Comparison between an in-flight UAV refueling platform and ground-based vehicles for plant protection product distribution

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Abstract

Limited payload range generally caused by the poor weight-energy performance, flight autonomy, manual replacement of spent batteries, and agrochemical tank refilling procedure are limiting factors affecting UAVs' agrochemical distribution. This work aims to evaluate the effectiveness of agrochemical distribution by a UAV operated by a reactive robotic payload replacement (M.A.R.S.) platform and compare it with ground-based distribution systems in a viticulture scenario. The work considers a hybrid technology UAV with an onboard gasoline-powered electric generator, characterized by an "in-flight" refill of fuel and agrochemicals without the need for landing. Results report a limited ability of the aerial system to cover large areas with a single tank, balanced by 2.3 minutes to perform a tank refill, significantly less than ground-based distribution systems. The volumes of plant protection products delivered per hectare by the aerial platforms are more suitable for low-volume treatments but they can be logistically advantageous because of their rapid response and lack of impact on soil and crops. The proposed approach represents a solution for UAV implementation for spraying operations on vineyards and opens new scenarios for large areas treatments.

Keywords: spraying UAV, precision viticulture, agrochemicals distribution

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1. Introduction

Agrochemical spraying by tractors is a common method used by farmers to protect their crops from pests and diseases [1]. The process involves using a sprayer attachment mounted on a tractor to distribute agrochemicals over a field. There are several different types of sprayers that can be used, each with their own advantages and disadvantages. Boom sprayers are the most common type and consist of a long boom that is attached to the back of the tractor [2]. The boom has several nozzles that distribute the agrochemical evenly over the field. Boomless sprayers, on the other hand, use a fan to create a fine mist of agrochemical that can reach the entire field [3]. The use of agrochemicals can greatly increase crop yields, but it can also have negative effects on the environment and human health. Agrochemicals can contaminate water sources, harm beneficial insects and wildlife, and even cause health problems for those who come into contact with them [4]. To mitigate these risks, farmers must take precautions when using agrochemicals. This includes using the correct amount of agrochemical, applying it at the right time, and using personal protective equipment such as gloves and masks. Farmers also need to be aware of the specific regulations regarding agrochemical use in their area. In the United States, the Environmental

Protection Agency (EPA) regulates the use of agrochemicals and sets guidelines for their safe application. In other countries, similar regulatory bodies exist to ensure that agrochemicals are used safely and responsibly. Despite the potential negative effects of agrochemical use, it is an important tool for farmers to protect their crops and maintain food security. By following proper guidelines and regulations, farmers can use agrochemicals safely and effectively [5]. Additionally, precision agriculture technologies such as drones, GIS mapping, and variable rate applicators have been developed to help farmers to apply agrochemicals more precisely, reducing the amount of agrochemicals needed and reducing their impact on the environment.

UAVs, high spatial resolution and temporal frequency remote sensing platforms [6], able to cover large areas without impacting and disrupting the ecosystem, have become a crucial tool for agricultural monitoring and biodiversity conservation [7]. Terrestrial plant protection products distribution are time and labor-intensive activities, which expose operators to health risks derived by the toxicity of the chemical substance [8]. Spraying UAV gained much attention in recent years, because of their ability to fly at low altitudes on complex patterns, adapt to heterogeneous terrain, and specifically perform very low-volume and site-specific agrochemicals applications. Droplet size, distribution performance, weather conditions, flight settings, and environmental effects are the key elements to consider when operating with spraying UAVs [9].

Fig. 1. Rendering of UAV equipped with bucket over vine rows

The main problems in using drones for agriculture are their limited autonomy (about a half-hour), and the fact that operator intervention is required to change the spent battery and refill the payload of the liquid to be distributed. In the case of precision agriculture, moreover, if one wants to compare distribution by UAVs with distribution by tractors, the volumes to be distributed can also be significant. For this reason, the use of heat-powered hybrid drones that are capable of carrying higher payloads has been considered. The poor weight/energy efficiency of batteries limits the transport payload since on average for every kg of liquid transported, the drone must spend 50% on components (motors, frame) and 50% on batteries to maintain a fixed flight range of at least 15min. This poor scalability limits the application to ultra low volume contexts (<50lt/ha), while ultra high volume applications, i.e. requiring more than 50lt/ha, require the use of drones with endothermic motors. In addition, automatic battery management and recharging in outdoor industrial settings requires that battery storage and recharging take place in an air-conditioned environment at 20°. In agro cultural settings, in the open field and in the summer treatment season, these constraints are definitely penalizing by requiring additional energy, and expense for the air conditioning system. Let us then assume that we have hybrid drones, i.e., with an on-board electric generator powered by gasoline, and equipped with a tank containing the agrochemicals to be spread on the crops if necessary. Let us further assume that we have a robotic platform capable of (i) sending the drones over the agricultural area to be monitored; (ii) performing in an automated manner and without the need for landing the refilling of the fuel and liquid containing the agrochemicals. We define such a system consisting of the platform and the drones M.A.R.S., acronym for Multiple Airdrone Response System.

