F. contributed to the design of the study plan, the methodology, the sampling, and the efficacy and statistical analysis. She was primarily responsible for drafting, writing, and revising the manuscript. S.T. contributed to the chemical and statistical analysis and drafting, writing, and revising the manuscript. G.M.B., M.C.F. and S.G. were responsible for the sample preparation and the chemical analysis of inorganic PPPs and contributed to the critical review and revision of the manuscript. A.L. and G.A. were responsible for the sample preparation and the chemical analysis of organic PPPs and contributed to the critical review and revision of the manuscript. M.G. contributed to funding acquisition, project administration, supervision, and resources. He conceived the research idea and designed the study plan and methodology, and contributed to the critical review and revision of the manuscript. E.M. contributed to the design of the study plan, the methodology, the sampling, the PPPs spraying techniques, and the revision of the manuscript. E.D. was responsible for UAV Spray application and the review of the manuscript. L.L., M.F.B. and L.N. contributed to sampling, sample preparation, efficacy analysis, and the review of the manuscript. T.C. conceived the research idea and designed the study plan and methodology, and contributed to the critical review and revision of the manuscript. N.A.S. contributed to funding acquisition, project administration, supervision, and resources. She conceived the research idea and designed the study plan and methodology, and contributed to drafting, writing, and revising the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article and Supplementary Materials. Further inquiries can be directed to the corresponding authors.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UAVs	Unmanned Aerial Vehicles
UASS	Unmanned Aerial Spray Systems
PPPs	Plant Protection Products
IPM	Integrated Pest Management
UTC	UnTreated Control plot
H	High (canopy portion)
L	Low (canopy portion)
DAT	Days After Treatment
QuEChERS	quick, easy, cheap, effective, rugged, and safe
HPLC	High-performance liquid chromatography
LC-MS/MS	Liquid Chromatography Tandem Mass Spectrometry
LOD	Limit of detection
Cu	Copper
Met-M	Metalaxyl-M
UASS-Cu	Cu-based fungicide from simulated aerial spray
UASS-Met-M	Met-M-based fungicide from simulated aerial spray
Ground-Cu	Cu-based fungicide from ground spray
Ground-Met-M	Met-M-based fungicide from ground spray
d.w.	Dry weight

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