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DROPLET SIZE STATISTICAL ANALYSIS IN CHEMICAL CROP PROTECTION WITH UNMANNED AERIAL VEHICLE

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Abstract: The development of modern technologies in agriculture, particularly the use of unmanned aerial vehicles (UAVs), has enabled significant advancements in pesticide application, resulting in greater efficiency and precision in crop protection. This study aims to analyze the effects of various UAV flight parameters, specifically flight altitude, on droplet size and distribution uniformity. Field trials were conducted on the municipality of Zemun-Belgrade, Republic of Serbia, Latitude: North 44° 49' 22.2" and Longitude: East 20° 13' 19,2", with an altitude of 73 m. Different flight heights (1.5 m and 2.5 m) were tested at a constant flight speed of 3 m/s.

The results indicated that smaller droplets, generated at higher flight altitudes, contributed to more uniform droplet distribution, while larger droplets at lower flight altitudes ensured better coverage.

The most favorable outcomes were observed at a flight altitude of 2,5 m, where droplet distribution was both more uniform and of higher quality.

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These findings emphasize the importance of optimizing UAV flight parameters to enhance pesticide application, leading to improved precision, reduced pesticide use, and a lower risk of environmental contamination.

Keywords: *Volume median diameter (VMD), coverage, UAV systems, flight altitude, flight velocity, chemical protection, pesticides.*

INTRODUCTION

The main methods of crop protection include agrotechnical, mechanical, thermal, biological, and chemical approaches. Among these, chemical protection, relying on the use of pesticides, is considered the fastest and most effective. However, its efficiency depends on the proper selection of pesticides, application techniques, the technical system used, and the training of the operator [2]. Pesticides are mixtures of active substances intended for plant protection. Their application is typically classified based on the physical state of the substance being released from the technical system, distinguishing between solid, liquid, and gas formulations. It is crucial to note that the form in which the substance is emitted from the machine significantly influences application efficacy [2].

In addition to the physical state, droplet size is a key factor in successful chemical protection. Droplet size affects surface coverage, penetration, and the distribution of plant protection products. Accordingly, classification can also be made based on droplet size, which is closely related to the type of machinery and equipment used [2]. The droplet size classification is as follows [3]: spraying (>250 μm), misting (50–250 μm), fine misting (25–125 μm), and fogging (<50 μm). Droplet characteristics play a critical role in the efficacy of chemical crop protection, as droplet size directly affects deposition, coverage uniformity, and penetration into plant surfaces. Fine droplets facilitate deeper penetration and more uniform coverage, which is essential for achieving optimal biological efficacy. In contrast, larger droplets provide less uniform coverage but are less susceptible to off-target movement. Upon exiting the nozzle, droplets are typically spherical; however, during flight, aerodynamic forces cause deformation, often resulting in a flattened shape, which can enhance surface contact. Nevertheless, external factors such as wind can significantly influence droplet trajectory, leading to spray drift. Drift represents the fraction of the pesticide that fails to reach the intended target, posing risks to non-target areas and potentially causing phytotoxicity in adjacent crops. This phenomenon is particularly critical with smaller droplets, which are more easily displaced by air currents, thereby compromising application efficiency and environmental safety [3].

Another critical factor influencing the efficacy of chemical plant protection is the phenological stage of the crop, as the morphology and surface area of above-ground plant organs vary significantly throughout the growing season. These structural changes affect both the interception and retention of spray droplets. Therefore, achieving uniform and effective coverage across different growth stages, while maintaining a consistent application volume, is essential to ensure optimal pesticide performance and to avoid under or over application [3]. The choice and performance of pesticide application equipment are equally pivotal to treatment success.

Studies indicate that approximately 70% of application inefficiencies are attributed to the mismanagement of application technology. Specifically, 40% of failures are linked to suboptimal equipment functionality (e.g., nozzle wear, pump irregularities), while 30% result from improper handling or incorrect calibration by the operator.
The remaining issues arise from unsuitable pesticide selection and poorly timed applications, which can compromise efficacy and increase the risk of resistance development or environmental contamination [3].

The advent of modern technology, particularly in the context of precision agriculture, has enabled more efficient and site-specific management of key agronomic and environmental variables, ultimately supporting optimal crop growth and resource utilization. UAVs have proven to be one of the most influential technologies in precision agriculture and forestry, as they are highly versatile and adaptable and can improve the accuracy and timing of field operations [1, 12, 13, 14]. UAVs are currently used in a variety of agricultural applications, including remote sensing, field mapping, crop reconnaissance and chemical protection. Their ability to navigate complex terrain and execute pre-programmed flight paths makes them particularly valuable in regions where conventional ground-based machines are limited. Modern or advanced UAV spraying systems can carry up to 70 liters of pesticide solution and carry out treatments with high spatial accuracy, reducing labor demand, minimizing operator exposure to hazardous substances, and lowering the risk of unintended environmental contamination [4].

