https://doi.org/10.17221/87/2023-RAE

The efficiency of unmanned aerial vehicles application for rapeseed productivity in Ukraine

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Citation: Melnychuk F., Alekseeva S., Hordiienko O., Nychyporuk O., Borysenko A., Didenko N. (2024): The efficiency of unmanned aerial vehicles application for rapeseed productivity in Ukraine. Res. Agr. Eng., 167–173.

Abstract: In modern conditions, high-precision technologies, such as unmanned aerial vehicles (UAVs), are the basis for increasing the efficiency of agricultural land use and crop productivity. Nowadays, new technology development needs to be improved, so the study and the implementation of various innovations in this field are quite relevant and important. The research aimed to find effective pesticides and a selection of spraying solution norms to increase rapeseed yield. The least significant difference test was used to separate the means of the dependent variables in response to predictor variables at $P \leq 0.05$. It was established that herbicides applied using UAV provided effective protection of crops against cereal weeds. The spraying solution (herbicide) Evolution, together with Amigo Star, contributed to destroy of annual cereals by 94–100%, which was at level of effectiveness for ground sprayer application. The higher yield of rapeseed was 4.08 t·ha^{-1} for variant with spraying solution by UAV with a consumption rate of 15 L·ha^{-1} and corresponding indicator reaches 4.13 t·ha^{-1} with a rate of 200 L·ha^{-1} for ground-based spraying. The advantage of using UAVs is the quicker application, as well as a lower rate of water consumption for preparing spraying solution, compared to ground spraying.

Keywords: cereal; ground spraying; herbicide; high-precision technology

Rapeseed (*Brassica napus*) needs comprehensive and high-quality herbicide protection. It is impossible to obtain maximum winter rapeseed yields without reliable weed control. In spring, the problem is complicated by the fact that, along with the early spring weeds, winter rapeseed crops usually contain a number of weeds that have come down from the fall and successfully overwintered (Hannes et al. 2018).

Analysing modern technologies for growing crops proves that obtaining high yields is impossible without using plant protection products to systematically control weeds, diseases, and pests (Stokstad and Grullon 2013; Kalogiannidis et al. 2022).

The desire to comprehensively improve the treatment quality is a determining factor in the effective use of pesticides and the environmental safety of their service, and it can be attributed to the main

https://doi.org/10.17221/87/2023-RAE

direction of the modern technical means of development and technologies for chemical plant protection (Stoytcheva 2011). At the same time, the unjustified application of a large pesticide number causes significant negative pressure on the environment and should be reduced to accomplish the sustainable development goals (Kubiak et al. 2022).

Modern innovative approaches to chemical plant protection technologies involve and require a transition from traditional methods of applying pesticide solutions with rates of 200–500 L·ha^{-1} to low-volume spraying with rates of 50–100 L·ha^{-1}. One of the most promising areas of application of ultra-low volume (ULV) spraying technology is the use of unmanned aerial vehicles (UAVs) or agricultural drones (Rao et al. 2020). The UAVs for agriculture can be effectively used for all technological operations of applying plant protection products for the chemical treatment of crops (Chen et al 2019; Nordin et al. 2021).

Certainly, the advent of UAVs represents a significant advancement in aerial spraying technology (Song 2022). However, the precise impact of spray volume alterations on deposition and pesticide control's efficacy remains poorly understood. Considering this, the main goal of the conducted research is to find effective pesticides for weed control and to determine the optimal concentrations of solutions for spraying rapeseed. This work is directed at increasing the yield of the crop, optimal conditions for its growth, and providing it with better protection from wreckers. As a result of the research, it is expected to improve the yield of rapeseed, which can lead to an increase in agricultural productivity. At the same time, the main criteria for the implementation of UAVs is economic feasibility and the critical need for the agricultural producer to carry out technological operations in a very limited time frame. It depends on the phase of plant vegetation and the development of diseases or pests on the crops, as well as the high cost or lack of sprayers on the farm.

