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Droplet Distribution and Weed Control Efficacy of Unmanned Aerial Vehicle Sprayer in Wheat Crop

Santosh Kumar[1], Manjeet Singh[2], S. K. Singh[3] and Makhan Singh Bhullar[4]

[1]Scientist (FMPE), [2]Principal Scientist-cum-Head, Department of Farm Machinery and Power Engineering, [3]Principal Scientist (REE), Renewable Energy Engineering Department, College of Agricultural Engineering, PAU, Ludhiana; [4]Principal Agronomist-cum-Head, Department of Agronomy, PAU, Ludhiana-144004(Punjab), India. Corresponding Author Email Address: Caetsantosh@Pau.edu

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ABSTRACT

Herbicide application with Unmanned Aerial Vehicle (UAV) is among few breakthroughs due to drift risk and loading capacity limitations. This study explored a perspective of using UAVs to spray herbicides. Effects of different treatments (control, knapsack sprayer, knapsack sprayer with adjuvant, UAV sprayer, UAV sprayer with adjuvant) were observed in pre- and post-herbicide spray applications in wheat crop to compare droplet distribution pattern and *Phalaris minor* weed control efficacy of UAV sprayer with a knapsack sprayer, and its effect on yield of wheat (*Triticum aestivum* L.) crop. Uniformity Coefficient was found in the range of 1.80 - 2.25 using a UAV sprayer, and was similar (1.18 - 2.12) to that for the use of knapsack sprayer. However, volume median diameter (VMD) of UAV sprayer was in the range of 437.33 µm to 540.67 µm, while it was in the range of 670.33 µm to 768.33 µm in case of knapsack sprayer. The droplets of UAV sprayer with adjuvant and knapsack sprayer with adjuvant were bigger in size as compared to treatments without adjuvant. Least *Phalaris minor* weed density after 60-day crop was observed in the case of UAV sprayer with adjuvant treatment, but there was no significant difference between UAV sprayer and knapsack sprayer in weed control density. Higher yield was observed with UAV sprayer treatments as compared to knapsack sprayer and control treatments.

Wheat (*Triticum aestivum L.*) is counted as one of most important food cereal grain consumed and produced all over the world. It is ranked as the third largest food crop in terms of volume after rice and corn **(**Anon**.**, 2019). Worldwide total wheat area, yield and production were estimated as 219 Mha, 3.53 $t.ha^{-1}$, and 772 Mt, respectively, and increased remarkably in the year 2017 (Anon., 2017) due to favourable climate conditions. India ranks second among the world's wheat producing countries for more than two decades. In the crop year of 2020-21, the total wheat area, yield, and wheat production were 31.36 Mha, 3.43 $t.ha^{-1}$, and 107.59 Mt, respectively (FAOSTAT, 2022). The production and consumption of wheat grain products play significant role in the society.

Weed is an undesirable plant that affects the yield of the main crops. Weeds act as a host plant for the multiplication of diseases and pests and serve as food and shelter throughout a crop season. *Phalaris minor* is a major weed of wheat crop, and may cause yield loss up to 35.33% (Dash *et al*., 2020). Adoption of precise weed control practices to protect the wheat plants from such destructive weeds causing minimal reduction in plant population, growth, biomass, grain yield, quality, environments, economic and health reasons (Mohammadi and Ismail, 2018). Conventionally, the crop protection products are applied through manually-operated or engine power-operated knapsack sprayer, or tractor-operated power boom sprayer (Kumar *et al*., 2020a) in India. More than 90% chemical is applied through these methods. Manual method is simple, but has several disadvantages like poor spray distribution and high labour cost (Kumar *et al*., 2020b).