The purpose of this work is to evaluate the effectiveness of agrochemical distribution using a UAV managed and supplied (both fuel and the liquid to be distributed on crops) by a robotic platform and compare it to terrestrial distribution systems.

2. Description of the system and scenario for comparison.

To carry out the comparison between airborne (UAV) and ground-based vehicles, we assume that we have a drone management platform that can ensure their operational continuity by refilling the fuel and liquid containing the agrochemical to be distributed on crops. In recent times, UAV docking stations are becoming popular for various applications [10]–[13]. They are mainly based on charging the drone, while more rarely a battery replacement is assumed, so that the drone is immediately available, without the wait for charging time. A limitation of electrically powered drones is the generally limited payload range, due to the poor weight-to-energy performance of the batteries. In this paper, we instead consider UAVs with hybrid technology, i.e., with an on-board electric generator powered by gasoline. We also assume that the refill of fuel and liquid to be sprayed on crops occurs "in flight," without the need for landing. As a refilling mode, was assumed the method described in the patent [14], owned by the company Inspire [15], but the methodology are applicable to other possible types of drone management platforms.

2.1 Description of the scenario for comparison

The following reference scenario was chosen to make the comparison between the distribution by ground vehicles and UAV managed through the M.A.R.S. system. The reference area has the following characteristics: 1 ha surface area; square shape; 100 m side; 100 m row length; 2.5 m inter-row width; number of rows equal to 40 (100 m/2.5 m) and number of inter-rows equal to 40 (100 m/2.5 m). The wall vine training form has a developed and moderately dense canopy (leaf area 4000-15000 m2 /ha).

Table 1: schematization of the characteristics of the reference surface.

Reference surface characteristics	
area (ha)	1
form	square
side (m)	100
row length (m)	100
inter-row width (m)	2.5
no. of rows	40
no. of rows	40
route length (km/ha)	4

2.2 Operational choices for the M.A.R.S. platform

Although the distribution medium is aerial, the system used for distribution is of the hydraulic spraying type, assisted by an aeroconvection system represented by the downward airflow generated by the rotors of the Unmanned Aircraft System (UAS) for transporting the droplets of phytoiatric product to target. To carry out the comparison, operational choices were made for the M.A.R.S. system based on available literature. A forward velocity of 10.8 km/h (3 m/s) was chosen because it appears to be the right compromise between the minimum velocity of 5.4 km/h (1.5 m/s) and 18 km/h (5 m/s) found in most scientific publications analyzed [16]–[21]. An operating pressure between 3 and 5 bar is also assumed, which is optimal for performing treatments at low distributed mixture volumes (l/ha) and high operating capacity (ha/h). Regarding the reduction of the drift effect and the ability of the system to distribute the phytoiatric mixture uniformly and effectively within the leaf wall, scientific publications have not yet reached a uniformity of results that can be used to confirm these assumptions.

Given the widespread and more experienced use of cone nozzles, their use was chosen for comparison, using nozzle characteristics provided by ASJ (https://asjnozzle.it), a leading nozzle manufacturer. Although the values used vary from company to company, they are not a decisive and determining factor in the comparison of aerial and ground vehicles. Given the need in viticulture to carry out timely and effective interventions to combat attacks caused by fungi, insects and weeds, it was decided to evaluate the performance of nozzles suitable for the purpose and that were compatible with the distribution systems (sprayers) used in viticulture. Based on the nozzles listed in the catalog on the ASJ website [22], a list of nozzles recommended for the distribution of plant protection products by atomizer was obtained. The distribution performance of the system varies according to the number and type of nozzles used (which are associated with a different flow rate in l/min depending on the pressure exerted by the pumping system), as well as the width of the inter-row, forward speed and operating pressure of the pump. The Table 2 summarizes the operational choices made for the comparison.

Table 2. Operational choices using M.A.R.S. platform.

M.A.R.S. platform operational choices.	
forward speed (km/h)	10.8
forward speed (m/s)	3.0
travel time (h)	0.4
travel time (min)	22.2
pump operating pressure (bar)	3-5
nozzles installed (n)	2-4

Three different distribution volumes are assumed to make the comparison between land vehicles (tractors) and air vehicles (M.A.R.S. system): low, medium and high.

2.3 UAV Low volume treatments

The type of nozzle identified for low volume treatments is the hollowcone nozzle, capable of distributing volumes between 50 l/ha and 200 l/ha (maximum reference volume for low volume). It was mainly opted for Nozzles with a spray spectrum size between 100-200 µm for anticryptogamic spraying and 200-250 µm for insecticide distribution. Based on [22], the volumes of phytosanitary mixture that can be dispensed per hectare with the selected nozzles range from a minimum of 17.8 l/ha to a maximum of 205.3 l/ha (these values were considered, however, since they are just above the maximum value that distinguishes low volume). It should be emphasized that with the same nozzles used and reference area, lower distribution volumes would be achievable only by increasing the speed of the UAS carrying the spraying system. The average of such distributions is 94.8 l/ha and 113.4 l/ha for distributions dispensed with the nozzles at minimum pressure and maximum pressure between 3 and 5 bar, respectively, and guaranteeing a low volume dispensing between 50 and 200 l/ha.

