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Optimizing UAV-based herbicide applications for sustainable wheat weed management by a novel multi-parameter field evaluation under variable environmental conditions

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ABSTRACT

Unmanned aerial vehicles (UAVs) offer potential for precise, sustainable herbicide application in wheat, but their efficacy under variable field conditions requires robust evaluation. This study aims to rectify these research gaps and introduces a novel multi-parameter field evaluation of UAV-based herbicide applications for sustainable wheat weed management, explicitly evaluating the critical impact of real-time meteorological variability and application parameters. Field experiments over two growing seasons (2021/2022 and 2022/2023) compared UAV applications (30 L ha⁻¹, fine-to-medium droplets) at 1.5 m and 2.5 m altitudes with conventional spraying (200 L ha⁻¹, medium-coarse droplets), using constant doses of two commercial herbicide formulations (1. *tritosulfuron* + *florasulam*; 2. *iodosulfuron-methyl-sodium* + *amidosulfuron* + *mefenpyr-diethyl*). Efficacy was measured via species-specific weed density and fresh mass reduction. UAV treatments achieved significantly higher or equivalent suppression of *Capsella bursa-pastoris*, *Lactuca serriola*, *Sinapis arvensis*, and *Veronica persica* compared to conventional spraying. Despite more challenging conditions (high temperature, lower humidity, stronger wind) in the second season, overall efficacy increased, attributed to using a more effective herbicide formulation, underscoring the critical role of herbicide selection for UAV systems. *Lamium purpureum* exhibited significant weather sensitivity, with lower flight altitude enhancing fresh mass reduction. Correlation analysis suggested temperature positively ($r = 0.586$, $p = 0.045$) and wind velocity negatively ($r = -0.588$, $p = 0.045$) influenced treatment efficacy. UAV applications achieved up to 90 % efficacy in the second year by 31 DAHA (i.e., herbicide application) while using 85 % less water. This research provides the first multi-parameter field validation of UAV herbicide application under variable environmental conditions, demonstrating its viability and significant water-saving potential. The findings offer crucial, actionable inferences for optimizing UAV parameters (altitude, droplet size) with herbicide selection and real-time weather data, benefiting global precision agriculture efforts towards resource-efficient and environmentally responsible weed management.

1. Introduction

Wheat (*Triticum aestivum* L.) is the third most widely cultivated cereal crop globally, following rice (*Oryza sativa* L.) and maize (*Zea mays* L.), and ranks second in human consumption (FAO, 2024). Given its central role in global food security, effective weed management is essential to sustain high yields and mitigate yield losses. Weeds are responsible for up to 70 % yield reductions in wheat, depending on weed

species, emergence timing, and density (Gyawali et al., 2022). Globally, the average yield loss due to weeds is estimated at 13.1 %, underlining the urgent need for efficient, scalable, and environmentally sustainable weed control strategies (Gyawali et al., 2022).

Traditional herbicide application methods, including tractor-mounted field sprayers, self-propelled systems, and manual operations, are limited by low spray efficacy, chemical losses, and environmental contamination. Studies report that only 20–30 % of applied

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herbicides effectively reach target plants, with the remaining lost through drift, evaporation, or leaching (Torrent et al., 2017). These inefficiencies elevate production costs, heighten ecological risks, and pose compliance challenges with global sustainability goals, such as the European Green Deal's target to halve pesticide usage without reducing crop productivity. Beyond environmental drawbacks, conventional methods often result in soil compaction, uneven herbicide deposition, and restricted access during wet conditions. Additionally, large carrier volumes ($>200 \text{ L ha}^{-1}$) constrain field operations in water-scarce regions (Chen et al., 2023). These constraints necessitate alternate technologies that promote precision agriculture, conserve water, and minimize chemical overuse.

Unmanned Aerial Vehicles (UAVs) have emerged as a promising innovation in precision agriculture, enabling site-specific herbicide application with high operational efficacy, minimal crop disturbance, and substantially reduced input use (Ivezić, 2023). UAV spraying systems have demonstrated reductions in water usage by up to 90 % and pesticide consumption by 30–40 % without compromising weed control efficacy (Ivezić et al., 2023). UAVs eliminate the issue of soil compaction and allow for flexible operations in hard-to-reach terrain, offering further benefits through timely application during optimal environmental conditions (Zhang et al., 2021).

However, UAV-based applications present unresolved technical challenges. Prior studies primarily conducted in paddy rice or high-density crops indicate that UAV efficacy is highly sensitive to flight parameters such as altitude and velocity, as well as droplet characteristics (Lou et al., 2018; Qin et al., 2018; Abd Kharim et al., 2019). Fine droplets ($<200 \mu\text{m}$) produced by UAVs are prone to rapid evaporation and off-target drift, particularly under high temperature and low humidity conditions, leading to variable herbicide deposition and inconsistent weed suppression (Ahmad et al., 2020; Devkota, 2019). Moreover, UAVs typically use ultra-low volume (ULV) spraying $10\text{--}30 \text{ L ha}^{-1}$, necessitating the reformulation of herbicides or using surfactants to maintain efficacy (Chen et al., 2024).

Although UAV systems have shown promise in rice and orchard crops, limited research has explored their integration into wheat-based systems. Specifically, there is a lack of comparative studies evaluating UAV performance versus field sprayers across multiple herbicide formulations, weed species, and agro-climatic conditions. Most existing research has focused on insecticides, with insufficient evidence on how UAVs perform with systematic vs contact herbicides in dryland wheat ecosystems (Qin et al., 2018; Wang et al., 2019). Moreover, there is limited data on the interaction between reduced spray volume, droplet behavior, and herbicide efficacy under field-scale meteorological variability. This study addresses existing research gaps by evaluating the efficacy of commonly used herbicides applied via UAV systems in wheat cultivation and comparing their performance with field sprayers. By systematically identifying the strengths and limitations of UAV-based applications under field conditions, the research contributes to understanding the adaptation of traditional herbicides to emerging application technologies. The results provide evidence-based recommendations to facilitate the effective and sustainable adoption of UAV systems in agricultural practice.

To address these critical research gaps, this study aims to investigate the efficacy of UAV-based herbicide applications in wheat compared to conventional field sprayers under controlled experimental conditions across two cropping (vegetation) seasons. Two herbicide formulations, 1) *Tritosulfuron + florasulam* (Biathlon) applied in the first year, and 2) *Iodosulfuron-methyl-sodium + amidosulfuron + mefenpyr-diethyl* (Sekator) applied in the second year, were evaluated for weed suppression and mass reduction. The study examines the impact of reduced spray volume (30 L ha^{-1}) and UAV flight altitude on herbicide performance relative to the conventional application (200 L ha^{-1}) across various environmental conditions. Statistical comparisons were conducted using ANOVA and Tukey's HSD to determine significant differences in treatment efficacy.

This manuscript represents one of the first comprehensive, multi-parameter field evaluations of UAV-based herbicide applications under real-world, variable environmental conditions. The novelty of this research lies in its comprehensive, field-based, side-by-side assessment of UAV and conventional field sprayer systems under naturally variable environmental conditions, using two commercially available herbicide formulations. Unlike previous studies that often focus on aerial-specific products or idealized settings, this work integrates agronomically relevant variables, such as UAV flight altitude, spray volume, and key weather parameters (wind velocity, temperature, and humidity), to assess how these factors jointly influence herbicide efficacy and crop performance in wheat systems. Importantly, the study captures species-specific weed responses across multiple broadleaf species prevalent in cereal cropping, enabling a more nuanced understanding of treatment outcomes.

The research provides robust, comparative insights into real-world application efficacy by conducting trials over two years and applying standardized protocols across all treatments. This multi-parameter evaluation framework reflects operational decision-making scenarios encountered by farmers and agronomists, offering evidence-based guidance on how UAV settings and environmental conditions interact to affect field performance. The findings are globally relevant for agronomic practice, precision farming development, and policy frameworks aiming to reduce agrochemical inputs while maintaining high productivity in sustainable cereal systems.

The objectives of this study were to (i) compare the efficacy of UAV-based versus conventional herbicide application systems for control of key wheat weed species under field conditions representative of commercial production, (ii) evaluate how UAV operational parameters like flight altitude and spray volume, and meteorological variables (temperature, humidity, and wind speed) affect herbicide deposition and weed-control efficacy across the growing seasons, and (iii) assess the feasibility of applying two widely used commercial herbicide formulations via UAV technology and identifying the formulation-specific performance differences for investigating their optimization in low-volume aerial delivery systems.

2. Research method

2.1. Study area

The field experiments were conducted in Zemun, Republic of Serbia, in 2021, 2022, and 2023, at the geographical coordinates $44^{\circ}50'47''\text{N}$ $20^{\circ}11'10''\text{E}$, with an altitude of 73 m (Fig. 1). The research was conducted over two vegetation seasons. The first season spanned 2021/2022, with sowing performed in October 2021 and harvesting in July 2022. This period will hereafter be referred to as the first year. The second vegetation season occurred in 2022/2023, with sowing in October 2022 and harvesting in July 2023. To ensure clarity throughout the manuscript, the terms first year and second year will be used instead of "vegetation season". The soil at the experimental site was classified as loam to clay loam, with a slightly alkaline pH (7.95), low carbonate content (0.7 %), moderate humus level (1.75 %), and a balanced C/N ratio (8.2:1). The N content was 31.1 mg kg^{-1} , P (P_2O_5) $5.2 \text{ mg } 100 \text{ g}^{-1}$, and K (K_2O) $18.5 \text{ mg } 100 \text{ g}^{-1}$. The site followed a stable crop rotation pattern involving annual alternation between wheat and maize. During all years of the experiment, the soil in the winter wheat field was ploughed to a depth of 20 cm prior to sowing, with 300 kg ha^{-1} of NPK mineral fertilizer (6 N: 24 P_2O_5 : 12 K_2O) applied. Subsequent soil preparation included additional tillage, pre-sowing treatment, and field marking. The wheat was sown with a seeding rate of 240 kg ha^{-1} . The wheat variety was Sofru-RWA, while the pre-crop was maize. The wheat variety 'Sofru-RWA' (Lidea) is a winter bread wheat cultivar known for early maturity, cold tolerance, high specific weight, and stable agronomic performance under continental conditions. During the experiment, the wheat crop was supplemented three times with mineral