In recent years, unmanned aerial vehicles (UAV) have gained popularity in the field of agriculture, leading to accomplish various activities on farmer fields (Martinez-Guanter *et al***.**, 2020 and Verma *et al***.**, 2022). The UAVs have autonomous navigation, and fly at low altitudes with airborne sensors, allows data acquisition (Urbahs and Jonaite, 2013; Teske *et al*., 2018) with both ultra-high spatial and spectral resolutions (Pajares, 2015). Spray application rates with the UAV are generally very low (20-50 time) as compared to conventional spray application methods (Wang *et al*., 2019). Application of plant protection products (PPPs) with the help of UAV has number of advantages as site-specific, quick large area coverage, reduced drudgery, and health hazards by avoiding direct contact with chemicals (Xiongkui *et al*., 2017). It also allows a farmer to apply PPPs in small windows of opportunity as favourable weather conditions, weed growth period, diseases and pest growth cycle. UAVs do not cause any adverse effect of chemicals on human being, soil compaction and crop damage. In addition to the environmental damage caused by pesticide drift to neighbouring areas, prolonged contact with these products can cause various diseases to humans (Faical *et al*., 2017). UAV has large application potential in countries where most fields are of small-scale or fragmented (Xue *et al*., 2016) as well as it is also suited to large acreage cropping systems (Huang *et al*., 2009). Sustainable use of PPPs total depends upon the actual needs, application efficiency, and its scientific data of efficacy in various crops (Garcera *et al*., 2017).

Meng *et al*. (2018) studied the effect of aerial spray adjuvant application on the efficiency of small unmanned aerial vehicle for wheat aphid's control. Results of adding appropriate adjuvant showed the ability of improving the pesticide effectiveness by improving the control efficiency, reducing the pesticide dosage and residue. Literatures reviewed have mainly focused on advantage of UAVs spraying for the application of plant protection products to control disease, insects, pests, and weeds. However, little is known about how lower volume application would affect deposition and control efficacy. Keeping in view the benefits of use of the UAV, the present research work on aerial spraying platform was undertaken to study UAV aerial spraying system for application of crop protection products for control of P. Minor Mention in wheat crop, and compare with the prevailing practices.

MATERIALS AND METHODS

Description of Unmanned Aerial Vehicle

An UAV commercial model (Make: Shandong Joyance Intelligence Technology Co. Ltd., Model: JT sprayer 10-2016 make with 6 axles, 8 rotors) purchased by the Department of Farm Machinery and Power Engineering, PAU, Ludhiana had octocopter type of configuration of propellers, and its self-weight was 11 kg (Fig. 1). The UAV could provide spray mode, GPS (global position system) mode, altitude mode, return to home, and low battery protection function. Altitude mode GPS is not used for positioning, and the aircraft can only maintain altitude using the barometer. The UAV had maximum take-off weight capacity of 28 kg, and its flying time was 15-20 min with two lithium polymer batteries having capacity of 16,000 mAh. The

(a)1.Antennas 2. Sprayer switch 3. RTH Switch 4. Stick 5. Power switch 6. Screen (b) 1. GPS 2. Battery 3. Motor and propeller 4. Sprayer tank 5, Nozzle 6. Pump

Fig. 1: (a) UAV remote, (b) UAV, and (c) Knapsack sprayer used in field experiment of wheat crop

UAV used GPS or manual flight mode. A GPS receiver can locate the exact location of the UAV, and the altitude can be maintained by using a barometer. The UAV remote control system operated at 2.4 GHz radio wave frequency. Telemetry consisted of a radio modem and one ground control station, which provided real time information during a flight. The details technical information of the drone is mentioned in Table 1.

Spraying Systems

The UAV sprayer system consisted of a ten-litre capacity pesticide tank and four flat fan nozzles (LICHENG 11003VP, Flat fan 110˚cone angle) were used in the UAV sprayer and fitted beneath the four propellers. Swath width of the UAV sprayer was 2,660 mm with four nozzles at 500 mm distance with each other. Transparent PVC pipes with an inner diameter of 8 mm were used to connect and transfer the sprayer solution from the pump to the assemble body of nozzle; while a small independent 12 V electric power pump drawing power from the UAV batteries was used to develop desired liquid pressure of 404 kPa.The spray control system allowed the pump to be driven and its speed to be varied remotely from the UAV remote control station, and enabled autonomous application in specific areas using pre-established co-ordinates via the electronic system and GPS (U-blox m8n GPS). For this purpose, a spray switch was used to turn the switch to stop or adjust the flow rate. Turning the switch to the left progressively reduced the spray rate till the stop position. The spray rate could be started by turning the switch to the right, and subsequent increase in the spray rate. The flow rate of the nozzles could thus be varied between 0.2 $l.min^{-1}$ and 0.4 $l.min^{-1}$.