MATERIAL AND METHODS

The experimental trials were conducted at the farm "Korol" in Lyubartsi village of the Kyiv region of Ukraine in 2021–2022. A general climatic feature of the research area is a sufficient amount of heat and unstable amount of moisture. The lowest average monthly temperature in January was –8.7 °C, and the highest was –3.2 °C. The lowest average monthly temperature in July was +14.0 °C, and the highest was +25.4 °C. During the growing season, the total sum of precipitation was 429 mm, and 225 mm for the summer months. The average annual relative air humidity is 76%, and it ranges from 64 to 88% by month.

The soil of the experimental plot is represented by chernozem, podzolized deep low-humus on loess rock. The content of physical clay in the 0–25 cm layer is 27.1%, in the 25–50 cm is 26.2%, and in the 50–100 cm is 24.6%. Organic matter of soil content in the 0–50 cm is 2.35%. According to the degree of salinity, the soil of the plot is not saline (salt content does not exceed 0.064%). The content of absorbed sodium in a meter layer of soil does not exceed 0.04% of the total content of all absorbed cations and characterizes the soil as non-saline.

The field experiment was conducted in three replications with the split-plot method. To evaluate the effectiveness of two methods of applying herbicides from UPL Europe (UK) compared the ground application and UAVs. The experiment was used according to the experimental scheme (Table 1). The active ingredient of the combination

Table 1. Experiment scheme of herbicides application using a ground sprayer and unmanned aerial vehicle (UAV) on winter rapeseed crops (2021–2022)

Variant	Herbicide	Spraying solution	Spraying solution for a ground sprayer for UAV
	consumption rates (L·ha^{-1})		
Control	water treatment	–	–
Evolution + Amigo Star	0.35 + 0.6	200	15
	0.35 + 0.5	150	15
	0.35 + 0.5	100	10
	0.35 + 0.4	75	7

https://doi.org/10.17221/87/2023-RAE

solution of of Evolution together with Amigo Star (UPL Europe Ltd, Warrington, UK) is clethodim, 140 g·L^{-1} + quizalofop-P-ethyl, 70 g·L^{-1}. These preparations have good solubility, which is no less important in the case of their application in UAV, they stably and evenly cover the treated area and also form a dispersion cloud with high quality (Ahmad et al. 2019).

The scientific bicycle sprayer with a grip of the boom of 2.5 m which can apply different rates of pesticides and solution fluids was used for ground application spraying. Herbicide application was also carried out by a multi-copter, (XAGP-30) tank volume of 15 L and speed of 42 km·h^{-1} with spraying height of 2 m, coverage width of 4 m and droplet diameter of 125 µm. Registration of weeds and determination of the effectiveness of the tested preparations were carried out according to accepted methods (Trybel' 2001; Borysenko et al. 2022). Weeds were counted on fixed sites with a size of 0.25 m^2 (50 × 50 cm) in 8 times replication.

The application of pesticides was carried out in the early morning (before 10 a.m.) and evening (after 7 p.m.) with minimal upward air currents, with air movement speed not exceeding 3 m·s^{-1}, air temperature not higher than + 20 °C, relative air humidity was within 55–70%. Monitoring of meteorological factors of the environment was carried out by the "METEOSKOP-M" (portable meteorological monitoring device equipped with the NTM-Ekom software) microclimate parameters meter during the entire period of the solutions applied.

To assess the possible movement of the aerosol and contamination of the ground cover outside the treated areas, it was assessed the presence and density of the deposition of the solution drops in the possible erosion zone (10 m from the leeward side of the field) at a height of 0.5 m on artificial support, it was installed cards made of water-sensitive paper (76 × 26 mm; TeeJet 20301-1N, Spraying System, Switzerland). Cards were also installed in the area for application herbicides by different methods for comparison. The evaluation of the result was carried out by scanning the cards with SnapCard software (version 2.1.1). At least 5 water-sensitive cards with mandatory numbering were used in each version of the field study.

