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Comparison of the Effectiveness of UAV and Conventional Sprayers in Wheat Disease Control

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In this study, the influence of different water volumes applied by the unmanned aerial vehicle (UAV) and back motor sprayer (BMS) in fungicide control of wheat diseases (Tan spot – *Pyrenophora tritici-repentis* and Septoria tritici leaf blotch – *Zymoseptoria tritici*) was researched in field conditions. During the whole experiment, no phytotoxicity of the used fungicide (solatenol 75 g/L + prothioconazole 150 g/L) was observed (and that´s why); the UAV application can be considered as safe for the wheat crop in all tested spray volumes. The trial results showed that the fungicide efficacy (FE) of UAV application depends on the used spray volume and air temperature during application. The best FE was achieved by using a BMS of 100 and 300 L/ha spray volume. It is proven that the lowest FE was recorded by using a UAV spray volume of 10 L/ha applied at high temperatures (28°C). The use of UAV ultra-low spray volume is not suitable for application in high air temperatures, which could dramatically decrease the FE of the applied fungicide. Suitable temperatures (around 20°C) for application did not negatively influence low UAV spray application volumes of 10 L/ha. The FE by using UAV spray volume of 10 L/ha was approximately 10% lower than the FE of 300 L/ha BMS spray volume. The BMS spray volume of 100 L/ha and UAV volume of 50 L/ha showed similar FE in suitable conditions for application. The results showed that for practical UAV fungicide applications, it is needed to use a spray volume of 50 L/ha or more. Further studies are needed to evaluate the effects of other pesticides to estimate how widely the results are applicable in agricultural practice.

Key words: UAV, sprayer, wheat, fungicides, efficacy

Wheat is an important and strategic crop worldwide. The yield of wheat is strongly influenced by pests and diseases, which primarily reduce the leaf area. The time which the plants remain green is proportional to their ability to produce high yields (Thomas & Smart 1993). However, pests and diseases are primarily focused on using pesticides. In professional agricultural practice, the modern high-volume conventional machine sprayers constitute the main spraying equipment (Li *et al.* 2017). A disadvantage of these sprayers is the loss of pesticides caused by using high-water (Rincón *et al.* 2017). Recently, the unmanned aerial vehicle (UAV) has been tested and used for aerial spraying technology (Önler *et al.* 2023). A big advantage of UAVs in contrast to manned fixed-wing aircraft used in Europe is that, UAVs do not need a take-off airport and are cheaper. In comparison with machine boom sprayers, the UAVs could be more convenient for hard terrain and for small farms or small plot trials (Quin *et al.* 2016). In some countries, the spraying machinery is being changed by UAVs, because of

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their higher work efficiency, lower costs, and lower risk of personal operator pesticide exposure. In comparison with conventional ground sprayers, the UAV operates with lower labour need, lower operator exposure, with high working efficiency, especially in hard terrain and small trials (Wang *et al.* 2017). In general, contemporary UAVs are able to spray up to 10 ha per hour with a 30 – 40-litre liquid tank (He *et al.* 2017).

Even thought the application of pesticides by the UAV is banned in most European countries, including Slovakia, the UAVs are still the subject of research for their exploitation for pesticide application. Many studies are focused on the technical parameters of UAV application along with spray volume, which also has a high influence on biological efficacy (Berger-Neto *et al.* 2017). Menechini *et al.* (2017) studied the use of different water volumes (7.5, 13.5, 20, and 30.3 L/ha with the UAV fungicide application on corn disease control. They found out that the best plant coverage was achieved by a water volume of 30.3 L/ha. Fritz *et al.* (2006) presented that a low water volume (19 L/ha) caused higher tracer deposits in wheat. Hoffmann *et al.* (1998) highlighted that the water volume of 4.7 – 14.1 L/ha did not influence the product's efficacy, and more field area can be sprayed by using a lower water volume. Qin *et al.* (2016) focused their study on the influence of UAV speed and flight height on biological efficacy against plant hoppers with positive results.

The main task remains whether a lower water volume application could affect the biological efficacy of the applied plant protection product. In this work, several different water volumes applied by the UAV and back motor sprayer (BMS) were compared with the use of model fungicide to control wheat diseases in field conditions in the years 2022 and 2023. This study aimed to estimate the best UAV spray water volume that has comparable efficiency with classical conventional spraying technology, represented by BMS.