Knapsack sprayer

A conventional battery-operated manual knapsack sprayer (KS) (Make: M/s. Blue Stallion Equipment’s Private Limited) was used, which had a tank of 16 l capacity. A12 V DC 8AH sealed lead acid battery of brand SUPER GARDEN was used to operate the pump (ASPEE, 12 V, 2.2 A DC) having open flow rate of 3.1 $l.min^{-1}$ at maximum pressure of 400 kPa to atomise the liquid. Cut-flat fan-type nozzle was fitted at the end of lance to atomise the spray solution into medium droplets of 250-400 µm. Flat-fan nozzle works on the deflection principle conveying a water vein onto a machined deflection surface, and produce a jet with a wide-angle flat spray pattern, medium impact value, and medium size droplets.

Table 1. Technical specifications of drone and knapsack sprayer used in the experiment

Sl. No.	Technical parameter	UAV sprayer	Battery operated knapsack sprayer
Drone with spray system			
1.	Pesticide tank, liter	10	16
2.	Self-weight, kg	11	7.5
3.	Max. take-off weight, kg	28	-
4.	Flying time, min	10-15	-
5.	Flying radius, m	0-100	-
6.	Flying height, m	0-200	-
7.	Flying speed, $m.s^{-1}$	0-12	-
8.	Spray speed, $m.s^{-1}$	0-8	0-1
9.	Sprayer width, m	4	1
10.	Nozzle, no.	4	1
11.	Spray flow, $l.min^{-1}$	0.2-0.4	-
12.	Flying downwards air flow $m.s^{-1}$	4-15 m/s	-
13.	Machine size W × L × H, m	1.8 ×1.3×0.4	-
Power system			
1.	Motor	12 S brushless heavy-duty motor	-
2.	Propeller	Carbon fibre	-
3.	ESC, rapid throttle response, A	100	
	Working voltage, V	50.4	
Remote control			
1.	Model	Futaba T8FG	-
2.	Work frequency, GHz	2.4GHZ	-
3.	Signal distance, km	1.5	-

Design of Experiment

The experiment was carried out at the Research Farm of the Department of Agronomy, Punjab Agricultural University, Ludhiana, in crop year 2018-19. Wheat (variety: PBW-725) was grown as per the package and practices for crops of Punjab by PAU, Ludhiana (Anon., 2017). The area of the experimental field was 0.26 ha (64 × 40 m) for easy flying of the drone.

Each treatment was isolated by 2 m wide buffer zone between each plot. Five treatments [Control (T_1), Knapsack sprayer (T_2), Knapsack sprayer with adjuvant (T_3), UAV sprayer (T_4), and UAV sprayer with adjuvant (T_5)] were conducted to compare the droplets density, number median diameter (NMD), volume median diameter (VMD), percentage coverage, uniformity coefficient (UC), and weed control efficacy of UAV sprayer and knapsack sprayer for the pre- and post-emergence application of herbicide to control the weed in wheat crop (Table 2). The experimental field layout was split-plot design with three replications.

Experiment Procedure

Calibration of the UAV and knapsack sprayers were carried out before conducting an experiment to determine the amount of spray volume solution requirement for each treatment plot. For complete characterization of the equipment, laboratory tests at Spraying Laboratory of the Department of Farm Machinery and Power Engineering, PAU, Ludhiana, were carried out to determine the average flow rate of each nozzle in both configurations (one nozzle mounted at boom mounted on landing gear of UAV, and second w67890-configurations nozzle fitted beneath the four propeller) at full extreme position of pump on switch, and the liquid quantities were measured with graduated test tubes.

Field experiment

Five treatments with three replications were carried out for the application of pre-emergence herbicide Pyroxasulfone 85WG (M/s. Bayer Crop Science Ltd., Pune, India) at the rate of 176.5 g.ha[1], containing 85% (w/w) of Pyroxasulfone active ingredient. The chemical was applied at 0-1 day after sowing. Pyroxasulfone treatment drastically reduces the bio-synthesis of very long chain fatty acids (VLCFAs) and causes a build-up of fatty acid precursors. Pyroxasulfone specifically inhibits many elongation steps catalysed by VLCFA elongates. Similar experiment was repeated for the application of post-emergence herbicide (brand name:

Table 2. Test protocol of various treatments for efficacy evaluation by using different chemicals along with doses and water volume application rates