Quantitative determination of the drift of pesticide active ingredients was carried out using the aspiration method and sedimentation samples. The method is based on the detection of the content of the active ingredient settled on paper deashed "blue tape" (BT) filters with an area of about 38.5 cm^2, placed in Petri dishes and located on the leeward side. The preparation of filters and the determination of the settled number of active ingredients were carried out identically, as in the study of air samples by the aspiration method. Since the pesticide application was carried out from the air using a UAV, the monitoring of the drift of spraying solution was carried out at a distance of 10 m and 100 m from the edge of the cultivated plot of land (Figure 1).

Equipment Used

Scientific bicycle sprayer with a boom grip of 2.5 m for ground application spraying.
Multi-copter (brand XAGP-30) for herbicide application with specific specifications like tank volume, speed, spraying height, coverage width, and droplet diameter.

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Methodology

Registration of weeds and determination of effectiveness of preparations according to established methods.
Counting of weeds on fixed sites with specific dimensions and replication.
Pesticide application timings (early morning and evening) and consideration of meteorological factors.
Monitoring of meteorological factors using a microclimate parameters meter.
Assessment of aerosol movement and ground contamination beyond treated areas by evaluating solution drops deposition.
Use of water-sensitive cards for evaluation, scanning with SnapCard software.
Quantitative determination of pesticide drift using the aspiration method and sedimentation samples.
Monitoring of pesticide drift at different distances from the edge of the cultivated plot.

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Key Instruments and Techniques

Scientific bicycle sprayer, multi-copter, METEOSKOP-M microclimate parameters meter.
Water-sensitive TeeJet 20301-1N paper cards, SnapCard software.
Aspiration method, sedimentation samples, "blue tape" (BT) filters, Petri dishes

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Monitoring parameters

Weed count, effectiveness of preparations, meteorological factors (air, temperature, humidity), solution drops deposition, pesticide drift.

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Evaluation and analysis

Evaluation of solution drops deposition using water-sensitive cards and SnapCard software.
Quantitative determination of pesticide drift using aspiration method and sedimentation samples

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Distance consideration

Monitoring of pesticide drift at both 10 m and 100 m distances from the edge of the cultivated plot

Figure1. General scheme of materials and methods use in the studies

https://doi.org/10.17221/87/2023-RAE

The quantitative determination of the content of active ingredients in the atmospheric air was carried out by the methods of high-performance liquid and gas-liquid chromatography.

RESULTS AND DISCUSSION

In the recent years, there have been significant changes in the use of UAVs in agricultural production, which relate to the spraying of crops, first of all. The peculiarity of this method of applying pesticides is the application of extremely small droplets of the working liquid to the plant (Matthews 2021). Wang et al. (2019) conducted the UAV had comparable deposition and efficacy control to the electric air-pressure knapsack (EAP) at a higher spray volume (> 16.8 L·ha^{-1}) with coarse nozzles, but exhibited inferior deposition and efficacy control at a lower spray volume (< 9.0 L·ha^{-1}) with fine nozzles. The study by Carneiro et al. (2024) showed that treatments with spray volumes ranging from 5.0 to 25 L·ha^{-1} applied by UAV provided satisfactory desiccation percentages of groundcover regardless of species or location. As evidenced by the results of our research, during the autumn observations, after the ground application of the studied herbicides, on the 10th day, signs of wilting of annual grass weeds were noted on the crops of winter rapeseed, and on the 20th day, the impact of the herbicide was noticeable on perennial grasses. Herbicides on all variants showed high efficiency. A gradual yellowing, and obvious death of cereal weeds, in particular annuals, were observed on plots with spraying winter rape by a multi-copter-tested herbicide Evolution with Amigo Star.

