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Improving weed control efficiency through remote sensing and proper selection of nozzle type and application rate

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SUMMARY

This study explores the integration of unmanned aerial vehicle (UAV) technology with optimized herbicide application techniques to enhance weed control efficiency. A field trial was conducted in maize (*Zea mays* L.) in the 4–6 leaf stage ($BBCH_{14-16}$), combining pre-treatment multispectral drone imaging with variable nozzle types and spray volumes. Weed maps generated from UAV data enabled targeted application, while deposition was measured using a fluorescent tracer and spectrophotometric analysis. Results showed that TD-ADF twin nozzles achieved the highest deposition efficiency, especially at lower spray volumes (133-155 L ha^{-1}), without compromising herbicide delivery. The study also found that reduced spray volumes can maintain or even improve deposition when paired with proper nozzle selection and application speed. Findings support the use of low-volume, precision spraying systems guided by remote sensing to reduce input costs and environmental impact, while maintaining or improving weed control efficacy. This integrative approach aligns with the goals of sustainable and precision agriculture.
Keywords: remote sensing, drone, sprayers, deposit, weeds, precision agriculture.

INTRODUCTION

Weeds are among the most critical constraints to achieving optimal crop yields, competing with crops for water, nutrients, and sunlight, and often requiring extensive herbicide application. Traditional weed management practices, including ”blanket” spraying of herbicides, not only lead to environmental contamination but also increase production costs and the risk of herbicide resistance (Mohidem et al., 2021). In this context, precision agriculture techniques, particularly those integrating remote sensing technologies, have emerged as promising tools for site-specific weed management (SSWM) and sustainable crop production.

Unmanned Aerial Vehicles (UAVs) equipped with multispectral cameras enable rapid and non-destructive monitoring of weed presence and distribution across large agricultural fields. These systems provide high-resolution data suitable for vegetation classification, allowing for accurate weed detection during early crop development stages when visual differentiation is more feasible (Mateen and Zhu, 2019; Yang et al., 2024). Studies have shown that UAV-based weed mapping, combined with image analysis techniques and machine learning algorithms, significantly improves weed identification accuracy in real-time applications (Mota-Delfin et al., 2022; Rai et al., 2023).

However, accurate weed detection is only the first step. Efficient pesticides control depends largely on the proper selection of spray nozzles and application rates. The type of sprayer nozzle determines droplet size, coverage uniformity, and drift potential, all of which influence herbicide effectiveness and environmental safety. Adapting nozzle type and spray volume based on weed pressure and spatial distribution, as detected through UAV surveys, allows for optimized herbicide use (Mohidem et al., 2021).

Despite numerous advancements in remote sensing and intelligent spraying systems, integrated approaches that combine aerial weed detection with real-time variable-rate application remain underexplored. The aim of this study is to investigate the synergy between UAV-based weed mapping and the proper selection of nozzle types and application rates for improved weed control efficiency. By targeting only infested areas with the appropriate droplet size and spray volume, such integration enables a more efficient, economical, and environmentally responsible application of herbicides. This not only reduces herbicide use and minimizes off-target impacts, but also contributes to lowering production costs while maintaining or improving weed control efficacy. This integrated approach supports the principles of sustainable agriculture and precision farming, offering a promising path toward smarter and greener crop protection strategies.

MATERIAL AND METHODS

The field experiment was conducted on May 25th in a maize crop field, under stable weather conditions: air temperature 22°C, relative humidity 59%, and wind speed between 1-2 m s^{-1}. The total area used for all treatment combinations was 6.2 hectares. The trial was performed in the 4-6 leaf stage (BBCH$_{14-16}$) development of maize (*Zea mays* L.) on a plot sown with hybrid DKC 5075. Treatments included combinations of herbicides a.i.tembotrion and a.i. mezotrione, applied in combination with herbicide a.i. nikosulfurat. The aim of the experiment was to evaluate the effect of different nozzle types and spray application rates on herbicide deposition on weeds.

Prior to spraying, a weed detection survey was conducted using a DJI Mavic 3M drone equipped with a multispectral camera (bands: Green 560±16 nm, Red 650±16 nm, Red Edge 730±16 nm, Near Infrared 860±26 nm). The drone flights were planned to provide full coverage of the experimental plots, enabling identification of weed-infested zones. Images were processed using Pix4D Fields software to generate vegetation maps and support treatment decisions based on the spatial distribution of weeds.