Treatment	Indication	Application window	Product and dose	Chemical with water application rate, $l.ha^{-1}$
T_1 (Control)			No spraying	
T_2 (Knapsack Sprayer)	Herbicide 1	Pre-emergence at 0-2 DAS	Pyroxasulfone 85WG, dose 176.5 $g.ha^{-1}$	375-500
	Herbicide 2	Post emergence at 4-6 leaf stage of weed	Atlantis, dose 400 $g.ha^{-1}$	
T_3 (Knapsack Sprayer with Adjuvant 'A')	Herbicide 1	Pre-emergence at 0-2 DAS	Pyroxasulfone 85WG, dose 176.5 $g.ha^{-1}$+ Adjuvant, 1 $ml.l^{-1}$ of water volume	375-500
	Herbicide 2	Post emergence at 4-6 leaf stage of weed	Atlantis, dose 400 $g.ha^{-1}$+ Adjuvant, 1 $ml.l^{-1}$ of water volume	
T_4 (Drone Sprayer)	Herbicide 1	Pre-emergence at 0-2 DAS	Pyroxasulfone 85WG, dose 176.5 $g.ha^{-1}$	25 -40
	Herbicide 2	Post emergence at 4-6 leaf stage of weed	Atlantis, dose 400 $g.ha^{-1}$	
T_5 (Drone Sprayer with Adjuvant 'A')	Herbicide 1	Pre-emergence at 0-2 DAS	Pyroxasulfone 85WG, dose 176.5 $g.ha^{-1}$ + Adjuvant, 1 $ml.l^{-1}$ of water volume	25 -40
	Herbicide 2	Post emergence at 4-6 leaf stage of weed	Atlantis, dose 400 $g.ha^{-1}$+ Adjuvant, 1 $ml.l^{-1}$ of water volume	

Altantis, manufactured by M/s. Bayer Crop Science Ltd., Pune, India) at the rate of 400 g.ha[1] [Mesosulfuron methyl 3% + Iodosulfuron methyl sodium 0.6 w/w WDG (3.6 WDG)] was applied at 4-6 leaf stage of weeds. This chemical was selected to verify the bio-efficacy by using UAV sprayer and knapsack sprayer and to examine its suitability for UAV sprayer.

Adjuvant is a chemical that increase spared factor of droplets, which increase the effectiveness of chemical to control weeds. Adjuvant dose was mixed at the rate of 1 mg.l^{-1} of water volume applied with UAV sprayer (T5) and knapsack sprayer (T2) treatments. The operating parameters of UAV sprayer, knapsack sprayer, and metrological parameters (temperature, wind speed, humidity at the time of spray) were recorded and reported in Table 3.

Oil and water sensitive paper method was used to find various spray quality parameters for different

Table 3. Operating parameters of UAV, knapsack sprayer and metrological data

Parameter	Value	
Type of spray herbicide application	**Pre-emergence**	**Post emergence**
UAV Spraying System		
Crop after sowing (DAS)	0-1	40
Crop height, mm	0	200-250
Pilot mode	Auto pilot mode	
Fly height, mm (measure from crop canopy)	1,500	
Fly speed, m.s^{-1}	5	
Nozzle type	Flat fan 110°	
Operating pressure, bar	3	
Water volume application rate, l.ha^{-1}	33.65	28.84
Number of nozzles	4	
Spray width, mm	2,660	
Mixing quality with adjuvant(s)	Good	
Knapsack Sprayer		
Nozzle type	Flat fan	
Operating pressure, bar	3	
Water volume applied, l.ha^{-1}	375	
Metrological parameter		
Temperature, ºC	25	19
Relative humidity, %	38	59
Wind speed, km.h^{-1}	11.5	3

spray treatments (Kumar *et al.*, 2020) for pre- and post-emergence herbicide application. Before a spray, oil and water sensitive papers were placed at 0.5 m interval on ground surface in each treatment plots. After a spray operation, the oil and water sensitive papers were collected and stored in zip-lock polyethylene bag. The 'Dropscan' (developed by M/s.Leon Sistemas Digitais, Rua Washington Luis, 381CEP: 14580-000CentroBuritizal-SP) was used to determine droplet density (number of drops per square cm), area converge (%), volume median diameter (µm), number median diameter (µm), and uniformity coefficient. For the determination of sprayer performance parameters, oil and water sensitive paper was just put into the scanner, which scanned the paper with the help of software Dropscan. After scan of paper, the software digitized the image and gave the value of droplet density (number of drops per square cm), area converge (%), volume median diameter (µm), number median diameter (µm), and uniformity coefficient. The UAV sprayer and knapsack sprayer used in the experimental field are shown in Fig. 2.