MATERIAL AND METHODS

The field experiments were conducted on experimental field plots in the southwestern region of Slovakia (locality Rastislavice) in years 2022 and 2023. The water volume, type of application, and used fungicide are described in Table 1. The tested crop was winter wheat, cv. Genius. The crop maintenance (the use of fertilisers, herbicides and insecticides) was applied uniformly in the whole trial, corresponding to good agronomical practice (Tables 2, 3). The treatments of the field trial have four replications by plot randomisation of completely randomised block design. Each plot area was 20 m^2. In the experimental field area, plants surrounding the experimental plots were fungicide untreated with 1 m between each treatment as a buffer zone. For verification if raising the volume of spraying water can increase the fungicide efficacy against wheat diseases, a few water volumes (from 10 to 100 L/ha for UAV, and 100 and 300 L/ha for BMS) were tested. To determine whether weather conditions (mainly the air temperature) can influence the fungicide efficacy of the tested product, two timings of application were carried out – morning application (lower temperature, favourable for application) and afternoon application (higher air temperatures, not favourable for application). The main assumption for the morning application was the absence of water drops or dew on wheat leaves. An Agras T10 DRONE (DJI, SZ DJI Technology Co., Ltd., Shenzhen, China) was used for UAV application, and the high-pressure back motor sprayer (BMS) – SOLO 433 H (SOLO, Germany) for the conventional spraying. Fungicide treatments were applied in one application timing – T2 (BBCH 39). The flight speed of the used UAV was 6 m/s, and the flight height was 2 m to cover the treated plot area (1 plot = 20 m^2). BMS had four nozzles in a 1 m length boom, and a motor pump which provided a pressure of 2.0 bar. The travelling speed of the man applicator and BMS was 1.0 m/s, the boom height was 25 cm above the crop. The standard application volume for the wheat crop by BMS (300 L/ha) was chosen based on the recommendations of the common good trial and agricultural practice. For reaching other water volumes, the same working pressure was used, but the travelling speed was doubled or reduced. Water volume was then changed by reducing pressure. All conducted treatments are described in Tables 4 and 5.

Symptoms of possible phytotoxicity were estimated in 7, 14 and 21-day intervals after application, according to EPPO guideline PP 1/135(4) –

Phytotoxicity assessment. Disease severity was assessed in the growth stages BBCH69 and BBCH85. At each time, the percentage of diseased leaf area (attacked by pathogens' lesions) was counted on 25 leaves in four small areas per treatment. The assessments were carried out on separate leaves for separate diseases (pathogens), according to EPPO guideline PP 1/26(4) – Foliar and ear diseases of cereals. The fungicide efficacy (FE) was calculated according to Fan *et al.* (2016):

FE = [(disease incidence of control plot − disease incidence of treated plot)/(disease incidence of control plot)] × 100%.

For yield evaluation, plants were harvested by plot experimental combine harvester (Wintersteiger Classic, Austria) at the growth stage fully ripe (BBCH 89). At harvest, from each plot, the samples (1.0 kg) were separated for laboratory analysis to estimate the moisture and thousand-kernel weight. All data were used for the analysis of variance (ANOVA) by using Fisher's *LSD* test ($p = 0.05$).

RESULTS AND DISCUSSION

The fungicide application in 2022 was carried out on May 10th, 2022, at a desirable growth stage BBCH39, which is the usual term for T2 application timing against main leaf diseases of wheat in common agricultural practice. The weather was appropriate for the trial intention, because the temperatures in the afternoon were high (Table 3). The first assessment of fungicide efficacy was conducted at the growth stage BBCH69 on June 2nd, 2022. The fungicide efficacy of different spray volumes produced by two sprayers (UAV and BMS) on wheat diseases in 2022 season is indicated in Table 5. On the leaves, only two pathogens occurred – *Pyrenophora tritici-repentis* (Tan spot) and *Zymoseptoria tritici* (Septoria tritici leaf blotch). The disease severity in the untreated check reached a minimal infection level (min. 5% of leaf area attacked, accepted for registration trials of Plant Protection Products in the European Union registration authorities; unpublished information) that was achieved only on

T a b l e 1

Characteristics of field trial treatments, Rastislavice, 2022 and 2023

Tr. No.	Treatment name	Treatment description, dose [L/ha]	Water dose [L/ha]	Application equipment	Crop development	Application time
1.	Untreated check	Untreated check	–	–	BBCH[4] 39	–
2.	UAV10–AM[7]	Elatus Era[1] (1.0)	10.0	UAV[2]	BBCH 39	6 – 8 AM[5]
3.	UAV50–AM	Elatus Era (1.0)	50.0	UAV	BBCH 39	6 – 8 AM
4.	UAV100–AM	Elatus Era (1.0)	100.0	UAV	BBCH 39	6 – 8 AM
5.	BMS100-AM[8]	Elatus Era (1.0)	100.0	BMS[3]	BBCH 39	6 – 8 AM
6.	BMS300-AM	Elatus Era (1.0)	300.0	BMS	BBCH 39	6 – 8 AM
7.	UAV10-PM[9]	Elatus Era[1] (1.0)	10.0	UAV[2]	BBCH 39	3 – 5 PM[6]
8.	UAV50-PM	Elatus Era (1.0)	50.0	UAV	BBCH 39	3 – 5 PM
9.	UAV100-PM	Elatus Era (1.0)	100.0	UAV	BBCH 39	3 – 5 PM
10.	BMS100-PM[10]	Elatus Era (1.0)	100.0	BMS[3]	BBCH 39	3 – 5 PM
11.	BMS300-PM	Elatus Era (1.0)	300.0	BMS	BBCH 39	3 – 5 PM