Spray applications were performed using a Hardi Commander 4000 trailed sprayer, mounted with three types of blue-coded nozzles (ISO standard), (Table 1): ST – standard single flat-fan nozzle, ATP – twin flat-fan nozzle with a 60° forward/backward spray angle, TD-ADF (TurboDrop®) – air-induction twin flat-fan nozzle with a 10° forward and 50° backward spray pattern.

Table 1. Nozzles type

Nozzles appearance	Nozzles characteristics
	ST – standard
	ATP
	TD-ADF (TurboDrop®)

Each nozzle type was tested under four different spray volumes: 133, 155, 186, and 232 L ha^{-1}, achieved by adjusting the tractor speed (14, 12, 10, and 8 km h^{-1}, respectively) at a constant pressure of 5 bar (Table 2).

Table 2. Working parameters

Work speed	Pressure	Norm of treatment
8 km h^{-1}	5 bar	232 L ha^{-1}
10 km h^{-1}	5 bar	186 L ha^{-1}
12 km h^{-1}	5 bar	155 L ha^{-1}
14 km h^{-1}	5 bar	133 L ha^{-1}

Two herbicide treatments were evaluated (Table 3), both based on combinations of a.i. tembotrione or mesotrione with nicosulfuron, applied post-emergence. In all treatments, a fluorescent tracer was added to the spray tank to enable measurements of the deposition on weed surfaces. Fluoresent tracers were used to calculate herbicide deposits. To achieve this, 30 weeds were collected from three different positions for each application rate. Calculation of herbicide deposits was done using an IRIS HI801 spectrophotometer, based on fluorescence analysis. This allowed for the assessment of nozzle type and spray volume effects on coverage efficiency.

Statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate the effects of nozzle type and spray volume on herbicide deposition. Where appropriate, post hoc comparisons were conducted using Tukey's HSD test at a significance level of $p < 0.05$. The software used for statistical analysis was Statistica 14.0.

Table 3. Application doses for the comparative treatment using preparations based on the a.i. tembotrione and mesotrione.

Variant	A		B	
	Tembotrione	**Nikosulfuron**	**Mezotrione**	**Nikosulfuron**
POST MID	2 L ha^{-1}	0.75 L ha^{-1}	0.25 L ha^{-1}	0.75 L ha^{-1}

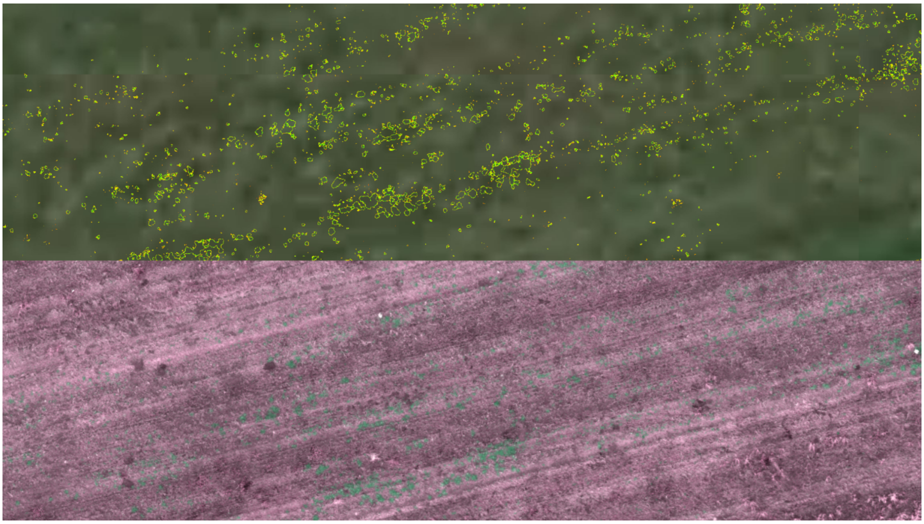
RESULTS AND DISCUSSION

Pre-treatment drone-based surveying was performed using the DJI Mavic 3M equipped with a multispectral camera capable of capturing spectral data in green (560±16 nm), red (650±16 nm), red-edge (730±16 nm), and near-infrared (860±26 nm) bands. These wavelengths are particularly effective in vegetation discrimination and were used to identify weed-infested zones prior to herbicide application. Flights were conducted at low altitude to ensure high spatial resolution, and the imagery was processed using Pix4D Fields software to generate vegetation indices and site-specific weed maps.