The *P. minor* was the major weed in the wheat crop area. The numbers of weeds at 15, 30, 45 and 60 days after spraying were counted, and the results were analysed. The number of weeds was counted at four spots in each treatment plot using a square quadrant (1 square meter quadrant). Every time *P. minor* count were carried out at the same location of each treatment to compare the weed density.

The percent Weed Control Efficiency (WCE) at 60-day after sowing was calculated using the following formula**:**

$$\text{WCE (\%)} = \frac{\text{Dry mass of weeds in untreated (control) plot} - \text{Dry mass of weeds in treated plot}}{\text{Dry mass of weeds in untreated (control) plot}} \times 100 \quad \ldots(1)$$

Various crop performance parameters (number of tillers per hill, number of tillers per metre row length, spike length, wheat plant height) of different treatment plots throughout the crop season were recorded. Wheat yield at harvest was used to find the differences in yields between the two spraying practices.

Statistical Analysis

The general linear model, completely randomized design (CRD) was used to analysis of variance at p≤0.05 level of significance with the help of IBM SPSS 20 (SPSS Inc., an IBM Company, Chicago, IL, USA)

Fig. 2: Post emergence herbicide spray with knapsack and UAV sprayer in what crop

statistical software. Tukey's B, of post hoc test was applied to compare effect between treatments.

RESULTS AND DISCUSSION

Droplet Distribution Pattern

Spray quality parameters as droplet density, percent area coverage, number median diameter (NMD), volume median diameter (VMD), and uniformity coefficient (UC) were obtained from the analyses of oil and water sensitive paper samples. A pictorial view of used oil and water sensitive paper to find sprayer performance parameters is shown in Fig. 3. The mean value of two spray experiments pre- and post- emergence herbicide applications separated from Tukey's B of post-hoc test of various spray performance parameters is reported in Table 4.

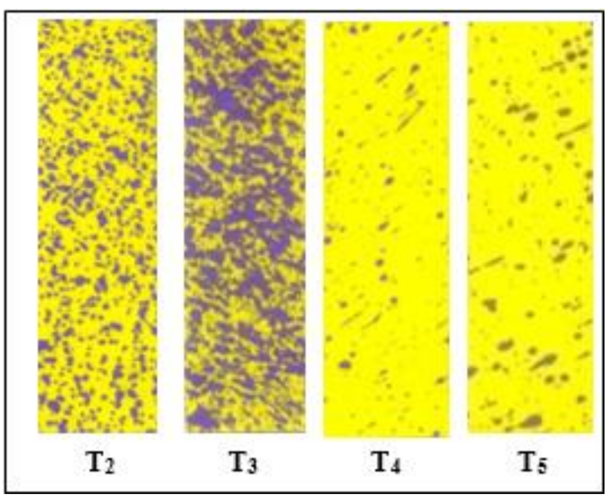

Fig. 3: Oil and water sensitive paper used to evaluate spray performance parameters in different treatments

The droplet density of UAV sprayer without using adjuvant(T_4) and with adjuvant (T_5) was 12.06 droplet. cm^{-2} and 16.48 droplet.cm^{-2}, respectively; whereas, the same for the knapsack sprayer without adjuvant (T_2) and with adjuvant (T_3) were higher at 32.91 droplet. cm^{-2} and 42.52 droplet.cm-^{2}, respectively. Droplet density was less (Table 4) in UAV sprayer and knapsack sprayer treatments. This might be due to low-volume application rate of 33.65 l.ha^{-1} of the UAV sprayer as compared to 375 l.ha^{-1} that of the knapsack sprayer. However, the treatments with adjuvant knapsack (T_3) and UAV sprayer (T_5) did not vary significantly with the knapsack sprayer (T_2) and UAV sprayer (T_4 without adjuvant), respectively.