After the recovery of winter rapeseed vegetation in the spring, high efficiency was established in all variants for both methods of applying herbicides. With conventional ground-based spraying, the maximum control of annual and perennial grass weed species was observed on the Evolution together with Amigo Star variant with consumption rates of 0.35 + 0.6 L·ha^{-1} (the consumption rate of the working solution is 200 L·ha^{-1}). At lower rates, a decrease in the effectiveness of the herbicide was noted due to insufficient coverage of cereal plants. In the variants with herbicides, yield of winter rapeseed was higher than in the control by 1.60–1.87 L·ha^{-1} (Table 2).

The use of a multi-copter for spraying the herbicide Evolution with Amigo Star on winter rapeseed on the variants with the highest rates of consumption of the solution contributed to the maximum controlling effect against of annual grass weeds (Table 3). In variants with herbicides the efficiency was at the level of 72.9–82.3% against perennial cereal plants. It should be noted that reducing the rate of consumption to the minimum recommended and working solution to 7 L·ha^{-1} led to a significant decrease in the effectiveness of the herbicide against the cereals due to the deterioration of the coverage of weed plants with the solution. In general, in the options with pesticide treatment, the share of the saved yield was 1.67–1.85 t·ha^{-1} compared to the control, which indicates the high efficiency and feasibility of applying pesticides by drones.

A visual analysis of the water-sensitive cards that were installed in the possible drift zone (10 m from the leeward side of the field) during the application by ground sprayer and UAV showed the presence of individual microdroplets of the pesticide working solution on some cards. Scanning of water-sensitive cards by the SnapCard software showed that their actual coverage is 0%, i.e. below the detection limit of this program, and scanning the water-sensitive cards that were installed within the cultivated land plot, the actual coverage ranged from 61 to 93%.

Table 2. Effectiveness of using herbicides on rapeseed crops by ground-based spraying application (2021–2022)

Solution (pesticide) for spraying	Consumption rates for SS (L·ha^{-1})	Efficiency of cereals (%)		Yield (t·ha^{-1})
		annual	perennial	
Control	water treatment	–		2.26
Evolution + Amigo Star	200	100.00	85.4	4.13
	150	100.00	84.2	4.07
	100	98.4	78.8	3.96
	75	95.1	71.5	3.86
LSD_{05}		2.3	4.5	0.18

LSD – the least significant difference; SS – spraying solution

https://doi.org/10.17221/87/2023-RAE

Table 3. Effectiveness of using herbicides on rapeseed crops by unmanned aerial vehicle (2021–2022)

Solution (pesticide) for spraying	Consumption rates for SS ($L \cdot ha^{-1}$)	Efficiency of cereals (%)		Yield ($t \cdot ha^{-1}$)
		annual	perennial	
Control	water treatment	–		2.23
Evolution + Amigo Star	15	100.00	82.3	4.08
	15	100.00	80.0	4.01
	10	97.2	77.4	3.94
	7	94.0	72.9	3.90
LSD_{05}		2.9	5.2	0.20

LSD – the least significant difference; SS – spraying solution

During studying the real danger of pesticide losses (drift of the pesticide) and environmental pollution, an assessment was made of the established concentrations of active ingredients. Last ones were determined during the simultaneous control of their content in atmospheric air and sedimentation on the soil (sedimentation samples) at a distance of 10 and 100 m from the edge of the cultivated areas from the leeward side when applying pesticides from the air using a UAV. The obtained results showed that in all sedimentation samples at mentioned distances from the boundaries of the area treated with a UAV, no active ingredients were detected, that is, their concentrations are lower than the limits of quantitative determination of the method. The data obtained during the aspiration sampling of air samples in the possible zone of pesticide drift were identical to the previous ones, that is, the concentrations of active ingredients are lower than the limits of quantitative determination of the method.

The obtained results of the analysis of the air of the drift zone, selected by aspiration and sedimentation methods, indicate that the drift of the pesticide droplets did not exceed 10 m under the studied conditions of its application (speed, altitude of UAV movement, rate of consumption, type of nozzles) and meteorological parameters. This finding is in alignment with several studies in the existing literature.