The tank volume employed by the UAS was then divided by the minimum and maximum volumes that can be distributed per hectare with the listed nozzles. These values ranged from a minimum of 0.10 ha/tank to a maximum of 1.1 ha/tank. The pressures required in order to ensure the nozzle spraying performance listed above range from a minimum of 3 bar to a maximum of 5 bar (the predetermined pressure range in order to ensure adequate phytosanitary treatment). As for the minimum and maximum flow rates of each nozzle, these values range from 0.2 l/min to 2.31 l/min. The minimum number of refills required per hectare related to the minimum flow rate obtainable from the selected nozzles is 0.9 n/ha, while the maximum number of refills required per hectare derived from the maximum flow rate obtainable from the selected nozzles is 10.3 n/ha. The performances are summarized in the Table 3.

Table 3. Low volume performance using M.A.R.S. platform.

Low volume performance M.A.R.S. platform	**Min.**	**Mas.**
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	17.8	205.3
Average volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	94.8	113.4
treatable hectares with the tank (20 l) employed by uas (ha/tank)	0.1	1.13
required pump pressures (bar)	3	5
single nozzle flow rate (l/min)	0.2	2.31
Number of refills required per hectare (n/ha)	0.9	10.27

2.4 UAV Medium volume treatments

The type of nozzle identified for medium volume treatments is the hollow cone type, capable of distributing volumes between 200 l/ha and 600 l/ha (maximum reference volume for medium volume). Nozzles with an atomization spectrum size between 100-200 µm for anticritogamic delivery and 200-250 µm for insecticide delivery are considered. As reported in [22], the volumes of plant protection mixture that can be dispensed per hectare range from a minimum of 205.3 l/ha to a maximum of 275.6 l/ha. The average of such distributions is 216.8 l/ha and 249.9 l/ha for distributions dispensed with the nozzles at minimum pressure and maximum pressure between 3 and 5 bar, respectively, and guaranteeing a medium-volume dispensing between 200 and 600 l/ha. The maximum flow rate that can be delivered with the type of nozzles selected and with the limited operating pressures of the UAS system do not allow high distribution volumes to be achieved.

The reservoir volume employed by the UAS was then divided by the minimum and maximum volumes that can be distributed per hectare. These values ranged from a minimum of 0.06 ha/tank to a maximum of 0.1 ha/tank. The pressures required in order to ensure delivery performance range from a minimum of 3 bar to a maximum of 5 bar. As for the minimum and maximum flow rates of each nozzle, these values vary between 2.31 l/min and 3.1 l/min. The minimum number of refills required per hectare related to the minimum flow rate obtainable from the selected nozzles is 10.3 n/ha, while the maximum number of refills required per hectare derived from the maximum flow rate obtainable from the selected nozzles is 15.5 n/ha. The performances are summarized in the Table 4.

Table 4. Medium volume performance using M.A.R.S. platform.

Medium volume performance M.A.R.S. platform	**Min.**	**Mas.**
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	205.3	275.6
Average volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	216.8	249.9
treatable hectares with the tank (20 l) employed by uas (ha/tank)	0.06	0.1
required pump pressure (bar)	3	5
single nozzle flow rate (l/min)	2.31	3.1
Number of refills required per hectare (n/ha)	10.3	15.5

2.5 UAV High volume treatments

High volume treatments cannot be performed with the selected nozzles. The only useful strategy for high volume distribution using UAS involves speed reduction or the combined use of pumps capable of working at higher pressures. The main limitation of such systems, as far as high volume is concerned, concerns the limited pressure that can be exerted by the pump but also the limited reservoir that, at higher pressures, would lead to continuous refills after a few minutes.

3. Description of ground vehicles used for comparison

This Section separately analyzes the performance of land-moving trailed/carried machines, such as carried-jet hydraulic sprayers (atomizers) and pneumatic sprayers (foggers) in terms of distributed volume and timing.

3.1 Carried-jet hydraulic sprayers (atomizers)

Hydraulic aeroconvection sprayers (the most similar in terms of operation to distribution by UAS) used for low volume (50<V<200 l/ha), medium volume (200<V<600 l/ha) and high volume (600 l/ha<V<1000 l/ha) distributions [23]. Given the use of hydraulic spraying systems equipped with a fan to transport the droplets of phytoiatric product to target and an operating scenario characterized by a vertical trellis system with a developed and moderately dense canopy, the passage of the operating machine along all the inter-row spacing was planned, resulting in the treatment of one row at a time (two sides at a time). The forward speed of 6 km/h turns out to be the right compromise between the minimum speed of 5 km/h and the maximum speed normally employed of 7 km/h for treatments performed with such systems. The forward speed of 6 km/h and an operating pressure between 3 and 10 bar turn out to be the right compromise for the execution of treatments characterized by a reduced drift effect, adequate penetration of the product within the vegetation (in the medium and advanced stages of development), a reduction in the volumes of mixture distributed (l/ha) and operating capacity (ha/h).