Knapsack sprayer with adjuvant(T_3) had higher percent area coverage (83.97%), followed by knapsack sprayer without adjuvant (T_2) with area coverage of 58.71 per cent. UAV sprayer with adjuvant (T_5) had coverage of 6.45%, and UAV sprayer without using adjuvant (T_4) had coverage of 3.29 per cent. It was also observed that the treatments with adjuvant had significantly larger percent area coverage as compared to treatment without adjuvant while using both type of sprayers. The per cent coverage area of each sprayer had non-significant effect on use of adjuvant. However, the knapsack sprayer and UAV sprayer had significant difference in percent coverage area.

While no significant difference was observed in NMD of both sprayers, the VMD of UAV sprayer was of smaller size as compare to knapsack sprayer (Table 4). From the ANOVA analysis (Table 4), significant difference in size of droplets released by the UAV sprayer and the knapsack sprayer were noticed. However, within sprayer treatments of knapsack

Table 4. Mean separated by Tukey's B of post-hoc test of different sprayer performance parameters under various treatments

Treatment	Droplets density, Droplet.cm^{-2}	Coverage, %	NMD, µm	VMD, µm	UC
T_2	32.91±9.37^b	58.71±33.43^b	373±111.23^a	670.33±110.50^{cb}	1.80±0.75^a
T_3	42.52±6.78^b	83.97±22.11^b	362.67±140.76^a	768.33±92.11^c	2.12±0.88^a
T_4	12.06±4.14^a	3.29±0.36^a	243±52.72^a	437.33±40.22^a	1.80±0.61^a
T_5	16.48±3.52^a	6.45±1.83^a	240.33±57.73^a	540.67±56.62^{ba}	2.25±0.45^a

Note: Mean ± SD, Means within a column, followed by the same letter in superscript are not significantly different at P < 0.05. Different superscript letter represents significant difference at P < 0.05

sprayer without adjuvant (T_2) and knapsack sprayer with adjuvant (T_3), no significant difference was noticed. Large sized droplets were observed in both UAV and knapsack sprayed plots because of properties of the adjuvant.

Uniformity coefficient data was statistically analysed (Table 4), and the results showed that there was no significant difference between the spraying machines. Higher variation in uniformity coefficient was observed in treatment with adjuvant for both spraying methods, and was due to adjuvant spreading property over the leaf surface causing more percent leaf area coverage.

Weed Density Reduction in Wheat Crop

Sprayer treatments pair comparison and mean data of the *P. minor* weed density (number of weeds.m^{-2}) was analysed using Tukey's B post-hoc test of different sprayer treatments at 5% level of significance (Table 5). Early stage of wheat crop and weed growth at 15-day and 30-day after sowing with pre-emergence herbicide application of pyroxasulfone 85**%** **(**WG**)** did not have significant difference at 5% level of significance. This might be due to the reason that during the early stage of weed growth, not much population of *P.minor* weed was identified. However, pre-treatment application of herbicide was found to be relatively safe, and could effectively suppress other weed emergence. Similar effect of pre-emergence herbicides and timing of soil saturation on the control of six major paddy weeds and their phytotoxic effects on paddy seedling show the moisture in the soil is crucial in increasing the efficacy of PRE herbicides as it facilitates the movement of the herbicide into the soil, thereby reducing herbicide losses from the soil surface and increasing the absorption of the herbicide by the emerging seedlings for controlling weeds effectively (Varshney *et al*., 2012; Awan *et al*., 2016).

After the post-emergence herbicide application, *P. Minor* weed count on 45th day of crop sowing in plots with herbicide spray by UAV sprayer and knapsack sprayer with and without adjuvant were significantly different as compare to control. Minimum number of *P. Minor* weed (3.33.m^{-2}) was observed in plots treated with UAV with adjuvant (T_5) on 60th day after sowing; whereas, maximum number of weed (40.00 weed.m^{-2}) was observed in un-treated control plots. The visible action of Mesosulfuron-methyl 3**%** **+** Iodosulfuron-methyl sodium 0**.**6 w/w WDG **(**3**.**6 WDG**)** of herbicide was the arrested weed growth within first few days after application and the appearance of chlorotic patches, followed by slow shoot necrosis of *P. minor*.