Multispectral remote sensing enables early-stage detection of weed patches, which are often unevenly distributed within crop fields. This spatial information is crucial for the implementation of site-specific weed management (SSWM) strategies, where herbicide input is tailored to localized weed pressure (Gerhards and Christensen, 2003; Mohidem et al., 2021). Studies have shown that SSWM can reduce herbicide consumption by 40-60%, depending on weed density, crop stage, and algorithm accuracy (Timmermann et al., 2003; Mota-Delfin et al., 2022; Yang et al., 2024). Furthermore, early detection helps prevent competition between weeds and crops in critical growth stages, thereby preserving yield potential (Zhang et al., 2003; Mateen and Zhu, 2019).

In the present study, weed maps were used to determine treatment zones and to optimize nozzle selection and spray volume, aiming for maximal deposition efficiency. Although the UAV data were not quantitatively validated in this trial, their operational integration enabled herbicides to be applied only where necessary, enhancing both cost-effectiveness and environmental protection. Such synergy between remote sensing and application technology forms the foundation of modern precision herbicide application systems (Young et al., 2020; Rai et al., 2023).

By combining UAV-guided detection with appropriate nozzle types and adjusted spray rates, the effectiveness of herbicide delivery to target weeds is significantly improved. This integrated strategy minimizes off-target spraying, reduces herbicide drift, and promotes sustainable agricultural practices in line with the goals of eco-efficient crop protection (Gerhards and Christensen, 2003; Young et al., 2020; Mohidem et al., 2021).



Picture 1. Example of weed density mapping using UAV-based multispectral imaging.

Weed detection imagery such as this provides valuable insights into the spatial variability of weed infestations across the field. By analyzing weed density through UAV-acquired data, it becomes possible to make informed, site-specific decisions regarding herbicide dosage. In practice, this allows for increasing the herbicide dose within the legally permitted limits in areas with higher weed pressure, and reducing it in cleaner zones, thereby optimizing input use and minimizing environmental risks.

Although quantitative vegetation indices such as NDVI were not extracted in this study, UAV imaging served as an operational decision support tool to delineate weed-infested zones based on visual spectral differences and plant morphology.

In the present study, although variable-rate application was not implemented in the field, the impact of spray volume on herbicide deposition was evaluated. This assessment serves as a foundational step toward future implementation of fully integrated UAV-guided precision herbicide applications, where both dosage and deposition can be spatially adapted based on real-time field conditions. Table 4 presents the achieved deposits (as a percentage of the dose) for both herbicide application variants, using different rates and types of sprayers.

Table 4. Measured Herbicide Deposition (%) on Weeds Across Different Nozzles and Spray Volumes.

		Variant A		
Norma L ha^{-1}	**232**	**186**	**155**	**133**
ST	13.0%	18.2%	19.5%	20.4%
ATP	51.9%	53.0%	54.1%	48.8%
TD-ADF	55.1%	56.6%	60.9%	62.6%
		Variant B		
Norma L ha^{-1}	**232**	**186**	**155**	**133**
ST	14.7%	16.2%	21.3%	19.1%
ATP	47.8%	50.3%	49.2%	50.8%
TD-ADF	51.1%	52.4%	57.6%	55.3%

The percentage of herbicide deposition on weeds achieved with Variant A and Variant B was similar. For example, a 51.1% deposit indicates that, for a herbicide dose of 2 L ha^{-1}, only half of the applied amount actually reached the weeds. Variant A recorded slightly higher deposition values at almost all application rates; however, these differences were not statistically significant and can be considered biologically irrelevant under the conditions of the trial conducted in the spring of 2021 at the Lovćenac site.

Although Table 4 shows numerical differences among nozzle types and application rates, statistical analysis (ANOVA, Tukey HSD) confirmed that these differences were not statistically significant ($p > 0.05$), corroborating the earlier claim that the observed variations are biologically negligible.

In both variants, a clear difference in deposition was observed between the standard single-nozzle and twin-nozzle spray tips. For example, in Variant A, the use of the TD-ADF TurboDrop® nozzle resulted in herbicide deposition levels three to four times higher than those achieved with the standard flat-fan nozzle. This result was expected, as previous studies (Bugarin et al., 2018; Sedlar et al., 2020) have shown that standard and single-injector nozzles commonly used in practice tend to produce the lowest deposition results during EPost and PostMID applications. This can be attributed to the fact that, at these stages, weeds are in the cotyledon stage or are otherwise very small, making it difficult for the fine droplet spectrum produced by standard nozzles to reach the target due to drift. On the other hand, large droplets produced by injector nozzles often run off or miss the small leaf surface entirely.