As with the UAS, cone nozzles were chosen [22], as they are among the most common. Given the need in viticulture to carry out timely and effective interventions to combat attacks caused by fungi, insects and weeds, we opted to evaluate the performance of nozzles suitable for the purpose and that were compatible with the distribution systems (sprayers) used in viticulture. The performance of each sprayer, relative to optimal operating conditions free from the influence of external factors (weather adversity, operator skills and expertise, or malfunctions of various kinds), varies according to the number and type of nozzles used (with which a different flow rate in l/min is associated depending on the pressure exerted by the pumping system), as well as the aforementioned parameters (inter-row width, forward speed and pump operating pressure). The operational choices are reported in the Table **5**.

Table 5. Schematization of operational choices for the atomizers

Operational choices distribution by atomizers	
forward speed (km/h)	6
travel time (h)	0.67
travel time (min)	40
pump operating pressure (bar)	3-10
nozzles installed (n)	14

The type of nozzles identified for *low volume* treatments is hollowcone nozzles, capable of distributing volumes between 50 l/ha and 200 l/ha. Nozzles with a spray spectrum size between 100-200 µm for anticryptogamic delivery and 200-250 µm for insecticide delivery were mainly opted for. The spray angle width of the selected nozzles varies from 60° to 80°; therefore, nozzles characterized by a spray angle of 40°, which cannot meet the requirements, will be excluded. The performance of the nozzles understood as the volume of sanitary product delivered per hectare by the individual operating machine is computed depends on the flow rate (l/min) of each type of nozzle at pressures between 3-10 bar, the number of nozzles installed on the sprayer, the forward speed of the tractor machine and the width of the inter-row:

$$V\left(\frac{l}{ha}\right) = \frac{d\ Q\ n}{v\ D}$$

where Q represents the flow rate of the nozzle expressed in l/min, n the nozzle number installed on board of the atomizer, v the tractor speed in km/h, D the inter-row distance, and d = 600 a fixed factor.

3.2 Atomizer low volume treatments

The volumes of phytosanitary mixture that can be dispensed per hectare vary from a minimum of 112 l/ha to a maximum of 196 l/ha. It should be emphasized that with the same nozzles used and reference area, lower distribution volumes would be achievable only by increasing the speed of the tractor machine pulling/carrying the delivery system. The average of such distributions is 140 l/ha and 196 l/ha for distributions dispensed with the nozzles at minimum pressure and maximum pressure between 3 and 10 bar, respectively, and guaranteeing a dispensing volume between 50 and 200 l/ha. The average volume of tanks used by the sprayers were then divided by the minimum and maximum volumes of phytoiatric mixture that can be dispensed per hectare (l/ha) to obtain the minimum and maximum values of treatable hectares. These values ranged from a minimum of 1.3 ha/tank to a maximum of 19 ha/tank for solutions with larger tanks.

The pressures required in order to ensure the nozzle delivery performance listed above range from a minimum of 3 bar to a maximum of 10 bar (the predetermined pressure range in order to ensure adequate phytosanitary treatment). As for the minimum and maximum flow rates achievable by the selected nozzles, these values range between 0.2 l/min and 0.35 l/min. The minimum number of refills required per hectare (related to the minimum achievable flow rate of the selected nozzles combined with the largest volume tank) is 0.05 n/ha, while the maximum number of refills required per hectare (derived from the maximum achievable flow rate of the selected nozzles combined with the smallest volume tank) is 0.78 n/ha.

3.3 Atomizer medium volume treatments

The type of nozzles identified for *medium volume* treatments are hollowcone nozzles, capable of dispensing volumes between 200 l/ha and 600 l/ha (maximum reference volume for medium volume. Nozzles with a spray spectrum size between 100-200 µm for anticryptogamic delivery and 200-250 µm for insecticide delivery were mainly opted for. The volumes of phytosanitary mixture dispensed per hectare for medium volume distributions range from a minimum of 207.20 l/ha to a maximum of 616 l/ha (this parameter was included since it is just above the maximum volume range considered for medium volume). As pointed out for the low volume distribution, it is worth noting that with the same nozzles used and reference area, lower distribution volumes would be achievable only by increasing the speed of the tractor machine pulling/carrying the delivery system. The average of such distributions is 355.04 l/ha and 488.80 l/ha for distributions dispensed with the nozzles at minimum pressure and maximum pressure between 3 and 10 bar, respectively, and guaranteeing a dispensing volume between 200 and 600 l/ha. The average volume of tanks used by the sprayers (sheet 5 - performance sprayers) were then divided by the minimum and maximum volumes of phytoiatric mixture that can be dispensed per hectare (l/ha) to obtain the minimum and maximum values of treatable hectares. These values ranged from a minimum of 0.4 ha/tank to a maximum of 10.3 ha/tank for solutions with larger tanks.