The advent of modern technologies, particularly in the area of labor requirements, minimizes operator exposure to hazardous substances and reduces the risk of accidental environmental contamination [4]. Compared to conventional spraying platforms, UAVs offer greater control over key operational parameters such as flight altitude, speed and nozzle configuration, which in turn significantly influence droplet formation, spray pattern uniformity and target coverage. Droplet size and its distribution pattern are critical factors for application effectiveness and drift potential [5]. This research investigated the relationship between drone flight altitude and droplet formation dynamics, focusing on volume median diameter (VMD or $D_{v0.5}$) and spray deposition efficiency. The study also sought to determine how the variation in flight altitude affects the homogeneity of droplet distribution over the target area.

MATERIALS AND METHODS

Field trials were conducted on the municipality of Zemun-Belgrade, Republic of Serbia, Latitude: North 44° 49' 22.2" and Longitude: East 20° 13' 19,2", with an altitude of 73 m. Different flight heights (1.5 m and 2.5 m) were tested at a constant flight speed of 3 m/s., overing a total area of 0,48 ha.

Collectors were positioned in three replications, with a 10 m buffer zone between each. In each replication, the collectors were positioned linearly over a 20 m stretch within the spray path, spaced at 0,5 m intervals. Each collector was equipped with a single water-sensitive paper (WSP) placed on top, enabling the assessment of spray deposition and coverage quality.

The experiment included two treatment variants (Table 1., Fig. 1), differing in UAV flight altitude while maintaining the same flight velocity. The spray volume was set at 30 l/ha, and the UAV operated with a spray swath width of 3,3 m. Each treatment was replicated three times.

For consistency, the UAV took off and landed at the same location for all repetitions. A solution consisting of water and red dye, commonly used in spray pattern analysis, was applied, with the dye added at a concentration of 450 g/ha.

Table 1. Summary of experimental treatments

Treatment	Technical system	Operating parameters
T1	Unmanned Aerial Vehicle	h = 1,5 m; v = 3 m/s
T2	Unmanned Aerial Vehicle	h = 2,5 m; v = 3 m/s

*h - flight altitude; v – flight velocity.

Technical system

In this study, the DJI Agras T30 UAV (Figure 1) was utilized for pesticide application in field conditions. The UAV is equipped with six electrically powered rotors and operates using high-capacity lithium-ion batteries (29,000 mAh, 22.2 V), enabling a maximum flight duration of approximately 15 min per charge. The system's maximum take-off weight is 66 kg, which includes a 30-liter chemical tank intended for liquid pesticide formulations. The spraying unit is powered by a diaphragm pump capable of delivering up to 7.2 L/min under a working pressure of approximately 0.3 MPa. The UAV is fitted with sixteen SX11001VS flat-fan nozzles, allowing for a consistent spray distribution across an effective swath width of 5 to 7 meters, depending on the pre-set flight speed and altitude. During application, the UAV operates at a height of 2.5–3.0 m above the crop canopy and at a maximum forward velocity of 7.0 m/s. Droplet size, expressed as volume median diameter (VMD), typically ranges between 150 and 250 µm and is influenced by nozzle type, operating pressure, flight dynamics, and ambient meteorological conditions. The T30 is integrated with advanced navigation systems, including GPS and real-time kinematic (RTK) positioning, ensuring high-precision autonomous flight. Real-time terrain adaptation is achieved through onboard radar and ultrasonic sensors that maintain a constant application height over variable topography. Additional safety features include an obstacle-avoidance system and an automatic return-to-home function activated in case of low battery or signal loss. The onboard control unit dynamically adjusts spraying parameters in response to real-time environmental data, aiming to enhance deposition uniformity while reducing off-target drift and environmental exposure.

Figure 1. UAV system for pesticide application in wheat fields

Data Collection and Analysis

WSPs served as artificial collectors for droplet deposition assessment. The collected samples were scanned in grayscale at a resolution of 600 DPI to obtain digital records of spray coverage. Image processing and analysis were conducted using DepositScan™ software, which enabled the quantification of deposition parameters, including droplet density per unit area, percentage of surface coverage, and droplet size distribution [11]. The classification of droplet spectra was determined based on VMD and droplet diameter (DD), following the criteria outlined by Matthews [12].