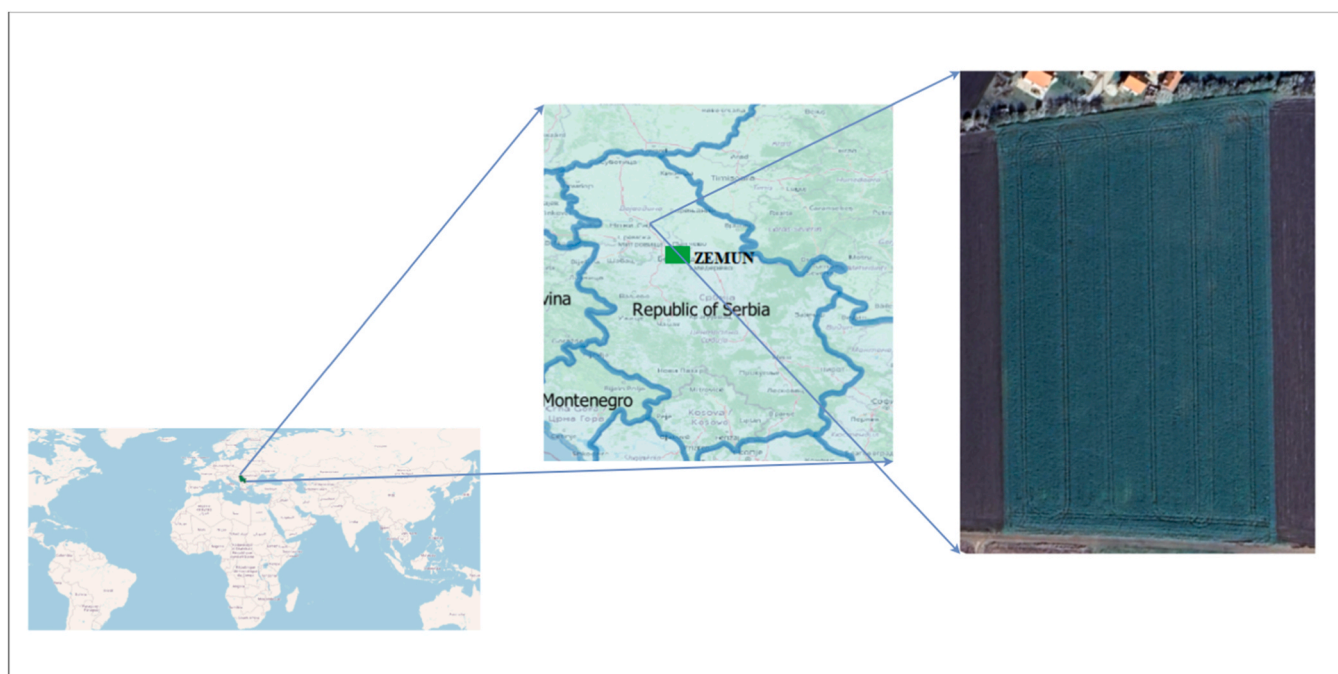


Fig. 1. Geographic location of the study area in Serbia.

fertilizer (I top dressing UREA 46 % N, 250 kg ha⁻¹ - the beginning of arrange in panicle; II top dressing KAN 27 % N, 4.5 % MgO, 6.5 % CaO 100 kg ha⁻¹ - before the beginning of flowering; III top dressing KAN 100 kg ha⁻¹ - in flowering).

2.2. Experimental design

A total of four different treatments were included in the experiment. The area of the elementary plot was 30 × 10 m. All treatments were set up in four replicates (Fig. 4). Between the treatments, an isolation zone of 10 m was left (Wang, 2019) in order to avoid the impact of herbicide solution drops on the non-targeted surface (Fig. 3). Different herbicides and formulations were used in the two experimental years because the composition of the weed flora differed between seasons. Therefore, the choice of herbicide was in accordance with the weed spectrum in each season and standard agronomic practice in the local region. In treatments T2, T3 and T4 (Table 1, Fig. 3), the herbicide (trade name: Biathlon; active ingredients: *tritosulfuron* (714 g kg⁻¹) + *florasulam* (54 g kg⁻¹), WG, (manufacturer: BASF, Germany) was applied in the amount of 0.05 kg ha⁻¹ with addition adjuvant (trade name: ES plus; active ingredients: *izodecil alkohol etoksilat* (900 g L⁻¹), SL, (manufacturer: Chemical Agrosava, Serbia)), in the amount of 0.2 L ha⁻¹ during the first year. In the second year, the herbicide (trade name: Sekator OD; active ingredients: *iodosulfuron-methyl-sodium* (25 g L⁻¹) + *amidosulfuron* (100 g L⁻¹) + *mefenpyr-diethyl* (protectant) (250 g L⁻¹), OD, (manufacturer: Bayer CropScience, Germany)) was applied in the amount of 0.15 L ha⁻¹ and an adjuvant containing fatty alcohol (trade

name: Inex; active ingredients: *ethoxylate* (20.3 %) and *polydimethylsiloxane* (1.0 %) in SL formulation (manufacturer: Cosmocel, Mexico) was applied at a concentration of 0.002 L per liter of water. The spraying volume of the UAV system was 30 L ha⁻¹, and the volume of the field sprayer was 200 L ha⁻¹ (Table 1). The application of herbicides during both years of the experiment was carried out at the leafing stage (BBCH 29–31), more precisely on April 15th, 2022, and April 12th, 2023.

2.3. Description of the chemical protection systems and equipment

All operational parameters for the conventional field sprayer were selected to reflect real-world application practices in cereal production, following manufacturer-recommended settings for spray volume, working pressure, and nozzle configuration. Similarly, two widely adopted commercial formulations of herbicide products used in this study were chosen based on their relevance and common usage in wheat-based weed control programs. This approach was intended to ensure that the study outcomes provide meaningful and transferable guidance for farmers, UAV operators, and crop advisors. For the UAV system, flight parameters such as altitude, velocity, and swath width were adjusted based on a combination of manufacturer specifications and published research on UAV herbicide application. Although the existing literature is limited, previous studies have provided valuable baseline data and practical recommendations that guide the setup of UAVs to ensure agronomic realism and comparability with conventional applications.

Before each spraying season, nozzle performance was verified using the AMMS Salvarini Nozzle Tester system to ensure flow rates were within the manufacturer's specified tolerances. This calibration procedure was conducted for the field sprayer and the UAV spraying system. The working pressure of the field sprayer was checked using an external calibrated manometer. In the case of the UAV, direct pressure calibration was not possible, as the manometer is integrated and not externally accessible. However, UAV flow rate consistency was confirmed through repeated measurements under standardized pre-flight procedures recommended by the manufacturer. Although droplet size was not directly measured in this study due to the absence of

Table 1

Overview of treatment variants for UAV and conventional sprayer herbicide applications.

Treatments	Technical system	Height of altitude /branch (m)	Flight/ movement velocity (m s ⁻¹)	Spray volume (L ha ⁻¹)
T1	Control (weeds left intact)			
T2	UAV system	1.5	3	30
T3	UAV system	2.5	3	30
T4	Field sprayer	0.5	4.45	200

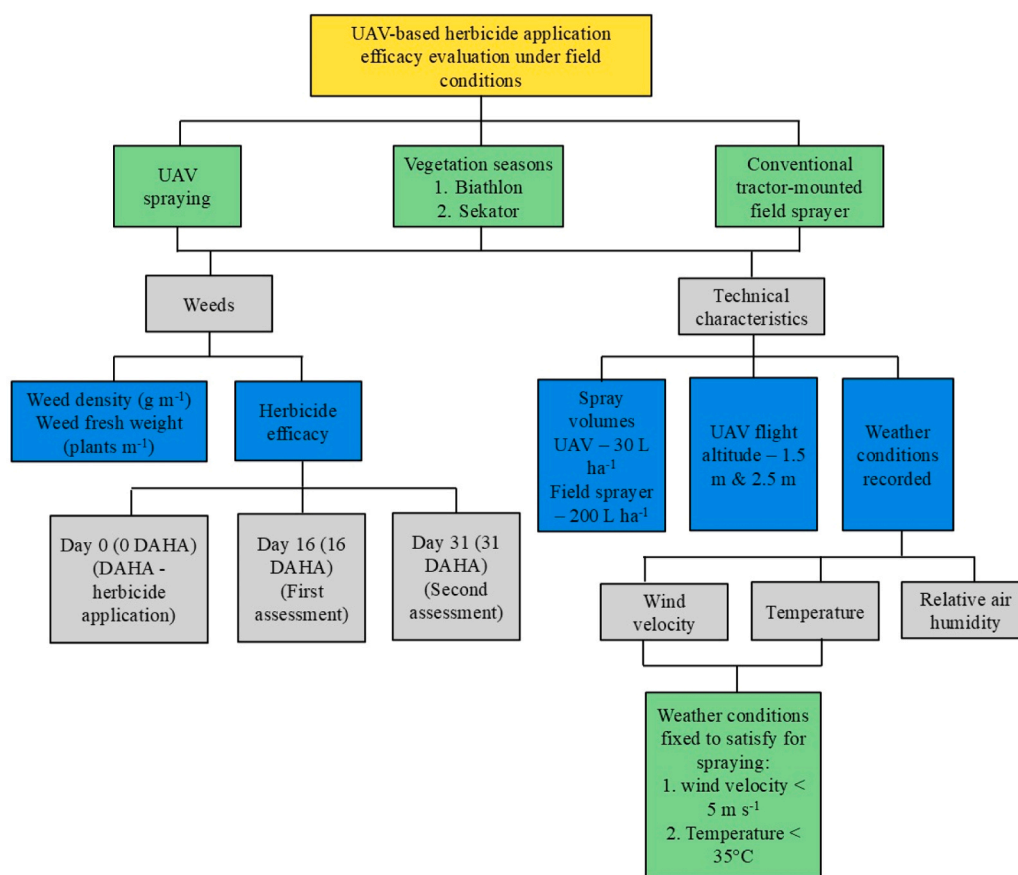


Fig. 2. Schematic overview of the experimental treatments and measured variables.

this parameter in the experimental design, nozzle selection was based on manufacturer-provided droplet classification charts.

The technical specifications of the UAV (DJI Agras T30) and the tractor-mounted field sprayer (Kubota XTS326) were based on the official product documentation provided by Shenzhen DJI Innovation Technology and Kubota Corporation, respectively (Bošković et al., 2023). The herbicide application treatments in this study were conducted using two different application systems: a UAV and a tractor-mounted field sprayer (Appendix, Table S1). The UAV was the DJI Agras T30, developed by Shenzhen DJI Innovation Technology, China. It is a widely recognized UAV system in precision agriculture for its high performance and adaptability to various environmental conditions. The T30 model has six powerful propellers and an advanced real-time kinematic (RTK) positioning system, ensuring precise navigation and stable flight paths even in challenging environments. The RTK system enhances accuracy by compensating for GPS signal drift, allowing the UAV to maintain consistent flight heights and cover the target area uniformly, minimizing herbicide drift and improving coverage (Lan, 2025).

The UAV system is designed for variable-rate applications, enabling adjustments to the spray volume based on the specific requirements of different field zones. The device features intelligent obstacle avoidance technology to prevent collisions and optimize the spraying process in fields with irregular terrain. DJI Agras T30 features a compact design with $2858 \times 790 \times 2685$ mm dimensions. It has 16 nozzles, a tank capacity of 30 L, and a working width that can be adjusted between 4 and 9 m, with a standard setting of 5 m. The system operates with a flow rate of 7.2 L min^{-1} and produces droplets ranging from the nozzles $130\text{--}250 \mu\text{m}$ (Tjeet XR11001), depending on the operating pressure. The maximum operating pressure is 0.5 MPa, with a flight duration of 7.8 min when the tank is full and 20.5 min when empty.

In parallel, a Kubota XTS326 (Kubota Corporation) tractor-mounted field sprayer was used as the traditional herbicide application method for comparison (Appendix, Table S1). This new-generation field sprayer is equipped with an advanced variable chemical protection system, allowing for precise adjustments in droplet size, spray volume, and application pressure. The Kubota XTS326 has 42 nozzles and a working width of 21 m, which provides extensive field coverage per pass. Its piston-diaphragm pump ensures a steady and reliable spray flow with a maximum operating pressure of 0.8 MPa. At the same time, its droplet size control system helps to optimize herbicide efficacy and minimize off-target drift. The nozzles on the field sprayer were Lechler IDK 120-03, which, depending on the pressure, produce coarse ($326 \mu\text{m}$) to very coarse droplets ($650 \mu\text{m}$) and are designed to reduce drift. Based on catalogue values and a spraying pressure of 0.4 MPa, these nozzles produce coarse droplets ranging from 326 to $400 \mu\text{m}$. The droplet size classification was done according to ISO 25358: 2018. These specifications highlight the differences in capacity, application efficacy, and versatility between the two systems, making UAVs more suitable for precision applications in areas with uneven terrain. At the same time, field sprayers remain optimal for larger-scale uniform treatments.