Table 5. Effect of different treatments on *Phalaris minor* population in wheat field

Treatment	Weed density, number of weed.m^{-2}				Reduction at 60 DAS, %
	15 DAS	30 DAS	45 DAS	60 DAS	
T_1 (Control)	24.00±2.65^a	28.33±2.08^a	34.00±5.00^b	40.00±1.53^b	-
T_2	28.33±5.13^a	17.33±8.35^a	7.67±3.06^a	5.00±2.65^a	87.50
T_3	25.33±5.51^a	22.00±7.94^a	11.33±7.23^a	4.00±2.65^a	90.00
T_4	25.33±7.37^a	20.67±3.51^a	17.33±8.62^a	3.67±0.58^a	90.80
T_5	24.00±8.89^a	16.33±5.86^a	16.00±4.36^a	3.33±1.15^a	91.67

Note: Mean±SD, Means within a column followed by same letter in superscript are not significantly different at P < 0.05.Different superscript letter represents differ significantly at P < 0.05

Weed population under different treatments were significant, and less as compared to control treatment. The treatments of herbicide application with UAV sprayer and knapsack sprayer, UAV with adjuvant and knapsack sprayer with adjuvant had non-significant differences between each other. Results also revealed that the UAV herbicide spray and UAV herbicide spray with adjuvant had better (26.60% and 16.75%) *P. minor* weed control over knapsack sprayer (T_2) and knapsack sprayer with adjuvant (T_3) treatments.

Phalaris minor Control Efficacy

Weed control effectiveness on the basis of dry mass of *P. Minor* was determined for each treatment to determine weed control efficiency (WCE), and reported in Table 6.

UAV with adjuvant (T_5) had maximum *P. Minor* weed control efficiency of 86.98%, followed by UAV herbicide spray (T_4), knapsack sprayer with adjuvant (T_3), and knapsack herbicide spray (T_2), which were 83.42%, 82.34%, and 77.43%, respectively.

Better control of *Phalaris minor* was observed in the UAV treated plots, possibly due to small size of droplets. UAV spray with adjuvant and knapsack spray with adjuvant had higher *P. minor* weed control efficiency due to higher percent coverage area. Statistical analysis (Table 6) showed that there was a significant difference between the treatments at 5% level of significance.

Sensitivity of Wheat to Selected Herbicides

None of the selected pre-emergence herbicides induced crop injury after the germination of crop. In the post-treatments, wheat crop did not show injury after mesosulfuron-methyl 3**%** **+** Iodosulfuron-methyl sodium 0.6 w/w WDG **(**3.6 WDG**)** application with the knapsack sprayer with high water volume application rate. However, mesosulfuron-methyl 3**%** **+** Iodosulfuron-methyl sodium 0.6 w/w WDG **(**3.6 WDG**)** application with UAV sprayer induced minor injury (average 30-40%) in the form of chlorosis on the leaf blade tips at turning spot point of UAVs.

Spraying with UAV sprayer using pyribenzoxim pretilachlor + cyhalofop-butyl showed stunting and yellow leaf colour for approximately 20 days post-spraying. The plants showed approximately30-40% injury at the points of turn of the UAV are shown in Fig 4. This might be due to excessive dose of spray during turns (Fig.4). The results show that UAV application of herbicides is possible using herbicides selected in this study for pre-emergence application was relatively safe to wheat crop. However, post-application of herbicides via UAV might induce severe crop injury even when the herbicide is safe when applied with knapsack sprayer or other high water volume application methods. From this result, we can say that herbicides should be tested before recommending for UAV application.

Crop Attributes and Grain Yield

The treatment T_1 (Control) significantly differed with all other treatments. Number of tillers per hill had no significant effect on the treatments, and ranged from 5.40 to 8.50. Plant height also had no significant effect on the treatments, and ranged from 1,079.0 mm to 1,116.0 mm. Spike length and number of tillers per

Table 6. Weed control efficiency of different spray treatments

Treatment	Dry mass of weeds at 60 DAS, g			Mean dry mass of P. minor weed, g (WCE, %)
	R_1	R_2	R_3	
T_1 (Untreated control)	35.00	27.80	49.40	37.40±11.00[a]
T_2 (KS herbicide spray)	9.20	7.80	6.60	7.87±1.30[b] (77.43)
T_3 (KS with adjuvant)	5.05	6.10	8.20	6.45±1.60[b] (82.34)
T_4 (UAV herbicide spray)	5.60	8.40	4.60	6.20±1.97[b] (83.42)
T_5 (UAV with adjuvant)	1.40	6.80	6.40	4.87±3.01[b] (86.98)