The ideal solution in such cases is the TD-ADF TurboDrop® nozzle, which, in addition to its twin spray pattern. TurboDrop® nozzles combine larger droplets at the edge of the spray pattern with finer droplets in the center, maximizing target coverage while minimizing off-target losses (Višacki et al., 2019; Sedlar et al., 2021). The larger edge droplets reduce drift, thereby protecting the finer central droplets that effectively reach the weeds. This unique combination makes TurboDrop® technology particularly well-suited for such treatments, as it is the only injector nozzle type that provides a droplet spectrum including both coarse and fine droplets essential for post-emergence efficacy.

Adjusting the application rate by changing the spraying speed from 8 to 14 km h^{-1}, while maintaining a constant pressure of 5 bar, demonstrated that deposition values did not decrease with lower spray volumes. In fact, application rates of 133 and 155 L ha^{-1} resulted in approximately 5% higher deposition compared to higher volumes. These findings, along with similar trials, indicate that application volumes close to 100 L ha^{-1} can be used effectively, provided that pressure is adapted to the nozzle type, the sprayer is equipped with boom height control, and twin-nozzle spray tips are employed. Injector and anti-drift nozzles require a pressure range of 4-8 bar, and for speeds above 12 km h^{-1}, TurboDrop® nozzles are the most suitable solution, as they are specifically designed for high-speed spraying. When integrated with UAV-based weed detection, such approaches enable data-driven, spatially precise treatments that are both economically and environmentally advantageous.

CONCLUSION

The integration of remote sensing technologies with optimized spray application techniques represents a promising advancement in modern weed management. In this study, drone-based weed detection enabled precise identification of infested zones, serving as a foundation for targeted herbicide application. Although UAV data were not quantitatively analyzed, their inclusion in the workflow facilitated more rational decision-making in nozzle and spray volume selection.

Among the evaluated nozzle types, the TD-ADF TurboDrop® consistently achieved the highest herbicide deposition rates, demonstrating its superior ability to deliver spray droplets to small weed targets under early post-emergence conditions. The use of twin-nozzle systems, particularly those with a mixed droplet spectrum, proved to be significantly more effective than standard flat-fan or single-injector nozzles.

Importantly, reducing spray volume from 232 to 133 L ha^{-1} did not compromise deposition levels; in fact, lower volumes performed equally well or better under certain conditions. These findings highlight the potential of low-volume, high-efficiency application systems especially when paired with intelligent sprayer technology and accurate weed mapping.

Overall, this study confirms that the combination of UAV-assisted detection, appropriate nozzle selection, and adjusted spray rates can lead to more efficient, economical, and environmentally sustainable herbicide applications, supporting the broader goals of precision agriculture and sustainable crop production.

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Unapređenje efikasnosti suzbijanja korova primenom daljinske detekcije i pravilnog izbora tipa rasprskivača i norme tretiranja

REZIME

Ova studija istražuje mogućnosti integracije tehnologije bespilotnih letelica (UAV) sa optimizovanim tehnikama primene herbicida u cilju povećanja efikasnosti suzbijanja korova. Terenski ogled je izveden u usevu kukuruza (*Zea mays* L.) u fazi 4-6 listova (BBCH 14-16), kombinujući multispektralno snimanje dronom pre tretmana sa različitim tipovima rasprskivača i normama utroška tečnosti. Na osnovu podataka dobijenih UAV snimanjem kreirane su mape zakorovljenosti koje su omogućile ciljan pristup tretiranju, dok je količina depozita na biljkama određena primenom fluorescentnog trejsera i spektrofotometrijskom analizom. Rezultati su pokazali da su TD-ADF dvomlazni rasprskivači ostvarili najveću efikasnost depozicije, naročito pri nižim normama (133-155 L ha^{-1}). Takođe je utvrđeno da smanjene norme tretiranja mogu zadržati ili čak poboljšati količinu depozita kada su uparene sa odgovarajućim izborom rasprskivača i brzinom kretanja. Dobijeni rezultati potkrepljuju primenu sistema niskih normi i preciznog prskanja vođenih daljinskom detekcijom, sa ciljem smanjenja troškova i negativnog uticaja na životnu sredinu, uz očuvanje ili poboljšanje efikasnosti suzbijanja korova. Ovakav integrativni pristup u potpunosti je u skladu sa ciljevima održive i precizne poljoprivrede.

Ključne reči: daljinska detekcija, dron, rasprskivači, depozit, korovi, precizna poljoprivreda.