To evaluate the uniformity of droplet deposition across different sampling points, the coefficient of variation (CV) was calculated. The distribution of spray droplets plays a key role in ensuring even pesticide coverage across the target surface. In this study, the uniformity of droplet deposition was analyzed based on variations in deposition patterns, droplet density, and surface coverage. A lower CV value indicates a more uniform distribution of droplets. The coefficient was calculated using [10], the following equations:

$$CV = \frac{SD}{M} * 100\% \quad \text{and} \quad SD = \sqrt{\sum_{i=1}^{n}(x_i - M)^2/(n-1)}$$

Where is,
SD - represents the standard deviation,
M - denotes the mean droplet deposition value,
x_i - refers to the number of droplets per square centimeter of WSP,
n - the total number of WSP collectors used in each UAV treatment.
During data processing, the following parameters were specifically evaluated [7]:

- $D_{v0.1}$ represents the droplet diameter below which 10% of the total spray volume is contained. It reflects the presence of very fine droplets in the distribution
- $D_{v0.5}$ (VMD) is the droplet diameter below which 50% of the spray volume resides. It serves as the median value, indicating that half of the total volume is composed of droplets smaller than this diameter, and half larger
- $D_{v0.9}$ corresponds to the droplet diameter below which 90% of the total spray volume is found. It provides insight into the coarseness of the spray, capturing the contribution of larger droplets

- RS (Relative Span) is an index describing the width of the droplet size distribution. It is calculated using the formula:

$$Rs = \frac{Dv0.9 - Dv0.1}{Dv0.5(VMD)}$$

A lower RS value indicates a narrower and more uniform droplet size distribution, which is generally desirable for consistent spray coverage.

Conversely, higher RS values reflect greater variability in droplet sizes, which may negatively affect application uniformity [7]. The data were analyzed using one-way analysis of variance (ANOVA) in the statistical software IBM SPSS Statistics (version 29.0.1.0). Where significant differences were observed, post hoc comparisons were performed using Student's t-test to determine pairwise differences between treatment means.

Before the statistical analysis, assumptions of normality and homogeneity of variances were tested using the Shapiro–Wilk and Levene's tests, respectively.

If necessary, coverage and droplet size data were subjected to appropriate transformations (e.g., log or square root) to meet the assumptions of parametric analysis. All results are reported as mean values (M) accompanied by standard deviations (SD). A significance level of $p < 0,05$ was considered statistically significant for all tests.

RESULTS AND DISCUSSION

Following the placement of collectors and water-sensitive papers at predefined field locations, application was performed using the UAV system. Upon completion, WSP papers were carefully retrieved and transported to the laboratory for subsequent analysis.

Statistical analysis of the collected data was conducted using IBM SPSS Statistics. A one-way analysis of variance (ANOVA) was employed to assess differences between treatment groups, with the results summarized in Table 2. Statistically significant differences were observed between treatments T1 and T2 for the VMD ($F = 6,430$; $p = 0,012$) and for $D_{v0.9}$, representing the droplet diameter below which 90% of the spray volume is contained ($F = 4,273$; $p = 0,041$). These findings indicate that flight altitude had a measurable impact on both the central tendency and the upper bound of droplet size distribution. To further elucidate the nature of these differences, pairwise comparisons were conducted using Student's t-test, focusing specifically on the VMD and $D_{v0.9}$ parameters.

On the other hand, no statistically significant differences ($p > 0,05$) were detected between treatments for the remaining evaluated parameters, suggesting that flight altitude did not have a pronounced effect on other aspects of droplet characteristics under the given experimental conditions. Nevertheless, despite the absence of statistical significance, the observed mean values indicates a consistent trend that may point to potential differences in spray performance depending on flight altitude. These tendencies, while not statistically confirmed, may still carry practical relevance, particularly in the context of optimizing UAV application protocols for enhanced efficacy in plant protection. Such findings underscore the importance of considering both statistical outcomes and biological or operational implications when interpreting field trial results, especially when aiming to refine UAV-based spraying strategies in diverse crop production systems.

Table 2. ANOVA results for spray deposition parameters

Factor	Parametars	DF	SS	F	p	Sig.
Flight height	Coverage	1	0,372	0,112	0,739	NS
	VMD	1	8181,22	6,430	0,012	*
	$D_{v0.1}$	1	2121,34	2,743	0,100	NS
	$D_{v0.9}$	1	322747,1	4,273	0,041	*

*Note: p represents the significance level of the factor affecting the result. $p < 0{,}01$ (**) indicates that the factor has a highly significant impact on the test result, $p < 0{,}05$ (*) indicates that the factor has a significant impact on the test result, and $p > 0{,}05$ (NS) indicates that the factor does not have a significant impact on the test result.