Both systems were carefully calibrated before application to ensure consistent and accurate herbicide delivery. The UAV system was flown at two heights (1.5 m and 2.5 m) and a set velocity of 3 m s^{-1} , while the field sprayer operated at a height of 0.5 m and a speed of 4.45 m s^{-1} (Table 1). This variation in flight and movement parameters allowed for a detailed assessment of their influence on herbicide distribution, weed control efficacy, and overall performance under environmental conditions. Operating pressure during spraying was 0.3 MPa (UAV) and 0.4 MPa (field sprayer).

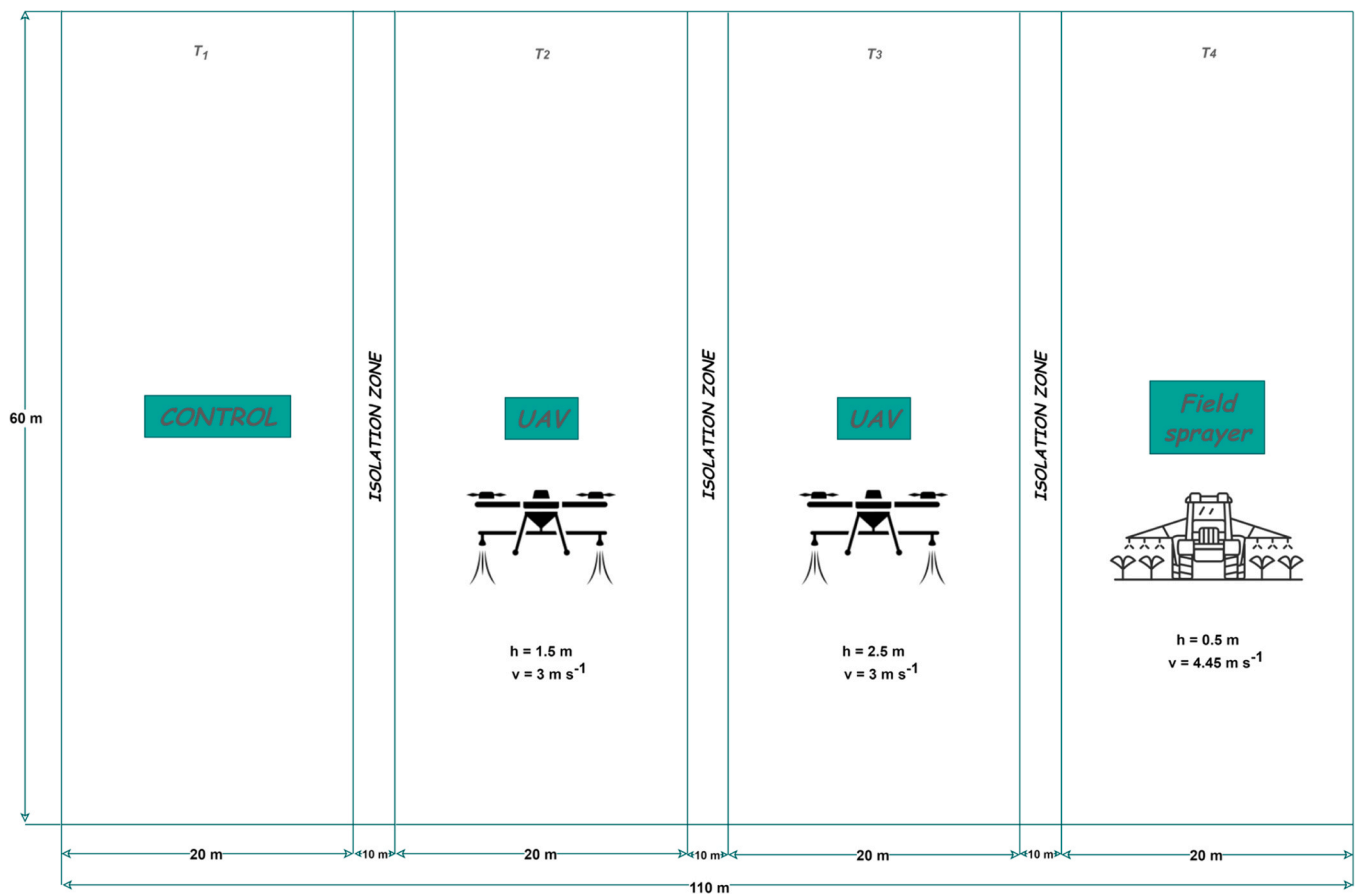


Fig. 3. Layout of the experimental wheat field showing treatments for herbicide application: T₁ – Untreated control, T₂ – UAV spraying at 1.5 m height, T₃ – UAV at 2.5 m height, T₄ – Conventional field sprayer.

2.4. Herbicide efficacy, yield, and meteorological impact assessment

Weed sampling and herbicide efficacy assessment were conducted by EPPO guidelines (EPPO, 2014). Before herbicide application (DAHA), weeds were sampled to establish the initial 0 DAHA (zero assessment) infestation level. Subsequent assessments were performed at 16 (I assessment) and 31 (II assessment) days after DAHA (Fig. 2). During each assessment, weed density and fresh mass were measured using wooden sampling frames measuring 25 × 25 cm (0.0625 m²). Two frames per plot were randomly placed within each of the four replications, avoiding plot edges to minimize border effects. Also, the frame was always placed within the inner zone of the plots, at least 5 cm from

the edges, and was placed by a person unfamiliar with the treatment arrangement. This procedure ensured truly random sampling frame placement and prevented subjective bias. All rooted weeds in the sampling area were carefully pulled, identified at the species level, counted, and weighed. This sampling procedure was applied consistently across all treatments and assessment dates (0, 16, and 31 DAHA). Efficacy estimation was interpreted based on all weed species present in the field before herbicide application. It is possible that some tolerant or less sensitive species survived herbicide efficacy, which is reflected in the final results. A schematic diagram illustrating the sampling layout within the plots is presented in Fig. 4. Data were recalculated and expressed per square meter for standardization and comparison across

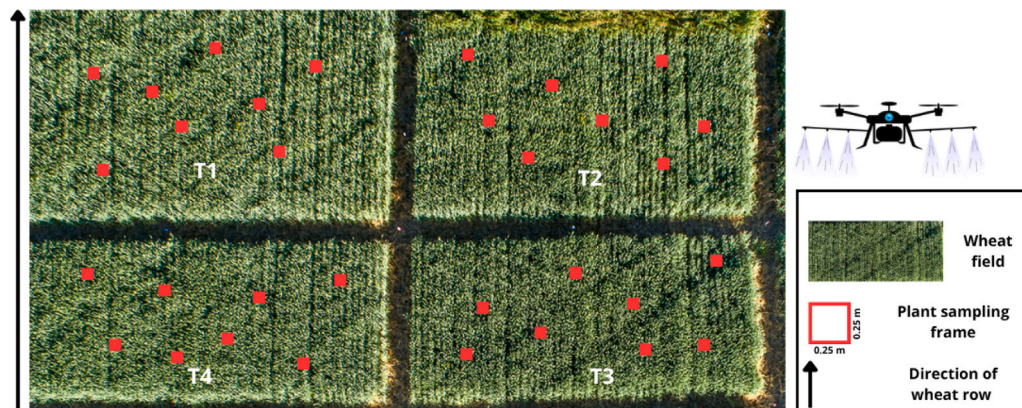


Fig. 4. Sampling layout for weed assessment within experimental treatments.

treatments. Herbicide efficacy (Ef, %) was calculated using Abbot's formula, based on both weed density and fresh mass of surviving weeds (Abbott, 1925):

$$E_f = \left(\frac{D_c - D_t}{D_c} \right) * 100$$

Where:

- E_f – Herbicide efficacy (%),
- D_c – weed density or fresh mass in the untreated control (T1),
- D_t – weed density or fresh mass in the treated plots (T2, T3, T4).

Wheat yield analysis was performed in all cropping experimental years. Samples were collected from a 1 m² area with five replicates for each treatment, seven days before harvest. Grain yield was measured from the elementary plot, adjusted to 14 % moisture content, and expressed in kilograms per hectare (kg ha⁻¹) (Zhao et al., 2023).

Herbicide applications were performed only under environmental conditions that met agronomic safety thresholds. Specifically, spraying was not conducted when wind speed exceeded 5 m s⁻¹ or ambient temperature was above 35°C. These limits were chosen based on practical guidelines and aligned with ISO 22866:2005, which regulates environmental conditions for field drift testing. Meteorological parameters (wind velocity, temperature, and relative humidity) were recorded individually for each treatment during herbicide application events using calibrated instruments and later analyzed in SPSS. Meteorological parameters, including air temperature, humidity (measured using Voltcraft DL-140TH), and wind velocity (measured with Testo 410i Smart Probe), were monitored throughout the study to evaluate their influence on herbicide application efficacy. According to the manufacturer's specifications, the DL-140TH has an accuracy of ±0.5°C for temperature and ±3 % RH for relative humidity, while the Testo 410i measures wind velocity with an accuracy of ±0.2 m s⁻¹ plus 2 % of the reading for relative humidity. These devices were positioned at 1.5 m and 2.5 m heights to match the UAV application heights. Fig. 5 illustrates the overall methodological flow of this study.

2.5. Statistical analysis

The data were analyzed using one-way analysis of variance (ANOVA) in the SPSS statistical software package (IBM SPSS Statistics 29.0.1.0). Before performing ANOVA, assumptions of normality and homogeneity of variances were tested separately for each parameter using the Shapiro–Wilk and Levene's tests, respectively. Where necessary, data on herbicide efficacy and yield were log-transformed to meet these assumptions (Appendix, Table S2). Statistical interpretations are based on transformed data, while untransformed means ± standard error (SE) and 95 % confidence intervals (CI) are presented for clarity. Post-hoc comparisons between treatments were performed using Tukey's HSD test at a significance level of $p \leq 0.05$. Effect sizes (i.e., Cohen's d) were calculated for all pairwise treatment comparisons based on the formula adapted for Tukey's HSD and the main ANOVA effects using eta squared (η^2) to assess the magnitude of observed differences. Cohen's d was calculated using the formula (Cohen, 1988):

$$d = \frac{M_1 - M_2}{SD_{pooled}}$$

where M_1 and M_2 are group means, and SD_{pooled} is the pooled standard deviation. Interpretation of d values followed Cohen's thresholds: small (0.2–0.5), medium (0.5–0.8), and large (>0.8). Effect size for the main ANOVA effects was expressed as eta squared (η^2), calculated (Cohen, 1988):

$$\eta^2 = \frac{SS_{between}}{SS_{total}}$$

The magnitude of η^2 was interpreted as small (0.01), medium (0.06), and large (≥ 0.14), following standard benchmarks for ANOVA.

Meteorological data (temperature, humidity, and wind velocity), recorded using Voltcraft DL-140TH and Testo 410i devices, were organized by treatment period and imported into SPSS for correlation analysis. Pearson's correlation coefficients (r) were computed to assess the relationship between herbicide efficacy and key meteorological variables, with significance tested at 0.05.