The pressures required in order to ensure the nozzle delivery performance listed above range from a minimum of 3 bar to a maximum of 10 bar (the predetermined pressure range in order to ensure adequate phytosanitary treatment). As for the minimum and maximum flow rates achievable by the selected nozzles, these values range between 0.37 l/min and 1.03 l/min. The minimum number of refills required per hectare (related to the minimum achievable flow rate of the selected nozzles combined with the largest volume tank) is 0.01 n/ha, while The maximum number of refills required per hectare (derived from the maximum achievable flow rate of the selected nozzles combined with the smallest volume tank) is 2.5 n/ha.

3.4 Atomizer high volume treatments

The type of nozzle identified for *high volume* treatments is the hollowcone nozzle, capable of distributing volumes between 600 l/ha and 1000 l/ha (maximum reference volume for high volume. It will mainly opt for nozzles with a spray spectrum size between 100-200 µm for the delivery of anticryptogamics and 200-250 µm for the delivery of insecticides. The way of calculating nozzle performance understood as volume of sanitary product delivered per hectare is the same as described for low and medium volume treatments. The volumes of phytosanitary mixture that can be dispensed per hectare for high volume distributions range from a minimum of 616 l/ha to a maximum of 1036 l/ha (this parameter was included because it is just above the maximum volume range considered for high volume). As pointed out for the low and medium volume distributions, it is worth noting that with the same nozzles used and reference area, lower distribution volumes would be achievable only by increasing the speed of the tractor machine pulling/hauling the delivery system. The average of such distributions is 752.20 l/ha and 969.42 l/ha for distributions dispensed with the nozzles at minimum pressure and maximum pressure between 3 and 10 bar, respectively, and guaranteeing a dispensing volume between 600 and 1000 l/ha. The average tank volume used by the sprayers (sheet 5 - Sprayers performance) were then divided by the minimum and maximum volumes of phytoiatric mixture that can be dispensed per hectare (l/ha) to obtain the minimum and maximum values of treatable hectares. These values ranged from a minimum of 0.2 ha/tank to a maximum of 3.4 ha/tank for solutions with larger tanks.

The pressures required in order to ensure the nozzle delivery performance listed above range from a minimum of 3 bar to a maximum of 10 bar (the predetermined pressure range in order to ensure adequate phytosanitary treatment). As for the minimum and maximum flow rates achievable by the selected nozzles, these values vary between 1.1 l/min and 1.85 l/min. The minimum number of refills required per hectare (related to the minimum achievable flow rate of the selected nozzles combined with the largest volume tank) is 0.3 n/ha, while The maximum number of refills required per hectare (derived from the maximum achievable flow rate of the selected nozzles combined with the smallest volume tank) is 4.1 n/ha. The performances of atomizers are reported in Table 6.

Table 6. Performances atomizers

Low volume performance atomizers	Min.	Mas.
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	112	196
Average volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	140	196
Treatable hectares with average tank volumes used by sprayers (ha/tank)	1.3	19
required pump pressure (bar)	3	9
single nozzle flow rate (l/min)	0.2	0.35
Number of refills required per hectare (n/ha)	0.05	0.78

Medium volume performance atomizers	Min	Max
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	207.20	616 l/ha
Average volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	355.04	488.80
Treatable hectares with average tank volumes used by sprayers (ha/tank)	0.4	10.3
required pump pressure (bar)	3	10
single nozzle flow rate (l/min)	0.37	1.03
Number of refills required per hectare (n/ha)	0.01	2.5

High volume performance atomizers	Min.	Mas.
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	616	1036
Average volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	752.20	969.42
Treatable hectares with average tank volumes used by sprayers (ha/tank)	0.3	2.9
required pump pressures (bar)	3	10
single nozzle flow rate (l/min)	1.1	1.85
Number of refills required per hectare (n/ha)	0.3	4.1

3.2 Sprayers with pneumatic spraying and carried jet (foggers)

Following the verification of the performance of sprayers, pneumatic sprayer systems (nebulizers) with high performance for low volume (50<V< 200 l/ha), but also for medium volume (200<V<600 l/ha) and high volume (600 l/ha<V<1000 l/ha) distributions, with less homogeneous droplet spraying spectra and more prone to dripping **[23]**. Unlike the distribution performed with sprayers, the operational choices and performance of the sprayers will not be divided into low, medium and high volume, as these systems are not affected by the type of nozzles selected to deliver volumes belonging to the above three categories of treatments. Given the same operational choices, what will affect the total volumes distributed per hectare and timing will depend solely on the flow rate selected by the operator and the amount of rows treated at each pass. For this purpose, the minimum and maximum values delivered per hectare, the minimum and maximum number of hectares that can be treated with a single tank, and the timing required to complete a hectare will be given.