Results from Student's t-test confirmed that flight altitude had a statistically significant effect on both the VMD ($p = 0{,}012$) and $D_{v0.9}$ ($p = 0{,}042$), as shown in Table 3. These findings suggest that variations in UAV flight altitude can meaningfully alter droplet size characteristics during application. Analysis of mean values revealed that VMD decreased at higher flight altitudes, indicating the generation of finer droplets. This droplet profile may enhance coverage uniformity across the leaf surface and improve deposition on the target area, contributing positively to treatment efficacy. However, finer droplets are also more prone to spray drift, particularly under windy conditions, which introduces a potential risk for off-target contamination. A similar trend was observed for $D_{v0.9}$, with lower values recorded at higher altitudes. This further supports the conclusion that increased altitude results in a higher proportion of fine droplets within the overall spray volume. Such a distribution affects not only the biological efficacy and application precision but also the environmental safety of the treatment. Taken together, these results highlight the critical role of UAV flight altitude in shaping important technical parameters of pesticide application. Optimizing flight altitude is thus essential for balancing treatment effectiveness with drift reduction, ultimately supporting the goals of precision agriculture and sustainable crop protection practices.

Table 3. Comparison of VMD and $D_{v0.9}$ between treatments (t-test results)

Parameters	t	d.f.	p^*
VMD	2,536	122,31	0,012
$D_{v0.9}$	2,067	71,60	0,042

*p values less than 0,05 indicate a statistically significant difference.

Table 4., presents the mean values of all evaluated parameters, offering a comprehensive overview of application performance under different flight altitudes. The data indicate that at higher flight altitudes, the VMD was lower, suggesting the formation of finer droplets.

This was accompanied by a slight reduction in overall spray coverage, likely influenced by increased droplet dispersion due to higher release height and enhanced exposure to external factors such as wind and air turbulence.

However, this difference was not statistically significant. In contrast, lower flight altitudes resulted in larger VMD values, indicating the generation of coarser droplets. These larger droplets contributed to higher total coverage, but at the expense of uniformity, as evidenced by an increased CV.

Moreover, the RS, a measure of droplet size distribution uniformity, was lower at higher altitudes, reinforcing the observation that finer droplets were more evenly distributed across the treated surface. This finding is particularly relevant in the context of chemical application effectiveness, as uniform droplet distribution is essential for achieving consistent coverage and ensuring reliable protection across the entire target area.

Table 4. Mean values of spray application parameters by treatment

Treatment	Coverage (%)	VMD (µm)	$D_{v0.1}$ (µm)	$D_{v0.9}$ (µm)	RS
T1 (I)	5,82±3,25	273,62±27,95	129,48±11,44	594,95±91,80	1,72
T1 (II)	5,09±2,63	247±31,14	125,47±12,93	517,57±84,62	1,61
T1 (III)	3,67±2,16	281,09±32,52	128,81±9,95	611,62±123,64	1,71
T2 (I)	4,70±2,03	242,71±29,75	117,66±10,42	502,76±94,62	1,58
T2 (II)	4,99±1,13	232,09±27,26	115,47±8,41	467,095±63,36	1,52
T2 (III)	4,37±1,48	278,51±39,16	138,38±15,27	593,47±109,31	1,64

Figure 1., illustrates the mean values of the CV for spray coverage across treatments and replications. The results demonstrate that droplet distribution was notably more uniform at the higher flight altitude, whereas at the lower altitude, the CV exceeded 50%, indicating uneven and inconsistent deposition of the spray solution. This parameter is directly linked to the effectiveness of chemical crop protection, as high variability in coverage can compromise treatment efficacy and lead to insufficient pest or disease control. Although a lower VMD was recorded at the higher flight altitude, typically associated with finer droplets and improved spreading capacity, the data suggest that environmental factors, such as wind influence or UAV flight velocity, may have contributed to slightly reduce total coverage. Nonetheless, despite the marginally lower coverage, the distribution uniformity was superior at the higher altitude, as evidenced by the reduced CV values. This indicates a more consistent deposition pattern across the treated surface, which is critical for achieving uniform protection and minimizing untreated zones.