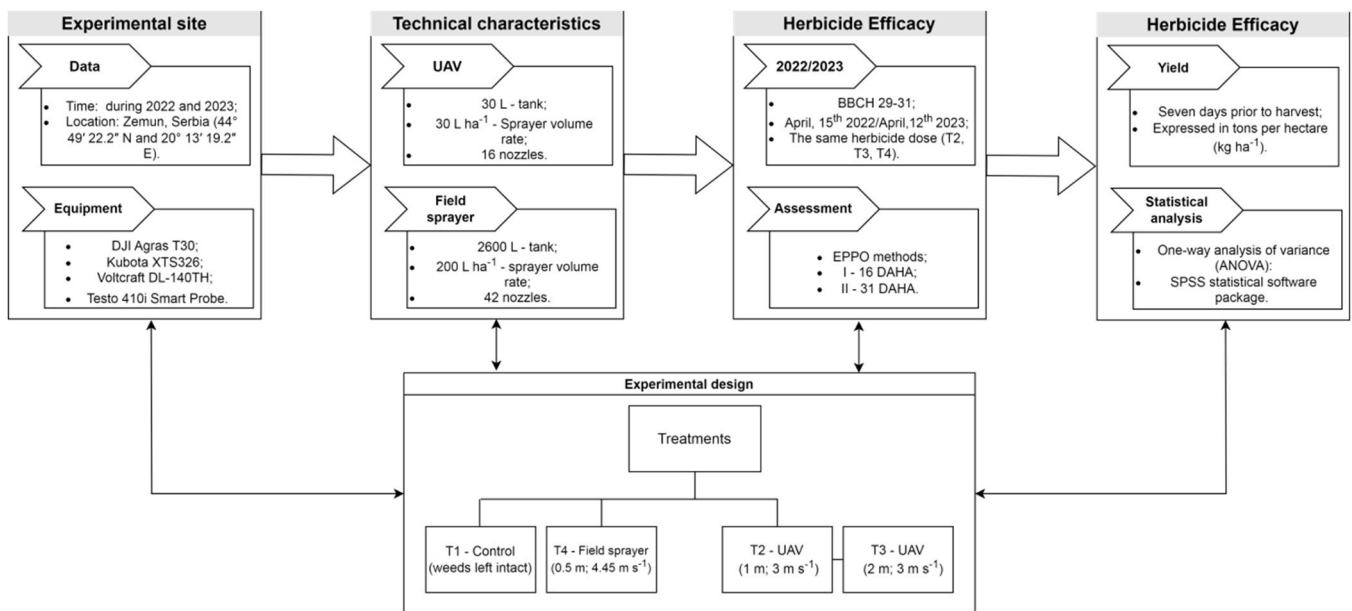


Fig. 5. Schematic representation of the methodological framework.

3. Results

3.1. Environmental conditions

According to the Serbian National Hydrometeorological Service (RHMZ, 2024), winters were mild in both study years. During the first year of study, the second-warmest winter was recorded in Belgrade. Additionally, spring conditions varied; the first year was drier and cooler than average, whereas the second year was wetter with near-average temperatures, which affected weed emergence dynamics. The weather conditions during herbicide application varied significantly between the two years (Table 2, Fig. 6). In the first year, the average conditions included moderate temperatures of approximately 16°C, relative humidity around 30–34 %, and low wind velocity. In contrast, the second year recorded much higher temperatures of about 30°C, lower humidity levels of around 24–28 %, and stronger winds.

Fig. 6 demonstrates significant variation in environmental conditions across the different years studied. In the first year, treatment T4 was administered at lower temperatures (approximately 16 °C) and higher relative humidity levels (31–34 %). In contrast, treatments T3 and T4 occurred at elevated temperatures (around 30 °C) and decreased humidity levels (24–28 %) during the second year. These year-to-year variations in weather conditions highlight the challenges associated with herbicide application.

3.2. Efficacy of weed control: density and fresh mass assessment

The distribution and density of weed species recorded in each treatment during the initial assessment are detailed in Table 3, highlighting variations in weed presence across the control and herbicide-treated plots. In the control treatment (T1), the highest weed density was observed in the first year, with 12 weed species recorded. The community was primarily dominated by *Veronica hederifolia*, followed by *Consolida regalis*, *L. purpureum*, *P. rheas*, and *G. aparine*. Other species were present at much lower densities, with fewer than 5 plants per square meter (Table 3). During the first two assessments, the densities of several species, including *Anthemis arvensis*, *G. aparine*, *L. serriola*, *L. amplexicaule*, *L. purpureum*, *P. rheas*, *Senecio vernalis*, and *V. hederifolia*, increased. In contrast, the densities of other species, such as *C. bursa-pastoris*, *S. arvensis*, and *V. arvensis*, remained stable but exhibited higher fresh mass. During the second assessment, the weed species *C. arvensis*, which was absent at 0 DAHA, was recorded. Considering the subsequent emergence of this species, the efficacy of the combination of *tritosulfuron* and *florasulam* for its suppression could not be determined (Table 3).

The presence of 9 weed species was confirmed in the treatment by applying the UAV system (T2, Table 3). The most abundant species in the T2 treatment was *L. purpureum* (100 plants m⁻²) during 0 DAHA. It is

followed by *V. hederifolia* (91 plants m⁻²), while the density of plants of the other weeds present was significantly lower. During 16 DAHA, both dominant species showed a slight increase, followed by a moderate decline at 31 DAHA.

The most abundant species in treatment T3 was *V. hederifolia*, with a density of 244 plants m⁻², followed by *L. purpureum* at 72 plants m⁻². Other weed species were observed in significantly lower densities. At 16 DAHA, there was a substantial decline in *V. hederifolia*, while *L. purpureum* initially increased before showing a reduction at 31 DAHA. During the 31 DAHA, we also noted the late emergence of *C. arvensis*. In addition to broadleaf weeds, *A. fatua* was recorded in treatment T3. However, it was not further analyzed as it falls outside the activity spectrum of the herbicide applied.

A total of 11 weed species appeared in the field sprayer treatment (T4). Including *A. arvensis* and *C. regalis* were not observed in UAV treatments (Table 3). As in the other treatments, the species *C. arvensis* was observed in 16 DAHA, which emerged after applying the herbicide. The dominant species was *V. hederifolia* (112 plants m⁻²), whose density gradually decreased and was significantly reduced by 31 DAHA. *L. purpureum* (28 plants m⁻²) was the second most abundant species, showing a temporary increase. Also, *C. regalis* (16 plants m⁻²) was represented with a slightly higher density, which increased in the first (20 plants m⁻²) and second (24 plants m⁻²) assessments. However, this is not the case in the control, where the density of this species per unit area stagnated (20 plants m⁻²). A similar situation was observed for the species *A. arvensis*, where the density of plants remained unchanged after applying the herbicide, which indicates that this herbicide is inefficient in controlling this weed species. Other species were present at low densities and were completely suppressed after herbicide application.

In the second year, 12 weed species were identified in the control treatment (T1) (Table 4). The most abundant weed species was *L. purpureum* (84 plants m⁻²), followed by *V. persica* (64 plants m⁻²), *V. arvensis* (41 plants m⁻²), *L. amplexicaule* (20 plants m⁻²) and *S. media* (16 plants m⁻²). During 16 and 31 DAHA, an increase in the number of weeds was noted in the T1 treatment. A significant increase in weed species *L. purpureum* (156 plants m⁻²) was recorded during 31 DAHA. Also, the weed species with < 5 plants m⁻² during 0 DAHA is *F. officinalis*, and 40 plants m⁻² were recorded on 31 DAHA. This may be attributed to its staggered germination pattern and relatively lower susceptibility to the applied herbicide. In addition, effective control of more sensitive species reduced interspecific competition, creating conditions that favored the emergence of new *F. officinalis* individuals.

Six weed species were identified in the UAV treatments (T2 and T3) (Table 4). *L. purpureum* and *V. persica* primarily dominated both treatments, while other species such as *V. arvensis*, *L. amplexicaule*, *S. media*, and *F. officinalis* were present in lower densities. After the herbicide application, weed densities decreased significantly. However,

Table 2

Overview of operational parameters, environmental conditions during application and herbicide efficacy for UAV and field spraying systems.

Year	DAHA	Treatments	Flight altitude (m)	Velocity of sprayer (m s ⁻¹)	Volume of sprayer (L ha ⁻¹)	Wind velocity (m s ⁻¹)	Temperature (°C)	Air humidity (%)	Herbicide efficacy (%)
First	16	T2	1.5	3	30	1.08	16.31	30.89	77.91
		T3	2.5	3	30	1.27	16.11	34.2	78
		T4	/	4.45	200	1.85	16.1	33.8	51
First	31	T2	1.5	3	30	1.08	16.31	30.89	84.3
		T3	2.5	3	30	1.27	16.11	34.2	83.21
		T4	/	4.45	200	1.85	16.1	33.8	65.24
Second	16	T2	1.5	3	30	1.9	30.89	28.55	77.86
		T3	2.5	3	30	1.18	34.2	24.36	69.15
		T4	/	4.45	200	1.52	33.8	27.66	73.26
Second	31	T2	1.5	3	30	1.9	30.89	28.55	87.49
		T3	2.5	3	30	1.18	34.2	24.36	90.36
		T4	/	4.45	200	1.52	33.8	27.66	92.16

Herbicide efficacy based on weed density.

DAHA = Days After Herbicide Application. Measurements were taken at 16, and 31 days after herbicide application.

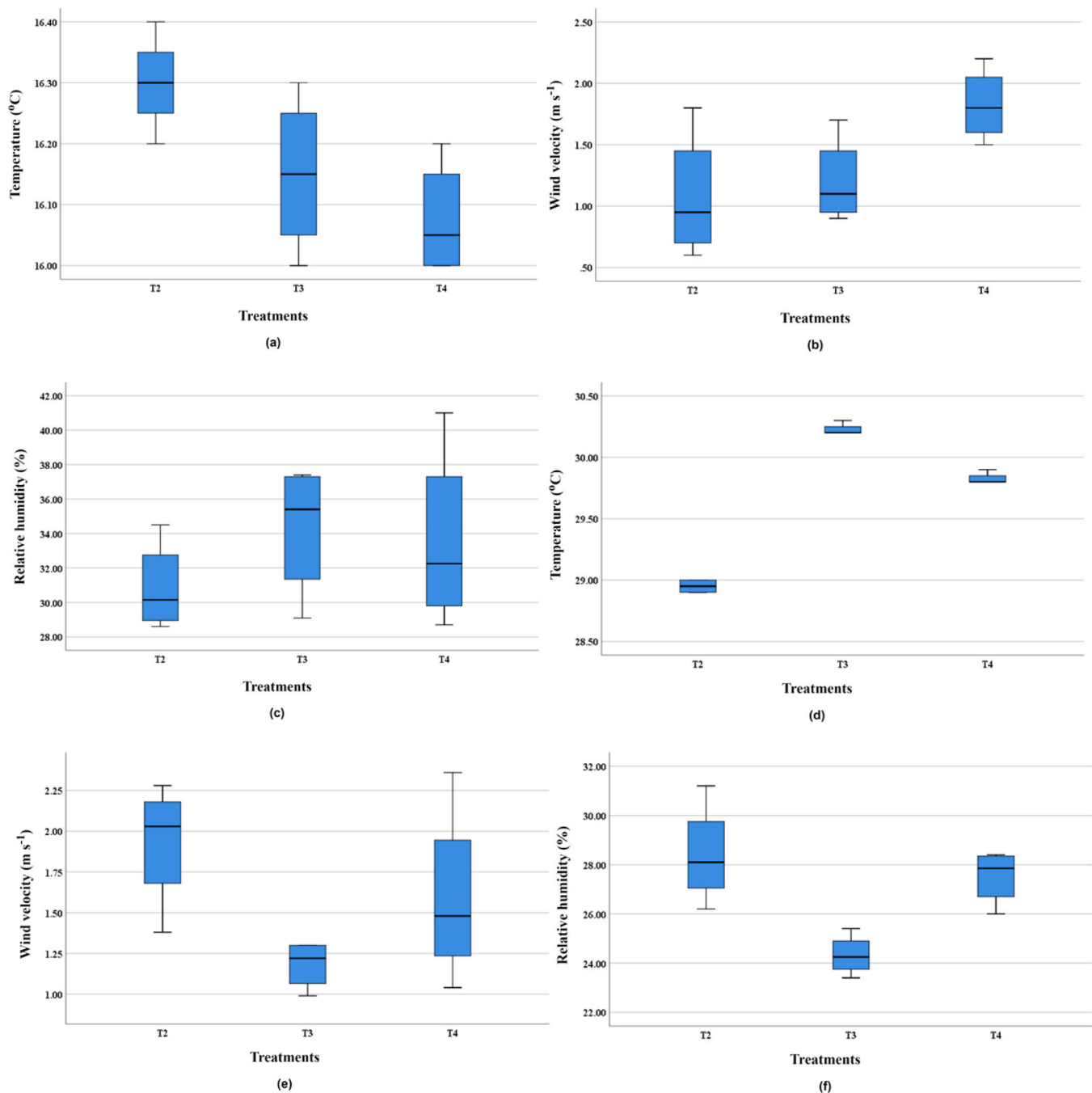


Fig. 6. Environmental conditions during herbicide application in the first and second year (a) Temperature (°C) in first year; (b) Wind velocity (m s⁻¹) in first year; (c) Relative humidity (%) in first year; (d) Temperature (°C) in second year; (e) Wind velocity (m s⁻¹) in second year; (f) Relative humidity (%) in second year.