[1]Elatus Era – fungicide, solatenol 75 g/l + prothioconazole 150 g/l, EC formulation (emulsifiable concentrate), manufactured by Syngenta; [2]UAV – unmanned aerial vehicle (drone); [3]BMS – backpack motor sprayer ; [4]BBCH – growth stages according to the BBCH scale; 6 – 8 AM[5] – application in the morning, at 6.00 – 8.00 o'clock AM; 3 – 5 PM[6] – application in the afternoon, at 3.00 – 5.00 o'clock PM; UAV10–AM[7] – application by UAV (10 L/ha) in the morning, at 6.00 – 8.00 o'clock AM; BMS-AM[8] – application by BMS (100 L/ha) in the morning, at 6.00 – 8.00 o'clock AM; UAV-PM[9] – application by UAV (10 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM; BMS-PM[10] – application by BMS (100 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM

the F3 leaf level for Tan spot only (6.5%). Thus, Tan spot infection of F3 leaf level is suitable only for FE consideration of the fungicide efficacy. As it can be observed from the results (Table 5), the spray volume and time of application had a significant influence on the fungicide efficacy. The best fungicide efficacy was achieved by using BMS in both tested spray volumes without a significant difference between the tested spray volumes. The reduced spray volume of 50 L/ha applied by BMS achieved lower but relatively satisfactory results (around 10 − 15% lower fungicide efficacy) in both application timings. Significantly lowest (zero) fungicide efficacy was observed in the lowest spray volume applied by the UAV (10 L/ha) at the second application timing (afternoon, at high temperatures). Despite the lowest spray volume (10 L/ha), morning UAV application at lower temperatures showed significantly higher (80.3%) FE. This could be caused by evaporation and very fast drying of the application slurry on wheat leaves at high temperatures, as mentioned in Table 3. As indicated above, the FE varied with different combinations of sprayer and water volume in both application timings. Spray volumes applied by different sprayers influenced the control efficacy differently. Low or insufficient spray volume could lead to a low percentage of spray coverage with adverse effects on the control efficacy of plant protection products (Wang *et al.* 2020).

The second assessment of fungicide efficacy was conducted at the growth stage BBCH85 on June 20th, 2022 (Table 6). The last (F1) leaf level was still green and infected by the mentioned pathogens. The disease severity in the untreated check reached an infection level of 10.5% only for Tan spot. As observed in these results, the best fungicide efficacy was achieved by using BMS of 100 and 300 L/ha, as in previous assessments. The spray volume of 100 L/ha applied by BMS and the UAV showed similar results.

Significantly lower FE was achieved in a spray volume of 10 L/ha applied by the UAV in the af-

T a b l e 2

Characteristics of growing measures and maintenance of wheat trial plots, locality Rastislavice

Maintenance	2022	2023
Cultivar	Genius	Genius
Sowing date	October 19th, 2021	November 25th, 2022
Sowing depth	2.5 cm	2.5 cm
Planting rate	240 kg/ha	240 kg/ha
Emergence date	November 15th, 2021	December 5th, 2022
Row spacing	12.5 cm	12.5 cm
Spacing within row	2.5 cm	2.5 cm
Fertilisation	February 12th, 2022 Nitrogen 27.5% (200 kg/ha)	February 16th, 2023 Nitrogen 27.5% (200 kg/ha)
Fertilisation	April 8th, 2022 Nitrogen 27.5% (200 kg/ha)	April 13th, 2023 Nitrogen 27.5% (200 kg/ha)
Herbicide treatment	April 4th, 2022 Zypar (1.0 L/ha)	April 26th, 2023 Mustang Forte (0.8 L/ha)
Insecticide treatment	April 20th, 2022 Rafan Max (0.05 L/ha)	April 26th, 2023 Decis EW 50 (0.15 L/ha)
Growth regulation	April 20th, 2022 Retacel Extra R 68 (2.0 L/ha)	May 4th, 2023 Moddus (0.4 L/ha)
Insecticide treatment	May 16th, 2022 Rafan Max (0.05 L/ha)	May 19th, 2023 Decis EW 50 (0.15 L/ha)
Insecticide treatment	April 26th, 2022 Rapid (0.08 L/ha) + Silvet Star (0.1 L/ha)	June 8th, 2023 Rafan Max (0.05 L/ha)
Harvest	July 12th, 2022	July 19th, 2023