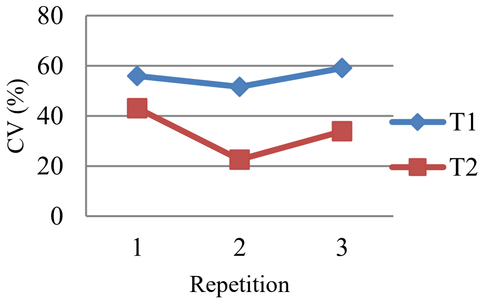

Figure 1. Droplet distribution by tested treatments based on the coefficient of variation

The findings of this study are in alignment with previous research investigating the influence of UAV flight altitude on the efficacy and uniformity of pesticide application. For instance, [9], reported poor droplet distribution uniformity at a flight height of 1 m, with the coefficient of variation (CV) exceeding 80%, significantly higher than that observed with conventional backpack sprayers [9].
Similarly, the present study recorded a CV greater than 50% at a flight altitude of 1,5 m, reinforcing the observation that lower flight altitudes may lead to uneven deposition patterns.
In a related study, [8] found that higher UAV flight altitudes (3–5 m) were associated with lower VMD values, leading to more uniform droplet distribution and improved coverage of lower leaf surfaces [8].
These findings are consistent with the current results, where higher flight altitude was linked to finer droplets and a more stable distribution across the treated area. However, it is critical to emphasize that finer droplets, while beneficial for coverage and canopy penetration, are also more susceptible to aerial drift, particularly under increased wind speeds. This underscores the importance of carefully calibrating UAV flight altitude and other operational parameters to balance application efficacy with environmental safety, thereby minimizing off-target deposition and pesticide loss.

CONCLUSION

The results of this study demonstrate that UAV flight altitude significantly influences key technical parameters of pesticide application, which in turn affect the overall quality of chemical crop protection. Statistical analyses, including ANOVA and Student's t-test, revealed significant differences in VMD and $D_{v0.9}$ values between treatments with differing flight altitudes. Lower VMD and $D_{v0.9}$ values recorded at higher flight altitudes indicate the formation of finer droplets, which may enhance droplet spread ability and surface coverage. However, these finer droplets are also more susceptible to spray drift, potentially reducing total coverage under suboptimal conditions.
Although no statistically significant difference was observed in total coverage between treatments, CV and RS values were lower at higher altitudes, indicating improved droplet distribution uniformity, a factor critical for achieving consistent and effective protection across the crop canopy.
These findings underscore the importance of precisely calibrating UAV flight parameters to balance three competing factors: coverage, distribution uniformity, and drift risk. UAV-based pesticide application presents significant potential for improving treatment efficiency and contributing to the sustainability of modern agriculture. However, to fully realize these benefits, continuous optimization of flight settings and integration of advanced technologies within precision agriculture frameworks are essential. Future research should expand to include additional operational variables, such as nozzle type, droplet velocity, and meteorological influences, in order to develop a more comprehensive understanding of conditions that ensure safe, efficient, and effective UAV-based pesticide application.

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STATISTIČKA ANALIZA VELIČINE KAPLJICA U HEMIJSKOJ ZAŠTITI BILJA KOD PRIMENE BESPILOTNIH LETELICA

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Apstrakt: Razvoj savremenih tehnologija u poljoprivredi, a naročito primena bespilotnih letelica (UAV sistema), omogućio je značajan napredak u primeni pesticida, doprinoseći većoj efikasnosti i preciznosti u zaštiti bilja.

Cilj ovog istraživanja bio je da se analizira uticaj različitih parametara leta UAV sistema, pre svega visine leta, na veličinu kapljica i ujednačenost njihove raspodele.

Terenski ogledi sprovedeni su na području opštine Zemun-Beograd, Republika Srbija , geografska širina: Severno 44° 49' 22.2" i geografska dužina: Istočno 20° 13' 19,2", na nadmorskoj visini terena od 73 m.

Ispitivane su dve visine leta bespilotne letelice DJI Agras T30 UAV (1,5 m i 2,5 m) uz konstantnu brzinu leta od 3 m/s.

Rezultati statističke analize su pokazali da manje kapljice, koje nastaju pri većim visinama leta, doprinose ujednačenijoj raspodeli, dok veće kapljice na manjim visinama obezbeđuju bolju pokrivenost ciljne površine. Najpovoljniji rezultati postignuti su na visini leta od 2,5 m, gde je zabeležena bolja ujednačenost i viši kvalitet raspodele kapljica.

Dobijeni rezultati ukazuju na značaj optimizacije eksploatacionih parametara UAV sistema u cilju povećanja efikasnosti primene pesticida, smanjenja njihove potrošnje i umanjenja rizika od zagađenja životne sredine.

Ključne reči: *Srednji prečnik kapljice (SPK), pokrivenost, UAV sistemi, visina leta, brzina leta, hemijska zaštita, pesticidi*

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