L. purpureum remained more persistent, especially in T3, which was still at a higher density than the other species at 31 DAHA.

Six weed species were recorded in the field sprayer treatment (T4) (Table 4). The most abundant were *L. purpureum* and *V. persica*, while *S. media*, *L. amplexicaule*, and *V. arvensis* occurred at lower densities. Weed density declined after application, but *L. purpureum* persisted, with 48 plants m⁻² still recorded at 31 DAHA, confirming its higher tolerance compared to other species.

Throughout both study years, the control treatments (T1) consistently showed the highest weed density, with 12 species recorded. In contrast, treatments T2, T3 and T4 significantly reduced weed populations. While most species were effectively suppressed after herbicide application, certain weeds, such as *V. hederifolia* in the first year and

L. purpureum in the second year, exhibited greater persistence, remaining at higher densities across assessments.

One-way ANOVA analysis revealed statistically significant differences between treatments for the density and the fresh mass of plants per square meter in both observed periods in the first year (Table 5). Significant differences were found for the density at 16 DAHA ($F = 41.77$, $p = 0.0$) and 31 DAHA ($F = 12.505$, $p = 0.003$), with the treatment effect being more pronounced in the earlier period. Similarly, fresh mass significantly differed between treatments at 16 DAHA ($F = 14.846$, $p = 0.001$) and 31 DAHA ($F = 19.973$, $p = 0.000$), with differences becoming more pronounced over time. In the first year of the study, all evaluated parameters showed large effect sizes, as indicated by eta squared (η^2) values ranging from 0.735 to 0.903 (Table 5). This suggests

Table 3
Weed species by treatments in the first year.

Treatments	<i>Anthemis arvensis</i>	<i>Capsella bursa-pastoris</i>	<i>Consolida regalis</i>	<i>Convolvulus arvensis</i>	<i>Galium aparine</i>	<i>Lactuca serriola</i>	<i>Lanatum amplexicaule</i>	<i>Lanatum purpureum</i>	<i>Papaver rhoeas</i>	<i>Sinapis arvensis</i>	<i>Senecio vernalis</i>	<i>Veronica hederifolia</i>	<i>Viola arvensis</i>
0 DAHA													
T1	4	4	20	/	6	4	4	12	8	4	4	126	5
T2	/	4	/	/	/	4	4	100	4	4	4	91	2
T3	/	5	/	/	/	4	3	72	6	3	5	244	4
T4	10	4	16	/	/	4	4	28	8	8	4	112	4
16 DAHA													
T1	12	4	20	/	8	8	16	34	32	4	18	126	4
T2	/	/	/	/	/	/	/	104	/	1	/	93	/
T3	/	/	/	/	/	/	/	88	/	/	/	92	1
T4	12	2	20	/	4	4	/	36	/	/	4	112	1
31 DAHA													
T1	20	4	20	8	8	8	16	36	32	4	20	126	4
T2	/	/	/	4	/	2	/	80	/	/	/	52	/
T3	/	/	/	12	/	/	/	72	/	/	/	54	1
T4	16	/	24	4	/	2	/	36	/	/	/	66	1

DAHA = Days After Herbicide Application. Measurements were taken at 0, 16, and 31 days after herbicide application.

that the applied treatments explained a substantial proportion of the observed variability in herbicide efficacy, confirming the strong influence of treatment selection under the prevailing environmental conditions.

The Tukey test confirmed the differences between treatments, identifying specific groups that were statistically significantly different. These results indicate that the treatments had a lasting effect on density and mass, with differences in fresh mass becoming more pronounced at 31 DAHA. A statistical analysis of herbicides' overall efficacy during the first year of the study, based on the density of weeds, indicates a significant difference between treatments with the UAV system and the field sprayer (Table 6). Based on the average values, it can be observed that the efficacy of the applied herbicide was significantly lower in the treatment with the field sprayer compared to the treatments with the UAV system. During the 16 DAHA, in treatment T4, the average efficacy was 51 %, while in the treatments with UAV, it ranged up to 78 %. After the 31 DAHA, the efficacy increased in treatment T4–65 % and in the UAV treatments to 84 %.

Based on the fresh weed mass during the first year of the study, statistically significant differences are observed in the treatments with the UAV system (T2 and T3) compared to the field sprayer (T4) treatments. The same conclusions were reached during the 31 DAHA (Table 6). The average efficacy of the herbicide formulations was higher in treatments with the UAV system, while in treatments with the field sprayer, it was lower. All significant pairwise differences exhibited large effect sizes ($d > 0.8$), confirming the practical relevance of the observed treatment effects (Table 6).

One-way ANOVA analysis for the second year showed different significance levels depending on the observed parameter and the period after herbicide application. No statistically significant difference was found between treatments at 16 DAHA ($F = 3.116$, $p = 0.094$) for the density. In contrast, the differences became significant at 31 DAHA ($F = 6.037$, $p = 0.022$), indicating that the effects of treatments became more pronounced over time. In the case of fresh mass, significant differences between treatments were identified as early as 16 DAHA ($F = 7.42$, $p = 0.012$). They became even more pronounced at 31 DAHA ($F = 23.875$, $p = 0.000$), suggesting that the treatments had a long-term effect on plant mass.

The Tukey test further clarifies which treatment groups were statistically significantly different. Outcomes indicated that the treatments had a more significant impact on mass than plant density, with effects becoming more pronounced later, 31 DAHA. Tukey test shows in the second year of the study, at 16 DAHA, no statistically significant differences in treatment efficacy were observed (Table 6). However, at 31 DAHA, a statistically significant difference was detected between the T2 and T4 treatments. This difference indicates a higher efficacy of the applied herbicide in the field sprayer treatment than in the treatment with the UAV system.

A statistically significant difference was found between treatment T2 and treatments T3 and T4 based on fresh mass (Table 6). It can be seen that the highest mean value of efficacy was recorded in the treatment T2 (78 %), while it was lower in the treatments T3 (73 %) and T4 (73 %). Still, there were significant differences during 31 DAHA, where treatments T2 and T3 differed significantly compared to treatment T4. In the T4 treatment, a high mean efficacy value was recorded compared to the treatments T2 and T3. Based on the data obtained after 31 DAHA, the field sprayer achieved good efficacy of the applied herbicide. In contrast, the UAV system achieved satisfactory efficacy of the applied crop protection product.

Correlation analysis revealed that temperature was positively correlated with herbicide efficacy in both years, reaching statistical significance in the first year ($r = 0.586$, $p = 0.045$, Table 7). Wind velocity, on the other hand, showed a significant negative correlation with herbicide efficacy in the first year ($r = -0.588$, $p = 0.045$, Table 7), suggesting that higher wind velocities may have reduced treatment efficacy due to drift or non-uniform deposition. No significant correlations

Table 4

Weed species by treatments in the second year.

Treatment	<i>Consolida regalis</i>	<i>Fumaria officinalis</i>	<i>Galium aparine</i>	<i>Lactuca serriola</i>	<i>Lamium amplexicaule</i>	<i>Lamium purpureum</i>	<i>Papaver rhoeas</i>	<i>Senecio vernalis</i>	<i>Senecio vulgaris</i>	<i>Stellaria media</i>	<i>Veronica persica</i>	<i>Viola arvensis</i>
0 DAHA												
T1	4	4	4	4	20	84	8	4	4	16	64	41
T2	/	8	/	/	24	92	/	/	/	20	64	40
T3	/	/	/	/	16	104	/	6	/	14	64	38
T4	/	/	4	/	16	96	/	/	/	20	72	12
16 DAHA												
T1	4	36	4	4	20	84	8	4	4	20	64	52
T2	/	8	/	/	6	56	/	/	/	/	4	4
T3	/	/	/	/	6	140	/	1	/	4	4	2
T4	/	/	1	/	8	60	/	/	/	/	8	6
31 DAHA												
T1	4	40	4	4	20	156	8	4	4	56	80	96
T2	/	4	/	/	4	56	/	/	/	/	4	4
T3	/	/	/	/	/	68	/	/	/	4	4	2
T4	/	/	/	/	/	48	/	/	/	/	8	6

DAHA = Days After Herbicide Application. Measurements were taken at 0, 16, and 31 days after herbicide application.

Table 5

One-way ANOVA summary for herbicide efficacy (density and fresh mass) and wheat yield.

Parameter		DF	F-value	p-value	η^2
First year					
Efficacy based on weed density (%)	16 DAHA	2	41.77	0	0.903
	31 DAHA	2	12.505	0.003	0.735
Efficacy based on fresh weight (%)	16 DAHA	2	14.846	0.001	0.767
	31 DAHA	2	19.973	0	0.816
Yield (kg ha ⁻¹)		3	1.914	0.168	0.264
Second year					
Efficacy based on weed density (%)	16 DAHA	2	3.116	0.094	0.409
	31 DAHA	2	6.037	0.022	0.573
Efficacy based on fresh weight (%)	16 DAHA	2	7.42	0.012	0.622
	31 DAHA	2	23.87	0	0.841
Yield (kg ha ⁻¹)		3	2.26	0.121	0.298

The difference between treatments is statistically significant when the F-test result from the one-way ANOVA is $p \leq 0.05$. Effect size values (η^2) were interpreted according to conventional thresholds: small (≥ 0.01), medium (≥ 0.06), and large (≥ 0.14).

DAHA = Days After Herbicide Application. Measurements were taken at 16, and 31 days after herbicide application.

were observed for relative air humidity in either year, although a weak positive trend was noted in the second year ($r = 0.38$, $p = 0.223$). The graphical representations (Fig. 7) confirm these trends and further illustrate that the inter-annual weather variability influences treatment outcomes.