ternoon, at high temperatures (around 28°C). The spray volume of 50 L/ha showed significantly lower FE only in the afternoon application timing. In the morning application timing, the spray volume of 50 L/ha applied by the UAV achieved comparable FE with the use of BMS. These results suggest that high temperatures can negatively influence lower spray volumes applied by the UAV, and under these conditions, this type of application (low spray volume) is not suitable. The results correspond with yield data, when achieved yield and thousand kernel weight are significantly lower by using a spray volume of 10 L/ha applied by the UAV (Table 9). Low spray volume is also considered not suitable for good control efficacy for POST application of herbicides (diflufenican + isoproturon, isoproturon + clodinafop-propargyl + mesosulfuron) too (Chen *et al.* 2019). Wang *et al.* (2020) stated that pest control significantly enhanced when the spray volume was raised from 9 L/ha to 18 L/ha. Moreover, persisting controlling efficiency observed at the UAV application indicates that the application of low water volume and high pesticide concentration enhanced the duration of pesticide activity (Subramanian *et al.* 2021).

The fungicide application in 2023 was carried out on May 28th, 2023. The weather for trials was not as appropriate for trials as in 2022, because the temperatures in the two application timings (morning and afternoon) were not very different (Table 4). The first assessment of fungicide efficacy was conducted at the growth stage BBCH69 on May 28th, 2023 (Table 7). On the last three evaluated leaves, only two pathogens occurred – *Pyrenophora tritici-repentis* (Tan spot) and *Zymoseptoria tritici* (*Septoria tritici* leaf blotch). The disease severity in the untreated check was very low on this date on

T a b l e 3

Application characteristics, winter wheat, cv. Genius, locality Rastislavice, year 2022

Parameter	Morning application	Afternoon application
Treatments No.	1,2,3,4,5,6	7,8,9,10,11
Date	May 10th, 2022	May 10th, 2022
Time	6.30 – 7.45 AM	3.45 – 16.50 PM
Growth stage (majority)	BBCH 39 (60%)	BBCH 39 (60%)
Crop high (majority)	60 cm	60 cm
Number of green leaves	4	4
Crop vitality	good	good, water
Crop coverage of soil	100%	100%
Soil temperature	17.3°C	20.5°C
Soil surface	dry	dry
Air temperature during application	18.5 – 19.7°C	27.5 – 28.3°C
Air moisture during application	45.3%	37.4%
Drying of application slurry on leaves	medium	very fast
Wind speed during application (min, max)	0.5 – 4 km/h	6 – 8 km/h
Wind direction	south-west	south-west
Cloud cover	20%	10%
Rain – sum of 1 week before application	27.45 mm	27.45 mm
Rain after application	3 days (May 13th, 2022) 6.15 mm	3 days (May 13th, 2022) 6.15 mm
Rain – sum of 1 week after application	7.05 mm	7.05 mm

Note: cv. – cultivar.

all leaves and in both pathogens on this date, and therefore, no data are acceptable for the assessments of biological efficacy. The second assessment was conducted at the growth stage BBCH85 on June 17th, 2023 (Table 8). The infestation achieved an acceptance level on F1 (5.6%) and F2 (40.3%) leaf level for Septoria tritici leaf blotch. Especially, the infestation of the F2 level was very high. As with the spray volume increase, the FE of UAV application was increased as well. As observed in these results, the best fungicide efficacy was achieved by using BMS of 100 and 300 L/ha, as in year 2022, while the spray volumes of 100 and 50 L/ha applied by BMS and the UAV showed similar results. Significantly lower FE was achieved by the spray volume of 10 L/ha applied by the UAV, only on the F1 leaf level. The spray volume of 50 L/ha showed comparable FE as other spray volumes applied by the UAV and BMS. This year, there are no significant differences between the FE achieved in the morning and afternoon application, because weather conditions (temperature) were suitable for fungicide application. These results suggest that suitable temperatures for fungicide application cannot negatively influence lower spray volumes applied by the UAV. The spray volume of 10 L/ha applied by the UAV is approximately 10% lower compared to 300 L/ha applied by BMS. The spray level of 50 L/ha applied by the UAV is comparable to the application of 300 L/ha by BMS. These results correspond with yield data, when the achieved yield and thousand-kernel weight were slightly lower by using a spray volume of 10 L/ha by the UAV. While any data were significantly different by using any spray volume or application equipment (Table 9).