Note:
Mean ± SD, Parenthesis values show weed control efficacy in percentage.
Means within a column followed by the same letter in superscript are not significantly different at P < 0.05.
Different superscript letter represents significant difference at P < 0.05

Fig. 4: Phytotoxicity effect of mesosulfuron-methyl 3% + Iodosulfuron-methyl sodium application with UAV sprayer in wheat crop

metre row length also were not significantly different between the treatments (Table 7).

Treatments T_2 and T_3 significantly differed with the treatment T_4 and T_5. Grain yield was in the range of 2.66 $t.ha^{-1}$ to 5.48 $t.ha^{-1}$. Tukey's B test analysis (Table 7) showed that the yield had significant differences between the treatments. It was also observed that the spraying with UAV using adjuvant had significant higher number of tiller and number of tillers per metre row length. Maximum yield of 5.48 $t.ha^{-1}$ was in the plot which was treated with adjuvant using UAV sprayer (T_5). However, this might also be due to no intervention of human in standing crops in case of UAV sprayer, and it also had uniform distribution of drop resulting better management of *P. minor* in treatment with UAV sprayer (T_4) and UAV sprayer with adjuvant (T_5) as compared to same chemicals used in knapsack sprayer as well as under control treatment.

The risk of drift is more with UAV sprayer application than with conventional application due to higher spray height, smaller droplet diameter, and high droplet concentration. Therefore, more experiments are needed to determine ways to reduce drift and whether it can be achieved by using drift reducing adjuvant or different type of nozzles. More herbicides and UAV configurations should be studied to further improve the control spectrum and weed management efficiency of UAV applied herbicides.

CONCLUSIONS

The droplet VMD and per cent area coverage of UAV sprayer was significantly less as compare to knapsack sprayer for spraying of herbicide with or without adjuvant. The VMD of droplet of herbicide with adjuvant applied with either knapsack sprayer or UAV sprayer was higher than herbicide without adjuvant. Spray uniformity coefficient was not significantly different when herbicide with or without adjuvant was sprayed by UAV sprayer or knapsack sprayer.

Maximum dry weight reduction (86.98%) of *P. Minor* was obtained by spraying herbicide with adjuvant using UAV sprayer after 60 days of sowing of wheat

Table 7. Effect of different treatments on yield attributes of wheat crop

Treatment	Tillers per hill, No.	Plant height, mm	Spike length, mm	Tiller per metre row length, No.	Yield, $t.ha^{-1}$
T_1	5.40± 1.65[a]	1116.00± 16.50[a]	102.00± 0.63[a]	71.80± 3.85[a]	2.66± 0.12[a]
T_2	5.70± 2.45[a]	1100.00± 14.90[a]	100.00± 0.82[a]	80.10± 4.09[a]	4.62± 0.08[b]
T_3	8.50± 1.90[a]	1091.00± 11.00[a]	98.00± 1.03[a]	78.50± 4.35[a]	4.75± 0.09[b]
T_4	7.50± 1.51[a]	1085.00± 20.70[a]	103.00± 0.82[a]	78.30± 3.62[a]	5.17± 0.04[c]
T_5	8.50± 1.18[b]	1079.00± 16.60[a]	099.00± 0.88[a]	80.80± 7.35[b]	5.48± 0.11[c]

Note: Means within a column followed by same letter in superscript are not significantly different at P < 0.05. Different letter superscript represents significantly at P < 0.05 crop. Other spraying treatments also showed good weed control efficiency (77.43 - 83.42%) against the weed. Plots sprayed by UAV and knapsack sprayer had significant higher number of tillers per hill, and number of tillers per metre row length as compared to plots without application of herbicide. Wheat crop yield was significantly higher in plots treated with UAV sprayer (with / without adjuvant) as compare to plots sprayed with knapsack sprayer (with and without adjuvant). Slight phytotoxicity effect of mesosulfuron-methyl 3**% +** Iodosulfuron-methyl sodium was observed in the plots treated with UAV sprayer**.** The results suggest that every herbicide should be tested before being recommended for UAV applications.

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