3.3. Weed control efficacy based on *L. purpureum* density and fresh mass

L. purpureum is one of the main weed species in the wheat fields in Serbia. Also, it was present in high abundance at the experimental field, especially in the second year. A statistical overview of *L. purpureum* density and fresh mass across treatments and assessment dates is presented in Table 8 and visualized in Fig. 8. During the first year, treatments T2 and T3 significantly reduced *L. purpureum* density and mass over time. By 31 DAHA, T2 achieved an 80 % reduction in plant density (from 100 to 20 plants m⁻²), while T3 showed comparable efficacy, despite a slightly lower initial density. Fresh mass weight followed a

similar trend, with a notable decline from 297.36 to 132.56 g m⁻² for T2 and 185.04–210.68 g m⁻² for T3. In contrast, the second year exhibited more variable results, with significantly higher initial weed pressure. Although all treatments started with high baseline densities (e.g., 104 plants m⁻² in T3), the final fresh mass at 31 DAHA varied considerably. T4 demonstrated the highest reduction in fresh mass from 298.60 g m⁻² to only 12.88 g m⁻², indicating strong herbicide performance under those conditions (Table 8, Fig. 8). UAV-based treatments (T2 and T3) were less effective, particularly in the second year, as reflected in the temporal dynamics of density and fresh mass.

Statistical analysis of the fresh mass weight data for *L. purpureum* at the 0 DAHA assessments indicated a significant difference ($p < 0.05$) among all treatments. The treatments T2 and T3 recorded the highest initial mass, while significantly lower values were observed in the treatments T1 and T4. By the 16 DAHA assessments, the differences in fresh mass remained statistically significant across all treatments. A notable reduction in fresh mass was seen in T3, while the other treatments, particularly T2, exhibited an increase in fresh mass.

At 31 DAHA, significant differences ($p < 0.05$) were again confirmed among nearly all treatments, except for T2 and T4, which were statistically similar. Treatment T2 exhibited the most significant reduction in fresh mass from baseline, suggesting that the applied herbicide had taken effect, inducing the weeds' visible senescence and physiological decline. Similarly, significant differences were also found between T3 and T4, confirming variable herbicide response across UAV and field sprayer (Table 8).

In the second year, the fresh mass of *L. purpureum* showed significant differences among treatments at all assessment dates ($p < 0.05$) (Table 8, Fig. 8). The treatment T1 continuously increased over time, reaching its highest values by 31 DAHA. In contrast, the treatment T4 achieved the most significant suppression, resulting in a sharp decline to the lowest final fresh mass. The UAV treatments (T2 and T3) offered partial control, with noticeable reductions, although not as pronounced as the results seen with T4.

Notably, at 31 DAHA in the second year, a clear statistical difference in *L. purpureum* fresh mass was observed between the two UAV treatments (T2 and T3). Treatment T2 resulted in significantly lower fresh mass (154.6 g m⁻²) than T3 (288.3 g m⁻²), suggesting that application altitude influenced herbicide deposition and retention. In contrast, plant density values between T2 and T3 did not differ significantly at the same time, indicating that flight altitude affected the physiological condition of the plants (fresh mass accumulation), rather than immediate plant mortality. This pattern supports the hypothesis that UAV operational parameters, specifically flight altitude, can influence herbicide efficacy beyond weed density.

Table 6
Herbicide efficacy in relation to weed density and fresh weight.

Year	DAHA	Treatments	Efficacy (%) based on weed density				Efficacy (%) based on fresh weight			
			Mean ± SE	95 % CI	Tukey	d	Mean ± SE	95 % CI	Tukey	d
First	16	T2	78 ± 4.43	[63–92]	a	T2-T4: 4.08	78 ± 3.71	[66–90]	a	T2-T4: 3.14
		T3	78 ± 1.45	[73–83]	a	T3-T4: 9.66	80 ± 2.68	[71–88]	a	T3-T4: 4.48
		T4	51 ± 1.30	[47–55]	b	T2-T4: 4.08 T3-T4: 9.66	61 ± 1.40	[56–65]	b	T2-T4: 3.14 T3-T4: 4.48
First	31	T2	84 ± 2.54	[76–92]	a	T2-T4: 2.89	88 ± 1.32	[84–93]	a	T2-T4: 3.60
		T3	83 ± 2.38	[76–91]	a	T3-T4: 2.77	88 ± 1.32	[84–93]	a	T3-T4: 3.63
		T4	65 ± 3.91	[53–78]	b	T2-T4: 2.89 T3-T4: 2.77	76 ± 1.99	[70–83]	b	T2-T4: 3.60 T3-T4: 3.63
Second	16	T2	78 ± 2.24	[71–85]	a	/	78 ± 1.66	[73–83]	a	T2-T3: 1.94 T2-T4: 2.22
		T3	69 ± 3.39	[58–80]	a	/	73 ± 0.82	[70–76]	b	T2-T3: 1.94
		T4	73 ± 1.13	[69–77]	a	/	73 ± 0.64	[71–75]	b	T2-T4: 2.22
Second	31	T2	87 ± 1.11	[84–91]	a	T2-T4: 2.35	88 ± 1.62	[83–93]	a	T2-T4: 3.69
		T3	90 ± 0.88	[88–93]	ab	/	87 ± 1.02	[83–90]	a	T3-T4: 5.47
		T4	92 ± 0.87	[89–95]	b	T2-T4: 2.35	98 ± 1.01	[95–101]	b	T2-T4: 3.69 T3-T4: 5.47

Different letters within a column indicate significant differences at the 0.05 significance level. Cohen’s d values indicate the magnitude of pairwise differences between treatments, with thresholds interpreted as follows: small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$), and large ($d \geq 0.8$).
DAHA = Days After Herbicide Application. Measurements were taken at 16, and 31 days after herbicide application.

Table 7
Pearson correlation between environmental conditions and herbicide efficacy based on weed density.

Variables	Vegetation season	Pearson (r)	p - value	Sig.
Temperature - Herbicide efficacy (density of weeds)	First	0.586	0.045	*
	Second	0.572	0.052	-
Wind velocity - Herbicide efficacy (density of weeds)	First	-0.588	0.045	*
	Second	-0.099	0.759	-
Air humidity - Herbicide efficacy (density of weeds)	First	-0.046	0.888	-
	Second	0.38	0.223	-

Statistical significance at $p \leq 0.05$.

3.4. Interannual variation in wheat yield under UAV and conventional herbicide applications

The statistical analysis in Table 5 shows no statistically significant differences in yield among treatments in the first year ($F = 1.914$, $p = 0.168$) or the second year ($F = 2.26$, $p = 0.121$), as the p-values exceed the 0.05 threshold. While some variation in yield was observed, it was not substantial enough to confirm a significant treatment effect. However, mean values indicate some variations in yield. In the first year, the highest yield was achieved in treatment T4 (8571.118 kg ha⁻¹), while the lowest was in treatment T1 (6842.144 kg ha⁻¹). Treatments T2 (8204.658 kg ha⁻¹) and T3 (7205.434 kg ha⁻¹) had intermediate values (Fig. 9).

In the second year, although the differences were not statistically significant, a noticeable decrease in yield was observed in treatment T4 (7610.794 kg ha⁻¹) compared to the previous year, while T2 (8126.748 kg ha⁻¹) and T3 (8026.366 kg ha⁻¹) maintained relatively high values. Treatment T1 also had the lowest yield in the second year (6905.900 kg ha⁻¹), similar to its result in the first year (Fig. 9).

This indicates that the herbicides used did not significantly impact crop yield, which remained consistent across different treatments, despite variations in weed suppression. Since fertilization and all other agronomic practices were applied uniformly across the plots, the absence of yield differences is more likely due to other uncontrolled factors, such as disease incidence and insect pressure, rather than the methods of herbicide application. The untreated control consistently produced significantly lower yields than all herbicide treatments, highlighting the detrimental effect of uncontrolled weed competition on crop performance.

4. Discussions

The performance of the treatments varied across the years, partly due to the influence of environmental conditions during herbicide

application. In the first year, moderate temperatures (around 16 °C), higher relative humidity (approximately 34 %), and lower wind velocity (1.1–1.3 m s⁻¹) created conditions that were generally favorable for herbicide deposition and absorption. In contrast, the second year was marked by elevated temperatures (around 30 °C), lower humidity (24–28 %), and higher wind velocity (about 1.9 m s⁻¹). These conditions typically lead to increased droplet evaporation, reduced absorption, and a higher risk of drift (Peterson et al., 2015; Wang et al., 2020). These findings are consistent with broader agricultural research indicating that meteorological factors play a crucial role in determining application outcomes. For instance, Martin et al. (2024) found that UAVs can create more drift than field sprayers at distances up to 10 m, particularly in windier conditions. Conversely, Gibbs et al. (2021) noted that when UAVs are precisely calibrated, they may produce less drift than field sprayers.

UAV systems with nozzles producing smaller droplets (130–250 μm) achieved even distribution under favorable environmental conditions (Zhou et al., 2023; Martin et al., 2024), contributing to enhanced herbicide efficacy in the first year. However, under high temperatures and low relative humidity, such fine droplets are more prone to rapid evaporation, limiting their absorption and biological activity, a trend previously observed by Ahmad et al. (2020). This was partially reflected in the second year, where elevated temperatures (~30 °C) and lower relative humidity (<28 %) coincided with slightly lower efficacy in T2, the UAV treatment applied from 1.5 m. While overall efficacy remained high across all treatments in the second year, T2 showed reduced weed suppression compared to T3 and T4, despite its lower flight altitude. This outcome likely stems from the fact that T2 experienced the highest wind velocity during application (1.9 m s⁻¹), increasing the likelihood of droplet drift. This interpretation aligns with data from the first year, where Pearson correlation analysis confirmed a significant negative relationship between wind speed and herbicide efficacy ($r = -0.588$, $p = 0.045$). Wang et al. (2020) showed that increasing wind speed significantly improves drift, especially at speeds above 3 m s⁻¹, highlighting the sensitivity of UAV applications to wind conditions. These findings suggest that wind-induced losses may offset the theoretical advantage of lower flight altitudes when not matched with calm weather conditions. Therefore, while UAV systems can provide excellent efficacy under moderate and challenging environments, their performance is closely tied to real-time environmental conditions. These results underscore the importance of adaptive UAV flight programming and nozzle calibration, particularly regarding wind velocity, to minimize drift and optimize herbicide delivery.