For the phytotoxicity of the applied plant

T a b l e 4

Application characteristics, winter wheat, cv. Genius, locality Rastislavice, year 2023

Parameter	Morning application	Afternoon application
Treatments No.	1,2,3,4,5,6	7,8,9,10,11
Date	May 11th, 2023	May 11th, 2023
Time	7.10 – 8.15 AM	15.15 – 16.25
Growth stage (majority)	BBCH 39 (60%)	BBCH 39 (60%)
Crop high (majority)	65 cm	65 cm
Number of green leaves	5	5
Crop vitality	very good	very good
Crop coverage of soil	100%	100%
Soil temperature	17.3°C	18.2°C
Soil surface	dry	dry
Air temperature during application	15.0 – 16.7 °C	20.2 –21.4°C
Air moisture during application	49.8%	47.6%
Drying of the application slurry on leaves	medium	medium
Wind speed during application (min, max)	0.9 – 3.5 km/h	5.2 –6.4 km/h
Wind direction	south-west	south-west
Cloud cover	90%	95%
Rain – sum of 1 week before application	1.78 mm	1.78 mm
Rain after application	1 day (May 12th, 2023) 13.46 mm	1 day (May 12th, 2023) 13.46 mm
Rain – sum of 1 week after application	80.78 mm	80.78 mm

Note: cv. – see Table 3.

protection products, the spray volume could be critical. Results of Chen *et al.* (2019) proved that for some herbicide combinations, the spray volume may affect crop safety. Using more water during application may increase the safety. Therefore, all herbicide applications by the UAVs must be tested in small plots before large-scale application (Chen *et al.* 2019). In our study, no phytotoxicity was observed during the whole experiment; thus, the UAV application of the tested fungicide was safe for the crop in all tested spray volumes.

As indicated above, the FE varied with different combinations of application equipment and water volume within both application timings, and with the amount of water applied in different ways. By using UAVs, the spray volume had a more significant influence on controlling wheat diseases. In contrast, an increased spray volume from 100 to 300 L/ha had no significant effect on the FE of BMS. In most assessments, the FE of the BMS application was better than using the UAV. The differences were greater with lower spray volumes (50 and 10 L/ha) used by the UAV. However, the control efficacy of the UAV meets basic field control requirements comparable to BMS, especially in optimal or appropriate conditions for pesticide application. Similar results were mentioned by Wang *et al.* (2019), who found that droplet deposition and the FE of UAV sprayer were not significantly different from conventional sprayers.

Our results showed the importance of spray volume and application equipment type (UAV and BMS) on the final quality of the FE in wheat. Using a conventional BMS sprayer on the wheat crop

T a b l e 5

The fungicide efficacy of tested applications against fungal diseases of wheat, BBCH 69, Rastislavice, June 2nd, 2022

Tr. No.	Treatment name	PYRNTR (F1)[5]	PYRNTR (F2)[6]	PYRNTR (F3)[7]	SEPTTR (F1)[8]	SEPTTR (F2)[9]	SEPTTR (F3)[10]
1.	Untreated check	IL F1[11] = 0.2%	IL F2 = 2.3%	IL F3 = 6.5%	IL F1 = 0.0%	IL F2 = 0.2 %	IL F3 = 1.5%
2.	UAV10–AM[1]	82.2[b12]	78.6[b]	80.3[b]	–	82.3[b]	89.2[b]
3.	UAV50–AM	100.0[c]	100.0[c]	87.2[b]	–	100.0[c]	100.0[c]
4.	UAV100–AM	100.0[c]	100.0[c]	91.2[b]	–	100.0[c]	100.0[c]
5.	BMS100-AM[2]	100.0[c]	100.0[c]	95.3[b]	–	100.0[c]	100.0[c]
6.	BMS300-AM	100.0[c]	100.0[c]	92.4[b]	–	100.0[c]	100.0[c]
7.	UAV10-PM[3]	–33.3[a]	24.3[a]	–32.7[a]	–	15.3[a]	8.44[a]
8.	UAV50-PM	100.0[c]	100.0[c]	89.3[b]	–	100.0[c]	100.0[c]
9.	UAV100-PM	100.0[c]	100.0[c]	91.2[b]	–	100.0[c]	100.0[c]
10.	BMS100-PM[4]	100.0[c]	100.0[c]	98.1[b]	–	100.0[c]	100.0[c]
11.	BMS300-PM	100.0[c]	100.0[c]	95.3[b]	–	100.0[c]	100.0[c]