Given the use of pneumatic spraying systems, which are often equipped with trenching systems capable of treating 1 to 3 rows simultaneously in a uniform manner, and an operating scenario characterized by wall-mounted vine cultivation with a developed and moderately dense canopy, one determines the passage of the operating machine along all the inter-rows with the simplest solutions, resulting in the treatment of one row at a time (two sides at a time), or being able to have solutions that allow alternating passage 1 row yes and 1 no (4 sides at a time), or 1 yes and 2 no (three sides at a time). The forward speed of 6 km/h is the right compromise between the minimum speed of 5 km/h and the maximum speed normally employed of 8 km/h for treatments performed with such systems. Operating pressure is not a determining factor in the performance of such a distribution system, as it only performs the function of transporting the droplets to the nozzles. The operating pressure is generally 1-2 bar but may vary depending on construction characteristics.

Such systems are not equipped with the nozzles described for hydraulic spraying machines, and their performance in terms of treatment efficacy depends heavily on the arrangement of the nozzles, orientation and distance from the row, forward speed, and the possibility of having overlanding systems. With regard to actual performance, it is necessary to refer to the instruction manual of each spraying system. Droplet size is highly dependent on the relationship between the flow rate of liquid reaching the nozzles and the speed of the outgoing air. As the air outlet velocity increases, the droplet size decreases and vice versa. Keeping the air velocity constant and increasing the flow rate results in larger diameter droplets and vice versa. The performance in terms of distributed volumes per hectare and work timing of each sprayer, relative to optimal operating conditions free from the influence of external factors (weather adversity, operator skills and expertise, or malfunctions of various kinds), varies depending on the forward speed, flow rate of the fluid delivery system, and air outlet velocity. The operational choices are reported in the Table 7.

Table 7. Operational choices using nebulizers.

Operational choices distribution by nebulizers	
forward speed (km/h)	6
passage time in each row (h)	0.7
travel time alternate row passages (h)	0.3
passage time every two rows (h)	0.2
passage time in each row (min)	40.0
travel time alternate row passes (min)	20.0
passage time every two rows (min)	13.3
pump operating pressure (bar)	1-2

The volumes of phytosanitary mixture that can be dispensed per hectare vary from a minimum of 46.67 l/ha to a maximum of 3333.33 l/ha in the case of treatment carried out on the minimum number of rows, and a minimum of 11.67 l/ha to a maximum of 2200 l/ha in the case of treatment carried out on the maximum number of rows at each pass. It should be emphasized that with the same number of dispensing heads employed and reference area, lower dispensing volumes would be achievable only by increasing the speed of the tractor machine pulling/carrying the dispensing system. The average tank volume employed by the sprayers were then divided by the minimum and maximum values of volumes of product dispensed per hectare (l/ha) to obtain the minimum and maximum values of treatable hectares. These values ranged from a minimum of 0.16 ha/tank to a maximum of 24.6 ha/tank for distributions made when treatment was carried out on the minimum number of rows and a minimum of 0.2 ha/tank to a maximum of 98.6 ha/tank when treatment was carried out on the maximum number of rows at each pass.

The pressures required in order to guarantee the nozzle dispensing performance listed above range from a minimum of 2 bar to a maximum of 4 bar, but these values do not affect the flow rate of the dispensing system as much as the size of the droplets it dispenses. Of course, lower dispensing volumes correspond to smaller droplet sizes, which in most cases suffer a strong drift effect or low effectiveness. However, these values remain valid for indicative purposes to make a number of considerations regarding the minimum and maximum volumes that can be dispensed per hectare and the area that can be treated with a single tank. The minimum number of refills required for a treatment carried out with the minimum number of rows treated at the same time per hectare (related to the minimum flow rate achievable combined with the higher volume tank) is 0.04 n/ha, while The maximum number of refills required per hectare (derived from the maximum flow rate achievable combined with the lower volume tank) is 6.67 n/ha. The minimum number of refills required for a treatment carried out with the maximum number of rows treated at the same time per hectare (related to the minimum flow rate achievable combined with the higher volume tank) is 0.01 n/ha, while The maximum number of refills required per hectare (derived from the maximum flow rate achievable combined with the lower volume tank) is 6,286 n/ha. The performances of foggers are reported in Table 8.

Table 8. Performance by foggers

Performance foggers	Min.	Mas.
Volumes of phytoiatric mixture deliverable per hectare (l/ha) with treatment performed on the minimum number of rows at each pass	46.67	3333.3
Volumes of phytoiatric mixture deliverable per hectare (l/ha) with treatment performed on the maximum number of rows at each pass	11.67	2200
Treatable hectares with average tank volumes used by sprayers (ha/tank) with treatment performed on the minimum number of rows at each pass	0.51	24.6
Treatable hectares with average tank volumes used by sprayers (ha/tank) with treatment performed on the maximum number of rows at each pass	0.2	98.8
Number of refills required per hectare (n/ha) with treatment performed on the minimum number of rows at each pass	0.04	6.67
Number of refills required per hectare (n/ha) with treatment performed on the minimum number of rows at each pass	0.01	6.28