Results of this study align with agronomic recommendations and manufacturer guidelines, which state that *iodosulfuron-methyl-sodium+amidosulfuron+mefenpyr-diethyl* performs optimally under warm and moist conditions when weeds are actively growing. In

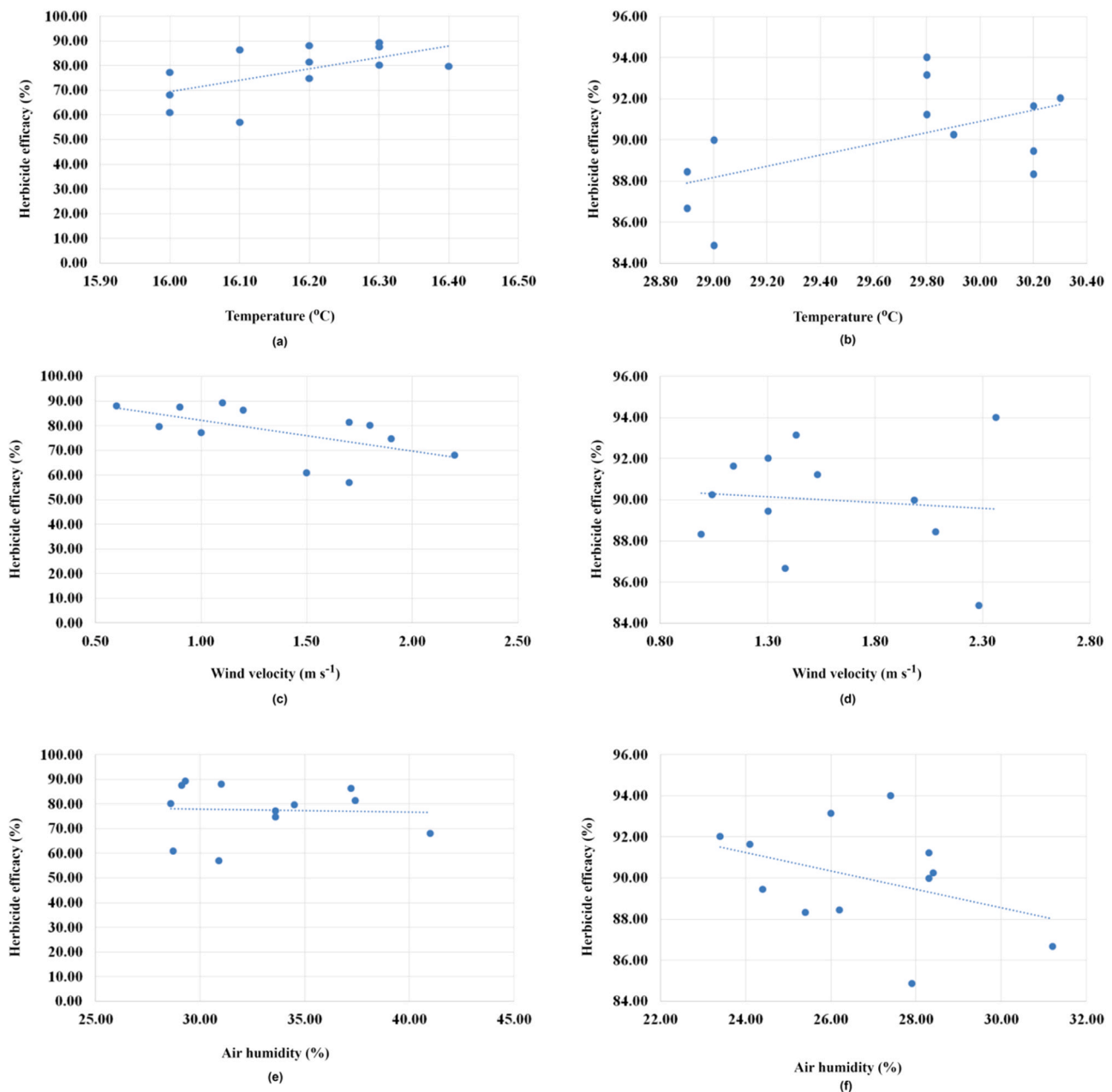


Fig. 7. Correlation between meteorological parameters and herbicide efficacy based on weed density (%) in the first and second years. (a) Temperature - Herbicide efficacy (first year), (b) Temperature - Herbicide efficacy (second year), (c) Wind velocity - Herbicide efficacy (first year), (d) Wind velocity - Herbicide efficacy (second year), (e) Air humidity - Herbicide efficacy (first year), (f) Air humidity - Herbicide efficacy (second year).

contrast, tritosulfuron + *florasulam* provides more consistent efficacy across a wider temperature range (Krieger et al., 2000). It is also well documented that weed control is delayed when air temperatures fall below 15 °C. In comparison, excessive heat (>30 °C) combined with low humidity (<50 %) can hinder absorption due to rapid droplet drying, thicker cuticles, and partial stomatal closure (Peterson et al., 2015). Our study reinforced these patterns observed in the field: higher wind velocity was linked to decreased herbicide efficacy, while increasing temperature was associated with improved efficacy. Paul et al. (2024) reported that UAV treatments performed optimally under 20–25 °C conditions, relative humidity above 50 %, and wind velocity less than 2 m s⁻¹, achieving a weed control efficacy of over 85 %. However, this efficacy dropped below 60 % when applications were made at higher temperatures and lower humidity levels.

Chen et al. (2019) reported 98–100 % weed control after

pre-emergence UAV application of *diflufenican* + *isoproturon* in wheat. However, post-emergence efficacy varied from 10 % to 70 % depending on environmental conditions and formulation. In the current study, UAV-applied treatments achieved 83–84 % efficacy in the first year and 87–90 % at 31 DAHA in the second year. Meanwhile, the field sprayer achieved high efficacy (up to 92 %) across the second year, but in the first year, it achieved a low efficacy of 65 %. Comparable UAV herbicide efficacy (86.98 %) was reported by Kumar et al. (2024) in wheat for *Phalaris minor* using commercial formulations with adjuvant. However, some studies have indicated that UAV systems may underperform when ultra-low-volume spraying is used without careful adjustment to canopy density and growth stage (Chen et al., 2019). By contrast, other studies, such as Paul et al. (2024), have shown that properly calibrated UAV systems adjusted for nozzle type, altitude, and herbicide concentration can achieve control levels similar to field sprayers, while offering

Table 8
Statistical analysis of mean density and fresh weight of *L. purpureum*.

<i>L. purpureum</i> – first year						
	Density (0 DAHA)	Density (16 DAHA)	Density (31 DAHA)	Fresh weight (0 DAHA)	Fresh weight (16 DAHA)	Fresh weight (31 DAHA)
	(Number of <i>L. purpureum</i> m ⁻²)			(g m ⁻²)		
T1	12 ± 0.71a	34 ± 2.74a	36 ± 2.42a	63.16 ± 2.56a	125.66 ± 2.64a	28.21 ± 1.39a
T2	100 ± 4.10b	104 ± 3.24b	80 ± 3.65b	269.04 ± 6.25b	297.36 ± 3.84b	132.56 ± 8.33b
T3	72 ± 4.56c	88 ± 4.60c	72 ± 4.34b	423.80 ± 5.56c	185.04 ± 5.39c	210.68 ± 6.80c
T4	28 ± 2.12d	36 ± 3.03a	36 ± 3.87a	119.04 ± 3.90d	204.36 ± 2.89d	111.76 ± 5.27b
<i>L. purpureum</i> – second year						
T1	84 ± 1.68a	84 ± 3.24a	156 ± 6.26a	385.76 ± 1.84a	454.24 ± 13.85a	506.16 ± 20.56a
T2	92 ± 2.97ab	56 ± 8.15b	56 ± 3.34bc	372.13 ± 20.20a	157 ± 7.38b	154.60 ± 10.87b
T3	104 ± 3.76b	140 ± 5.85c	68 ± 2.68b	389.11 ± 8.71a	249.64 ± 11.68c	288.28 ± 7.10c
T4	96 ± 2.86ab	60 ± 5.35ab	48 ± 3.24c	281.22 ± 13.28b	298.60 ± 10.06d	12.88 ± 2.35d

Different letters within a column indicate significant differences at the 0.05 significance level.
DAHA = Days After Herbicide Application. Measurements were taken at 0, 16, and 31 days after herbicide application.

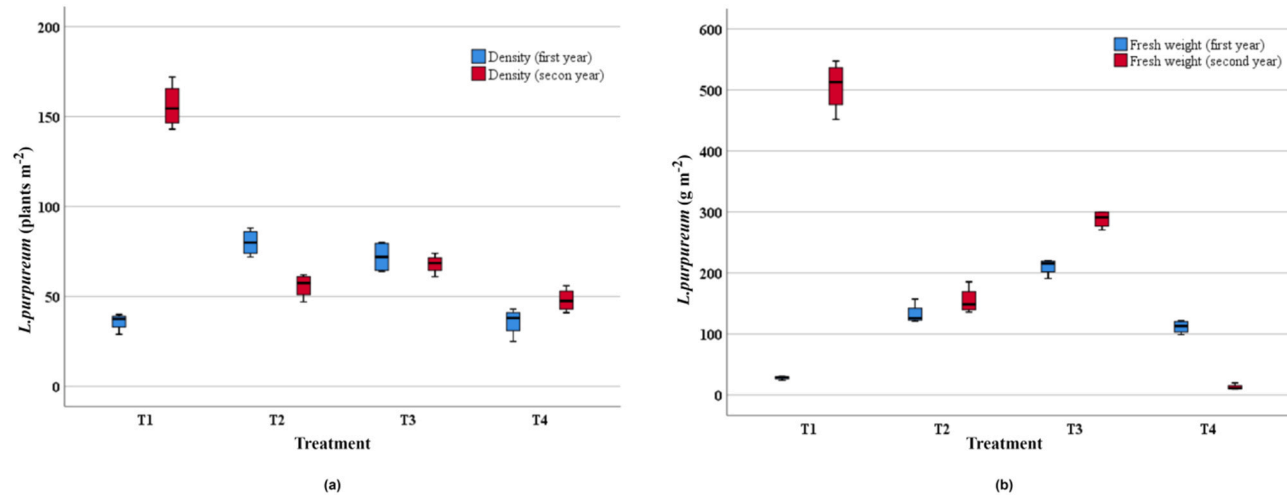


Fig. 8. Temporal dynamics of *L. purpureum* density and fresh weight under different herbicide treatments: (a) Plant density (plants m⁻²) at 31 DAHA in the first and second year; (b) Fresh weight (g m⁻²) at 31 DAHA in the first and second year.

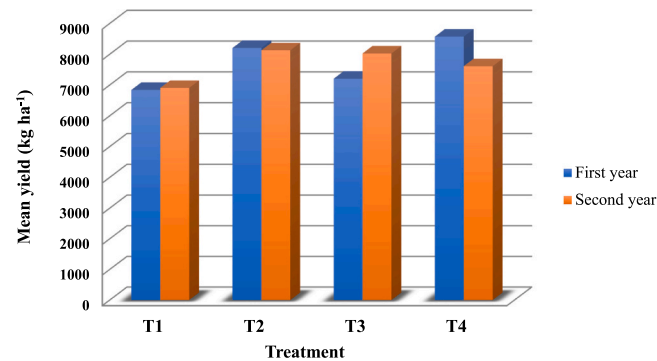


Fig. 9. Wheat yield (kg ha⁻¹) across different treatment variants (T1–T4).

benefits such as reduced soil compaction, minimal crop trampling, and substantial water savings.

These results emphasize that meteorological variables interact with herbicide chemistry and weed biology in complex ways, and their impact cannot be assessed in isolation. Consistent with prior studies, lower temperatures and higher humidity in the first year likely supported prolonged droplet retention and better systemic uptake (Wang et al., 2018; Huang et al., 2022). However, UAV-based efficacy was not consistently superior in the first year, suggesting that environmental conditions alone did not determine treatment success. Instead, the integrated influence of application method, herbicide properties, and

weed community dynamics shaped overall outcomes. Cultivar-specific traits such as plant height, leaf angle, and tillering capacity could affect spray penetration and herbicide efficacy (Kim et al., 2011).

Since different active herbicide ingredients and formulations were used across years, comparing absolute efficacy between years should be considered carefully. Nevertheless, within each year, treatments were internally consistent, and the relative differences observed among UAV flight parameters can be attributed to application conditions and herbicide chemistry. The herbicide efficacy in the second year was overall higher than in the first year, both in weed density and fresh mass reduction. This seemingly paradoxical outcome may be attributed to several factors: (1) the use of a different herbicide formulation in the second year (*iodosulfuron-methyl-sodium*+*amidosulfuron*+*mefenpyr-diethyl*), which may have provided greater systemic activity under dry conditions; (2) a higher initial weed pressure, which allowed more measurable reductions; and (3) possible enhanced herbicide translocation under stress-induced plant physiology.