UAV-AM[1] – application by UAV (10 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
BMS-AM[2] – application by BMS (100 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
UAV-PM[3] – application by UAV (10 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
BMS-PM[4] – application by BMS (100 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
PYRNTR (F1)[5] – biological efficacy [%] against Tan spot of wheat (*Pyrenophora tritici-repentis*) on leaf level 1 (flag leaf);
PYRNTR (F2)[6] – biological efficacy [%] against Tan spot of wheat (*Pyrenophora tritici-repentis*) on leaf level 2;
PYRNTR (F3)[7] – biological efficacy [%] against Tan spot of wheat (*Pyrenophora tritici-repentis*) on leaf level 3;
SEPTTR (F1)[8] – biological efficacy [%] against Septoria leaf spot of wheat (*Zymoseptoria tritici*) on leaf level 1 (flag leaf);
SEPTTR (F2)[9] – biological efficacy [%] against Septoria leaf spot of wheat (*Zymoseptoria tritici*) on leaf level 2;
SEPTTR (F3)[10] – biological efficacy [%] against Septoria leaf spot of wheat (*Zymoseptoria tritici*) on leaf level 3;
IL F1[11] – Infection level of leaf level F1 (flag leaf) in untreated check, estimated as average percentage of leaf area damaged by a certain pathogen;
[12]Different letters in the same column indicate that the values are significantly different ($p \leq 0.05$) according to ANOVA (analysis of variance), and 'Fisher's *LSD* (least significant difference) test.

proved that high-volume spraying easily leads to run-off and lower deposition (Wang *et al.* 2019). Many works mentioned that large-volume spraying is not necessarily associated with larger deposition (Wang *et al.* 2019). Our study was focused on common BMS volume spraying, which differs from low-volume UAV spraying (10 – 50 L/ha). The effect of spray volume and application equipment on the fungicide efficacy has rarely been studied.

Spray volume and type of application equipment significantly influenced the fungicidal efficacy against wheat diseases, especially at higher air temperatures. When the fungicide was applied under appropriate temperatures, the control efficacy was more comparable with both sprayers, even by using lower UAV spray volumes. Similar results were obtained by Wang *et al.* (2019), who stated that even though the UAV applied a lower water volume and provided a lower percentage of surface area coverage, the UAV control efficacy was equal to that of the BMS sprayer. The important factor seems to be the number of spray droplet deposits per area. Although the UAV crop coverage of application slurry is lower than BMS sprayer on account of the spray volume, the final number of spray droplet deposits was not different on the upper canopy (Wang *et al.* 2019). The droplet size applied by the UAV is generally lower than that produced by BMS sprayer (Prokop & Veverka 2006). Our results and findings of the mentioned authors suggest that for pesticide application, it is not needed to use a large amount of water spray, as a certain number of spray droplet deposits achieves good efficacy, particularly for systemic pesticides (Wang *et al.* 2019). Low spray volumes using a small droplet size could, in some cases, enhance the efficacy of some pesticides. Bryant and Yendol (1988) demonstrated that small droplets enhance the insecticide efficacy more than larger droplets (>150 μm). Our study showed that the limiting factor could be air temperature during application, which could significantly decrease the control efficacy of low water volumes applied by the UAV. Generally, BMS exhibited better spray penetration to the crop than the UAV, which may result in lower FE of the UAV, because most fungal infections are generated on the lower canopy (Wang *et al.* 2019). Prokop and Veverka (2006) discovered that translocation of the systemic fungicide compounds counteracted the effects with a lower number of droplet deposits, and crop coverage. Systemic fungicides are also influenced by the spray volume, resulting in improved number of spray deposits and crop coverage. This may be caused by higher evaporation under low-volume and small droplet conditions (Wang *et al.* 2019), which was confirmed by our results obtained at high temperatures of UAV application. Application of pesticides using the UAV, results in the use of low volume spraying, which causes a relatively high concentration of pesticides in comparison with classical sprayers. While excessive spray is responsible for their low deposition rate (Xiao *et al.* 2020). Wheat disease control was affected by sprayer type, spray volume and air temperature at appli-

T a b l e 6

The fungicide efficacy of tested applications against fungal diseases of wheat, BBCH 85, Rastislavice, June 20th, 2022