4. Comparison between the distribution by ground means and the M.A.R.S. system

Based on the parameters and scenarios described in Sections 2 and 3, a comparison between the M.A.R.S. platform and the two terrestrial distribution systems (atomizers and foggers) is performed in this Section. The area sprayed by a single tank of the UAS system is extremely small (0.07-1.1 ha) when compared to the area treated by terrestrial systems (1.7-15.5 in the case of sprayers and 0.345-69 ha in the case of distribution by atomizer), and this is mainly attributable to the limited tank capacity of the UAS (20 l). However, it is important to note that, unlike land-based systems, the M.A.R.S. system needs only 2.3 min to perform a complete refill of the tank (included in this count is the time required for the UAS to move to and from the point farthest from the refill platform), significantly higher than the 10.2-80.9 min of the atomizer and 12.6 - 55.1 min of the nebulizer. The presence of minimum and maximum values related to refill times can be attributed to the time required to fill the tanks characterized by minimum and maximum volume for both solutions.

Unlike the M.A.R.S. platform, which is characterized by a tank containing the phytoiatric mixture ready for refill of the UAS tank, land-based systems require the operator assigned to drive the tractor and distribute it to return to the farm center and follow a series of procedures for refilling the tank, complying with the practices necessary to carry out all operations safely and avoiding any product spillage into the environment. One also could consider positioning the platform at an optimal strategic location in order to optimize the UAS's movements for refill operations and further limit issues related to refilling the main tank. One of the advantages of the M.A.R.S. system relates to its ability to adapt to situations where there is no farm center for water supply to create the phytoiatric mixture, even if the area treated by a single tank is smaller.

Regarding the volumes of phytoiatric product dispensed per hectare, the volumes distributed by the M.A.R.S. platform are more limited and basically attributable to low volume treatments. These limitations are mainly due to the limited pressure that can be exerted by the pump installed on board the UAS (3-5 bar), which does not allow to take advantage of the higher flow rates. This problem can be remedied by reducing the forward speed of the UAS from the reference speed declared in the document (10.8 km/h=3m/s). However, the modern viticulture is moving toward the delivery of reduced volumes generally below 200 l/ha [24], [25], which is in line with what is the optimal performance of the UAS system. Moreover, although foggers seem to be the most versatile and high-performance systems, it is necessary to remember that they are designed to work mainly, and with greater performance, at low volumes.

Regarding the minimum volumes that can be delivered per hectare by UAS (17.8 l/ha) and sprayer (16.67 l/ha), they are very similar, highlighting a potential of the aerial system. The use of an automated aerial system can be logistically advantageous and versatile compared to traditional dynamics in which ground vehicles are used, which are characterized by larger footprint, difficulty of use in the immediate (a decisive factor in phytosanitary treatment and fertilization operations) and operational inability in soil conditions not suitable for the machine to enter the field (e.g., after intense rainfall phenomena). The maximum volume that can be delivered by the M.A.R.S. platform, understood as the indicative maximum volume supported on the selected area, is important since it can deliver with several passes high volumes, varying from a minimum 156.4 l/ha to 1231.2 l/ha. It is recommended in the case of high-volume treatments to take advantage of ground vehicles equipped with high-capacity tanks, they are certainly more effective for such volumes. The only possibility of using the M.A.R.S. platform with the described conformation concerns the need to carry out immediate treatments when vineyard conditions do not allow the entry of ground vehicles.

The M.A.R.S. system shows extremely low efficiency values (h/ha), thus high performance, both at the minimum value (0.1 h/ha) and at the maximum value (7.0 h/ha). The high performance can be attributed to the extremely limited time required to complete the refill (2.3 min), significantly less than the other two systems, and the ability to fly over obstacles represented by the vineyard rows. This parameter outlines the UAS as the optimal solution for performing immediate treatments (combined with the ability to perform treatments even when soil conditions do not allow machines to enter the field). With regard to the operating rate (i.e., the indicative time spent spraying versus the time spent on pitstops), the UAS presents maximum performance (91.6 %) in line with terrestrial systems on low volumes (88.5 % for the sprayer and 94.7 % for the atomizer). Although the UAS is forced to perform significantly more refills (for the same surface area considered), this operation requires significantly less time, 2.1 min versus 10.2-80.9 min for the atomizer and 12.6-55.1 min for the nebulizer. In contrast, the minimum operating rate of the UAS (41.4 %) is significantly lower than the minimum operating rate of the atomizer (86.8 %), but very close to the performance of the fogger (52.3 %). These results are also to be attributed in the construction characteristics of the three systems and by the profound differences in operation. The Tables in the annex summarize the results of the comparison between the three different technologies.