For instance, Qin et al. (2016) reported that the zone of drift for ground sprayers, when applied with UAVs, significantly decreased compared to traditional methods. Specifically, the drift was observed to reach 7.5 m downwind at a level of 1% of the total volume of pesticide, and to 0.1% at a distance of 32 m. Similarly, Brown and Giles (2018), demonstrated that UAVs can effectively minimize pesticide drift due to their ability to maintain a consistent application height and adapt to meteorological conditions, resulting in more precise deposition.

Chen et al. (2021) further confirmed these observations, showing that on average, only 0.28–0.54% of the total volume of the solution drifted outside the plot when applied with UAVs. Of this drifted volume, the majority (approximately 82%) settled within the first 7.5 m downwind.

The results of the other experimental study in Poland (Wang et al. 2020) demonstrated that the droplet density on the flag leaf and inverted two leaves was 29.7 and 9.5 cm^2, respectively. Notably, the control effect on wheat powdery mildew achieved a level of 85–90% after seven days. This outcome validated the effectiveness of the UAV spray method, which employed a high concentration of the active ingredient and a minimal spray volume. Use in agricultural UAVs is beneficial for pesticide penetration, covering the front and back of crop leaves and roots, and effectively improving the pesticide utilisation rate.

The results of utilizing a drone for the application of *Trichogramma* spp. against the European corn borer (Ma 2020) indicate that the low-height aerial application allows for precise dosing and satisfactory distribution of the biopesticide. The efficacy of drone-based spraying operations, which ranged from 60 to 85% (depending on the year), was comparable with that observed for ground application. The speed and high efficiency of the treatment make the use of a drone as a carrier of the biopesticide application system a promising alternative to other methods.

A review of the literature did not identify any negative effects associated with the use of UAVs in agriculture. It is also worth noting that the use of the UAVs for spraying crops has been

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demonstrated to result in a reduction in the use of pesticides. Moreover, the implementation of scientific crop rotation on farms provides a robust foundation for the effective reduction of pests and the promotion of ecological agriculture (Li et al. 2020).

CONCLUSION

During the treatment of crops by multi-copters using the ULV technology, significantly fewer pesticides enter the fertile soil layer, and most of them cover the plants – due to fine-dispersed spraying and a small volume of working solution. As a result, the phytotoxic load on both soil and crops is reduced. Accordingly, this has a positive effect on the growth of plants, and ultimately on the chemical and biological purity of animal feed and human food.

In our research, it was obtained high efficiency of herbicide protection of winter rapeseed with the applying preparations by UAV (drone). The use of a multi-copter for spraying the herbicide Evolution with Amigo Star on winter rapeseed on variants with the highest consumption rates of working solution contributed to the complete control of annual grass weeds, and its effectiveness against perennial grass plants reached 72.9–82.3%.

Using UAV for applying herbicides against segetal vegetation, in the initial phases of growth and development of annual and perennial cereal plants, it is necessary to observe the maximum rates of consumption of the working solution, since their reduction can lead to insufficient complete coverage of the surface of weed plants with pesticides, which has a negative effect on their effectiveness.

It was established that the drift of the working solutions of the studied pesticides does not exceed 10 m from the edge of the cultivated field under the studied conditions of application of the pesticide (speed, altitude of the drone, rate of consumption, type of nozzles) and meteorological parameters. This allows for minimisation of the risks of adverse effects of pesticides on the environment and people and increases the effectiveness of control of target objects.

Therefore, the use of unmanned aerial vehicles is a promising and innovative direction in plant protection, as it allows farmers to reduce the costs of applying pesticides up to 30%, thereby saving money and reducing the pesticide pressure on the environment.

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Received: August 23, 2023
Accepted: July 7, 2024
Published online: September 29 , 2024