Tr. No.	Application	PYRNTR (F1)[5]	SEPTTR (F1)[6]
1.	Untreated check	IL F1[10] = 10.5%	IL F1 = 0.5%
2.	UAV10–AM[1]	68.6 [b7]	82.3[a]
3.	UAV50–AM	85.4[c]	100.0[b]
4.	UAV100–AM	89.4[c]	100.0[b]
5.	BMS100-AM[2]	92.3[c]	100.0[b]
6.	BMS300-AM	93.9[c]	100.0[b]
7.	UAV10-PM[3]	0.0[a]	100.0[b]
8.	UAV50-PM	70.2[b]	100.0[b]
9.	UAV100-PM	81.2[c]	100.0[b]
10.	BMS100-PM[4]	82.1[c]	100.0[b]
11.	BMS300-PM	82.6[c]	100.0[b]

UAV-AM[1] – application by UAV (10 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
BMS-AM[2] – application by BMS (100 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
UAV-PM[3] – application by UAV (10 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
BMS-PM[4] – application by BMS (100 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
PYRNTR (F1)[5] – biological efficacy [%] against Tan spot of wheat (*Pyrenophora tritici-repentis*) on leaf level 1 (flag leaf);
SEPTTR (F1)[6] – biological efficacy [%] against Septoria leaf spot of wheat (*Zymoseptoria tritici*) on leaf level 1 (flag leaf);
[7]Different letters in the same column indicate that the values are significantly different ($p \leq 0.05$) according to ANOVA (analysis of variance), and 'Fisher's *LSD* (least significant difference) test.

T a b l e 7

The fungicide efficacy of tested applications against fungal diseases of wheat, BBCH 69, Rastislavice, May 28th, 2023

Tr. No.	Treatment name	PYRNTR (F1)[5]	PYRNTR (F2)[6]	PYRNTR (F3)[7]	SEPTTR (F1)[8]	SEPTTR (F2)[9]	SEPTTR (F3)[10]
1.	Untreated check	IL F1[11] = 0.0%	IL F2 = 0.0%	IL F3 = 0.1%	IL F1 = 0.2%	IL F2 = 1.2%	IL F3 = 3.6%
2.	UAV10–AM[1]	–	–	100.0[a12]	100.0[a]	89.3[a]	78.3[a]
3.	UAV50–AM	–	–	100.0[a]	100.0[a]	100.0[b]	89.2[a]
4.	UAV100–AM	–	–	100.0[a]	100.0[a]	100.0[b]	100.0[b]
5.	BMS100-AM[2]	–	–	100.0[a]	100.0[a]	100.0[b]	100.0[b]
6.	BMS300-AM	–	–	100.0[a]	100.0[a]	100.0[b]	100.0[b]
7.	UAV10-PM[3]	–	–	100.0[a]	100.0[a]	92.4[a]	82.6[a]
8.	UAV50-PM	–	–	100.0[a]	100.0[a]	100.0[b]	87.5[a]
9.	UAV100-PM	–	–	100.0[a]	100.0[a]	100.0[b]	100.0[b]
10.	BMS100-PM[4]	–	–	100.0[a]	100.0[a]	100.0[b]	100.0[b]
11.	BMS300-PM	–	–	100.0[a]	100.0[a]	100.0[b]	100.0[b]

Note: Abbreviations – see table 5.

T a b l e 8

The fungicide efficacy of tested applications against fungal diseases of wheat, BBCH 85, Rastislavice, June 17th, 2023

Tr. No.	Application	PYRNTR (F1)[5]	PYRNTR (F2)[6]	SEPTTR (F1)[7]	SEPTTR (F2)[8]
1.	Untreated check	IL F1[9] = 0.0%	IL F2 = 0.2%	IL F1 = 5.6%	IL F2 = 40.3%
2.	UAV10–AM[1]	–	100.0[a10]	85.2[a]	80.6[a]
3.	UAV50–AM	–	100.0[a]	91.2[b]	82.8[a]
4.	UAV100–AM	–	100.0[a]	98.3[b]	82.6[a]
5.	BMS100-AM[2]	–	100.0[a]	99.1[b]	89.4[a]
6.	BMS300-AM	–	100.0[a]	100.0[b]	92.2[a]
7.	UAV10-PM[3]	–	100.0[a]	75.3[a]	81.3[a]
8.	UAV50-PM	–	100.0[a]	92.4[b]	82.1[a]
9.	UAV100-PM	–	100.0[a]	91.3[b]	84.3[a]
10.	BMS100-PM[4]	–	100.0[a]	98.2[b]	91.5[a]
11.	BMS300-PM	–	100.0[a]	97.6[b]	93.4[a]