5. Conclusions

The work evaluated the effectiveness of executing agrochemicals distribution by a hybrid UAV with an onboard gasoline-powered electric generator, characterized by "in-flight" refueling of fuel and agrochemicals managed by a robotic platform, and to compare the system to consolidated terrestrial distribution technologies. Such combination theoretically nullified UAV autonomy and payload limits, opening new scenarios where agrochemical distribution can be operated airway by aerialsystems. The most appealing result is represented by the tank refilling operation, the core of the management platform, definetely lower than ground-based distribution systems. The main advantages of ground-based sprayers rely on the ability to spray at higher pressures and from a favorable position on the row spacing, which allows better penetration within the canopy. Further studies are needed to analyze the efficiency of UAV spraying in vineyards. Despite the limited ability of the aerial system to cover large areas with a single tank, the limited UAV's performance highlights the required improvements needed to perform efficient and environmentally safe agrochemical operations. New standards and regulations are essential for relevant scientific research advancement and operational comparison between UAVs and ground sprayers. The proposed approach represents a solution for UAVs implementation in vineyards spraying operations and open new scenarios for large areas treatments. Future works will analyze the benefits and improvements derived by swarms application capable of performing simultaneous spraying operations in different parts of the field.

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Annex

The following Tables summarize the results of the comparison between the three different technologies.

Performances of M.A.R.S.		
M.A.R.S. platform operational choices.	**Min.**	**Mas.**
nozzles (n)	4	
forward speed (m/s)	3.0	
pitstop speed (m/s)	6	
refill time (s)	70	
refill system connection time (s)	10	
refill system release time (s)	10	
tank (l)	20	
useful hours per day (h)	8	
Pump operating pressure (bar)	3	5
Performances dispensing	**Min.**	**Mas.**
single nozzle flow rate	0.2	3.1
total flow rate (l/min)	0.8	12.4
single tank spraying time (min)	1.61	25.0
single tank sprayed area (ha)	0.07	1.1
Single tank sprayed area (m^2)	725.8	11250
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	17.8	275.6
Negotiable acres with the tank (20 l) employed by uas (ha/tank)	0.06	1.1
Number of refills required per hectare (n/ha)	0.9	15.5
operating accrual (%)	41.4	91.6
single pass time (min/ha)	3.5	422.9
single pass time (h/ha)	0.1	7.0
maximum volume (l/ha)	156.4	1231.2
Timing	**Min.**	**Mas.**
travel time 1 ha (min)	22.2	
travel time 1 ha (h)	0.4	
maximum pitstop distance	141.4	
flight time to/from platform (s)	23.6	
total refill time (min)	2.3	

Performances of Atomizers		
Operating Choices ATOMIZER	**Min.**	**Mas.**
nozzles (n)	14	
forward speed (m/s)	1.6	
pitstop speed (m/s)	6	
refill time (s)	487.5	4725
refill system connection time (s)	30	
refill system release time (s)	30	
tank (l)	325	3150
useful hours per day (h)	8	
pump operating pressure (bar)	3	10
Performances dispensing	**Min.**	**Mas.**
single nozzle flow rate	0.2	1.85
total flow rate (l/min)	2.8	25.9
single tank spraying time (min)	67.1	620.5
single tank sprayed area (ha)	1.7	15.5
Single tank sprayed area (m^2)	16771.2	155133.9
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	112	1036
Negotiable acres from the atomizer (ha/tank)	0.2	19.0
Number of refills required per hectare (n/ha)	0.05	4.1
operating accrual (%)	86.8	88.5
single pass time (min/ha)	4.1	2613.9
single pass time (h/ha)	0.1	43.6
maximum volume (l/ha)	95.1	6595.9
Timing	**Min.**	**Mas.**
travel time 1 ha (min)	41.7	
travel time 1 ha (h)	0.7	
maximum pitstop distance	200	
Transfer time to/from recharge tank (s)	33.3	
total refill time (min)	10.2	80.9

Performances of Nebulizers		
Operating Choices ATOMIZER	**Min.**	**Mas.**
nozzles (n)		
forward speed (m/s)	1.6	
pitstop speed (m/s)	6	
refill time (s)	450	3000
refill system connection time (s)	120	
refill system release time (s)	120	
tank (l)	300	2000
useful hours per day (h)	8	
pump operating pressure (bar)	2	5

Performances dispensing	**Min.**	**Mas.**
single nozzle flow rate		
total flow rate (l/min)	1.1	83.3
single tank spraying time (min)	13.8	982.9
single tank sprayed area (ha)	0.345	69
single tank sprayed area (m^2)	3450	690000
volumes of phytoiatric mixture that can be dispensed per hectare (l/ha)	16.6	3333.3
acres treatable by the nebulizer (ha/tank)	0.16	90
Number of refills required per hectare (n/ha)	0.01	6.7
operating accrual (%)	52.3	94.7
single pass time (min/ha)	0.3	6920.1
single pass time (h/ha)	0.00	115.34
maximum volume (l/ha)	115.6	13627.8
Timing	**Min.**	**Mas.**
travel time 1 ha (min)	41.7	
travel time 1 ha (h)	0.7	
maximum pitstop distance	200	
flight time to/from platform (s)	33.3	
total refill time (min)	12.6	55.1