During both study years, winters were mild, especially in the second year, when RHMZ (2024) reported the second warmest winter in Belgrade. These conditions favored the development of winter annual weeds alongside wheat. Our study confirmed this trend with an increased presence of early spring species such as *S. media*, *V. persica*, *L. purpureum* and *L. amplexicaule*. Similar findings have been reported by Masson et al. (2024) and Zhang et al. (2021a), who noted that mild winters and moist springs encourage early weed emergence and extend the reproductive cycle, particularly for *L. purpureum*. This rapid development can diminish herbicide efficacy, as plants may surpass the

optimal stage for susceptibility. Furthermore, the seeds of *L. purpureum* are capable of germinating even in winter under mild and moist conditions, highlighting the strong connection between climate and weed dynamics, explaining the rapid growth of this weed species in the second year.

Although flight altitude did not have a statistically significant main effect on overall herbicide efficacy across all treatments, year-to-year comparisons based on *L. purpureum* fresh mass suggest that application height may still influence biological outcomes. In both years, treatment T2 (UAV application at 1.5 m height) consistently reduced fresh mass more than T3 (2.5 m), despite both treatments using the same herbicide formulation and UAV platform. This pattern was particularly evident at 31 DAHA, where fresh mass differences between T2 and T3 were statistically significant in the second year, favoring the lower-altitude application. These findings indicate that, while flight altitude did not significantly affect final efficacy values, it may influence the efficacy of herbicides based on individual weeds. This supports the hypothesis that lower application heights can improve canopy coverage and reduce drift, especially under variable or adverse weather conditions, as Dengeru et al. (2022) reported.

Weed species-specific outcomes from this study reinforce the established principle that early and timely herbicide applications are critical for effective control, particularly for *L. amplexicaule* and *L. purpureum* (Mitkov et al., 2017; Yanev, 2022). *L. purpureum* was the dominant species across both years and proved highly responsive to herbicide timing, application method, and environmental conditions. Intensive fertilization likely gave *L. purpureum* a competitive advantage, especially under conditions that favored rapid canopy closure and nutrient uptake. These outcomes underscore the need for integrated weed management (IWM) strategies that combine timely herbicide application with balanced fertilization and effective crop rotation.

The emergence of *C. arvensis* during the later stages of the vegetation season revealed the impediments of post-emergence herbicides in managing perennial or late-germinating weeds. This observation aligns with prior findings on the reduced efficacy of tritosulfuron + florasulam against *C. arvensis* and suggests the need for sequential or alternative strategies when such species are present (Mitkov et al., 2017). Beyond weed control, yield variability across treatments and years highlights the broader role of agronomic management. In particular, differences in soil nutrient status and crop vigor appeared to exert a greater influence on final yield than herbicide efficacy alone, especially in the second year. These findings are consistent with Olsen et al. (2021) and Zhang et al. (2020), who emphasize that weed suppression is only one of several interrelated factors contributing to yield stability in complex agroecosystems.

In China, UAV-applied fluroxypyr-meptyl (600 mL ha⁻¹) increased wheat yield by 14.6 % compared to manual spraying, rising from 8100 to 9300 kg ha⁻¹ (Chen et al., 2019). In the present study, during the second year, UAV treatments also increased yield compared to the field sprayer (T4), with T2 achieving a 6.78 % increase and T3 a 5.46 % increase. In India, a combined approach using ground-based pre-emergence and UAV-based post-emergence herbicide applications limited yield loss to only 2.8 % compared to a weed-free control. In comparison, untreated plots experienced a 38 % yield reduction (Kumar et al., 2024a). Pranaswi et al. (2024) reported that UAV-only treatments produced wheat yields between 3215 and 3511 kg ha⁻¹. These treatments also resulted in reduced weed density and better herbicide distribution across the canopy. Our findings are consistent, as UAV applications effectively suppressed weeds and achieved yield levels comparable to conventional spraying.

This study indicates that weed pressure did not significantly impede yield development under the examined conditions. All treatments received the same fertilizer applications and followed the same agronomic practices, suggesting that nutrient availability is unlikely to have contributed to yield variations. While other biological factors, such as diseases and insect infestations, can influence yield, these variables were

not assessed in this research and are outside its scope.

It is also important to note that the benefits of weed control may not always be immediately apparent in yield during a single growing season. Effective weed suppression could provide indirect advantages, such as reduced seed banks, less early-season competition, and improved harvest conditions due to lower weed mass (Zhang et al., 2021; Masson et al., 2024). Although the yield differences between UAV and field sprayer treatments were not statistically significant in our study, UAV systems inherently avoid crop trampling and wheel tracks. Previous research indicates that this can help maintain up to 6 % of harvestable yield (Ivezić et al., 2023), showcasing an additional indirect benefit of UAV-based crop protection that was not captured in the current study.

In treatment T3, where the UAV was operated at a higher flight altitude, grain yield was lower in the first year than in the second year. The lower yield observed in the first year can be partly attributed to the presence of grass weeds, which were not effectively targeted by the applied herbicide, and the high incidence of *Convolvulus arvensis* in this treatment. Both of these weed groups are known to reduce wheat yield; specifically, *A. fatua* can cause yield losses of up to 10 % in cases of severe infestation (Jäck et al., 2017). Additionally, losses in wheat grain yield have been reported to range between 10 % and 28 % when *C. arvensis* densities are between 8–20 plants m⁻² (Safdar et al., 2019). In this study, 12 plants were recorded in the T3 treatment after 31 DAHA. This indicates that the reduced yield in the first year of T3, which was 10.2 % lower compared to the second year, was influenced by the UAV application parameters and the added pressure from weeds.

Unlike many prior studies focused mainly on droplet characteristics or drift potential, the present research contributes a dual-season biological efficacy assessment of commercially available herbicides under real-world environmental conditions. The results suggest that UAV efficacy can drop significantly under suboptimal environmental conditions when using standard agrochemical formulations. These findings emphasize the need for dynamic UAV application protocols, including real-time weather integration, adaptive nozzle calibration, and altitude control, to ensure stable and reproducible herbicide performance in diverse agronomic environments. This study also reconfirms crop safety during UAV-based applications. Despite higher herbicide concentrations delivered via UAV systems, no phytotoxic effects on wheat were observed. This suggests that UAV technology's precision and controlled deposition can safeguard crop health while maintaining effective weed suppression. Furthermore, the reduced water volume in UAV applications aligns with the increasing necessity for water-efficient agricultural practices, making UAV systems an environmentally friendly and economically sustainable choice for future weed management.

Overall, this research successfully achieved its aim and objectives with a comprehensive investigation of UAV-based herbicide applications compared to field sprayers, and its findings substantiate the potential of UAV-based herbicide application as an efficient, flexible, and environmentally conscious alternative to conventional spraying systems. However, its efficacy is highly contingent upon environmental conditions, herbicide formulation, and precise operational parameters. By integrating real-time weather monitoring, flight altitude, and droplet size optimization, UAV systems can meet and exceed, in some contexts, the performance of field sprayers, especially in conservation-minded or hard-to-access agricultural landscapes.

5. Conclusions

This study provides compelling evidence that UAV-based herbicide application represents a promising, efficient, and adaptable alternative to field sprayers for wheat weed management. By systematically comparing both application systems across two years under environmental conditions using (1) tritosulfuron + florasulam and (2) iodosulfuron-methyl-sodium + amidosulfuron + mefenpyr-diethyl, the research highlights that herbicide efficacy is shaped not only by the delivery platform but also by the complex interplay between environmental

variables, droplet behavior, herbicide formulation, and the growth stage of target weed species. UAV systems demonstrated strong performance against weeds, particularly under cooler, more humid conditions, while field sprayers proved resilient in warmer, drier environments. Furthermore, correlation analysis in the first year revealed that increased wind speed negatively affected herbicide efficacy. At the same time, higher temperatures were associated with improved control, indicating that meteorological factors should be integrated into UAV flight and nozzle calibration planning.

A key contribution of this study is that it demonstrates that UAV spraying, while operationally advantageous in maneuverability, resource efficacy, and soil preservation, also introduces new variables in herbicide performance and optimization. Notably, flight altitude alone did not dictate weed control success; however, fresh mass data for *L. purpureum* showed reduced values at the lower flight height (T2, 1.5 m), suggesting enhanced deposition. These findings help practitioners to establish a scientific basis for refining UAV-specific application protocols and emphasize the importance of precise herbicide timing, especially for species like *L. purpureum*, where the growth stage and environmental stress strongly influence treatment success. Policy-makers should use the study findings to integrate UAV-compatible protocols into sustainable farming guidelines, invest in training programs for precision agriculture, and promote research on formulation standards that align with emerging aerial application methods. Such efforts will accelerate the transition to resource-efficient, environmentally responsible crop management systems.

Overall, the major strengths of this study are:

- Direct side-by-side comparison of UAV and field sprayer systems across treatment scenarios over a two-vegetation season field experiment conducted under real-world production conditions, allowing assessment of seasonal variability in herbicide efficacy.
- Assessment of two widely used commercial herbicides (*tritosulfuron* + *florasulam* and *iodosulfuron-methyl-sodium* + *amidosulfuron*), representative of European wheat production.
- Species-specific efficacy analysis showing *L. purpureum* suppression of up to 85 % in the first year, with differences in fresh mass linked to UAV flight altitude.
- Robust statistical validation, including η^2 values up to 0.903 and Cohen's $d > 0.8$ for all significant pairwise comparisons.
- Operational insights highlighting UAV advantages (maneuverability, soil preservation, low volume: 30 L ha⁻¹) and limitations under high wind conditions.
- International relevance supported by external studies reporting UAV weed control efficacy of 86–100 % and yield gains of up to 14.6 %.
- Demonstrated potential of UAV systems to achieve up to 90 % weed control by 31 DAHA, despite reduced spray volume, supporting their efficacy in sustainable herbicide management.

Despite these promising outcomes, this study acknowledges certain limitations that warrant further research. The study was conducted in a single location (Zemun, Serbia), and the effect of environmental factors (soil type, topography, and regional weed flora) on the obtained results was not analyzed. Also, only one cultivar ('Sofru-RWA' (Lidea)) was used, limiting the generalization to other cultivars. Therefore, the results should be interpreted with caution beyond this site, and multi-location trials should be conducted to confirm the broader applicability of UAV herbicide application parameters. One of the interesting observations in this study is the simultaneous change of herbicide formula and the change in environmental conditions over two years. The interaction between environmental conditions and formula on drug efficacy needs to be further studied through comparative experiments with different formulas under the same environmental conditions to identify the underlying causation.

The absence of herbicide formulations specifically optimized and approved for UAV application remains a regulatory and technical

bottleneck. Additionally, payload constraints, weather-dependent performances, and the operational technicalities of UAV systems present real-world adaptation barriers and demand skilled technicians. These limitations highlight the need for continued innovation in equipment and application techniques, regulatory frameworks, and operator training. Future research should prioritize the development of UAV-compatible herbicide formulations, optimized droplet spectra, and adaptive flight control algorithms using machine learning techniques that enhance deposition consistency under diverse environmental conditions. Further investigations are also needed to assess the long-term agronomic and economic impacts of UAV-based weed control and establish policy guidelines that support the safe, effective, and scalable integration of UAV technologies into modern, sustainable agriculture systems.

CRediT authorship contribution statement

Milan Drazic: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kosta Gligorevic:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Velibor Spalevic:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Shuraik Kader:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Milos Pajic:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Funding acquisition. **Biljana Boskovic:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dragana Bozic:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Ethical approval

Not applicable.

Declaration of Competing Interest

The authors declare no conflicts of interest related to this article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127945.

Data availability

Data will be made available on request.

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