UAV10-AM[1] – application by UAV (10 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
BMS-AM[2] – application by BMS (100 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
UAV-PM[3] – application by UAV (10 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
BMS-PM[4] – application by BMS (100 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
PYRNTR (F1)[5] – biological efficacy [%] against Tan spot of wheat (*Pyrenophora tritici-repentis*) on leaf level 1 (flag leaf);
PYRNTR (F2)[6] – biological efficacy [%] against Tan spot of wheat (*Pyrenophora tritici-repentis*) on leaf level 2;
SEPTTR (F1)[7] – biological efficacy [%] against Septoria leaf spot of wheat (*Zymoseptoria tritici*) on leaf level 1 (flag leaf);
SEPTTR (F2)[8] – biological efficacy [%] against Septoria leaf spot of wheat (*Zymoseptoria tritici*) on leaf level 2;
IL F1[9] – Infection level of leaf level F1 (flag leaf) in untreated check, estimated as average percentage of leaf area damaged by a certain pathogen;
[10]Different letters in the same column indicate that the values are significantly different ($p \leq 0.05$) according to ANOVA (analysis of variance), and 'Fisher's *LSD* (least significant difference) test.

T a b l e 9

The yield parameters of winter wheat, Rastislavice, 2022 – 2023

Tr. No.	Application	Yield 2022 [t/ha]	Thousand kernel weight 2022 [g]	Yield 2023 [t/ha]	Thousand kernel weight 2023[g]
1.	Untreated check	4.97[a5]	35.21[a]	6.21[a]	36.83[a]
2.	UAV10–AM[1]	5.66[b]	36.34[b]	6.85[a]	37.69[a]
3.	UAV50–AM	5.89[b]	36.84[b]	6.82[a]	37.74[a]
4.	UAV100–AM	6.12[b]	36.42[b]	7.12[a]	38.20[a]
5.	BMS100-AM[2]	4.91[b]	37.11[b]	6.99[a]	38.11[a]
6.	BMS300-AM	6.38[c]	36.82[b]	7.12[a]	37.82[a]
7.	UAV10-PM[3]	5.09[a]	35.14[a]	6.36[a]	36.24[a]
8.	UAV50-PM	5.42[b]	36.12[b]	6.72[a]	37.23[a]
9.	UAV100-PM	5.53[b]	36.42[b]	7.32[a]	37.51[a]
10.	BMS100-PM[4]	5.62[b]	36.37[b]	7.16[a]	37.68[a]
11.	BMS300-PM	5.97[b]	36.42[b]	7.29[a]	38.21[a]

UAV10-AM[1] – application by UAV (10 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
BMS-AM[2] – application by BMS (100 L/ha) in the morning, at 6.00 – 8.00 o'clock AM;
UAV-PM[3] – application by UAV (10 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
BMS-PM[4] – application by BMS (100 L/ha) in the afternoon, at 3.00 – 5.00 o'clock PM;
[5]Different letters in the same column indicate that the values are significantly different ($p \leq 0.05$) according to ANOVA (analysis of variance), and 'Fisher's *LSD* (least significant difference) test.

cation. In appropriate weather and temperature conditions, the spray volume of 50 L/ha using UAV is equally effective to high-volume spraying by BMS. While ultra-low spray volume (10 L/ha) using UAV is about 10 – 20% less effective. Similar results were achieved by Wang *et al.* (2019), who found out that optimal FE using UAV was estimated at 16.8 L/ha for systemic insecticide and at 28.1 L/ha for contact insecticide and fungicide.

Many factors, such as diseases and pest species, plant parts, pesticide selection, spray volume, application configuration, weather, and environmental conditions, work together to have a significant influence on the UAV FE (Li *et al.* 2019). However, recent research has proven the suitability of low-volume UAVs for spraying in agrochemical applications to control pests and diseases (Shengde *et al.* 2017; Chen *et al.* 2020; Wang *et al.* 2020). The findings of many authors indicated that the UAVs are a promising alternative to conventional field sprayers in protection against fungal diseases in wheat (Köycü *et al.* 2024), rice (Ragiman *et al.* 2024) and almond (Li *et al.* 2021).

CONCLUSIONS

This study presents the results of a 2-year field trial focused on comparing the effectiveness of using UAV and BMS in controlling wheat diseases, influenced by different spray volumes and application conditions. The control efficacy on Tan spot and Septoria tritici leaf blotch was also investigated following fungicide application. The field experiments showed that compared with BMS, the efficacy of the UAV depends on the spray volume and air temperature during application. Based on fungicidal efficacy, the UAV application was comparable to BMS application at higher spray volumes (50 L/ha and more). The ultra-low spray volumes (10 L/ha) applied by the UAV achieved 10 – 20% lower efficacy in comparison to BMS application. This UAV low spray volume is not suitable for application at high air temperatures, which could dramatically decrease the biological efficacy of applied fungicide. Because our results are based only on a limited range of data, further studies should be conducted to evaluate the effects of larger number of plant protection products to estimate how widely these results are applicable in agricultural practice.

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