

Effect of unmanned aerial vehicle (UAV) mediated herbicide spray on weed management in maize (*Zea mays* L.)

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Abstract

Weed infestation is a major constraint to maize productivity, particularly under conditions of limited labour availability. A field experiment was conducted during *khari* 2022 at the Agronomy Field Unit, Zonal Agricultural Research Station, University of Agricultural Sciences, Bengaluru, to evaluate the efficacy of drone-mediated herbicide application on weed dynamics, crop growth, yield, and economics of maize. The experiment assessed different pre-emergence herbicides applied through drone spraying. Grasses were the dominant weed flora, followed by broad-leaved weeds and sedges. Pre-emergence application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ with a spray volume of 78 L ha⁻¹ recorded the lowest total weed density (2.24, 3.60, and 5.39 plants m⁻²) and weed dry weight (0.86, 1.34, and 2.43 g m⁻¹) at 10, 20, and 30 DAS, respectively. The same treatment also resulted in superior crop growth, evidenced by greater plant height, leaf number, leaf area, and dry matter accumulation, and was statistically comparable to Oxyfluorfen 23.5% EC @ 0.10 kg a.i. ha⁻¹. Enhanced weed suppression translated into improved yield attributes, including cob length (17 cm), rows per cob (17), kernels per row (30), kernels per cob (441), grain weight per plant (150 g), and seed index (31.87 g). Consequently, the highest grain yield (6644 kg ha⁻¹) and stover yield (8337 kg ha⁻¹) were obtained with Atrazine application. Economic analysis revealed maximum gross returns (₹138,704 ha⁻¹), net returns (₹96,976 ha⁻¹), and benefit-cost ratio (3.32) under the same treatment. The study demonstrated that drone-mediated pre-emergence application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ at 78 L ha⁻¹ is an effective and economically viable weed management strategy for enhancing maize productivity.

Key words: *Unmanned Aerial Vehicle, Drone, Herbicide, Weed Management, Spray Volume*

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide as a source of food, feed and industrial raw material. Competition from weeds, especially in the early stages of growth, often limits productivity. Weeds compete for nutrients, moisture, light and space with crop plants and can cause substantial yield reductions. The loss in maize yield due to weed infestation has been reported to vary from 18 to 65 per cent worldwide depending on weed intensity, crop management practices and environmental conditions (Gharde *et al.*, 2018). The critical period of weed competition in maize is generally two to six weeks after crop emergence, when appropriate weed control is needed to prevent yield losses (Swanton *et al.*, 2015).

Good weed management depends on correct identification of the weed flora and on using appropriate

control measures. Different weed management tactics are used in maize production, such as cultural, mechanical, biological and chemical strategies. Among these, chemical weed management has gained popularity due to its effectiveness, timeliness and less dependency on labour (Chauhan, 2020). Herbicides are quick and efficient weed control tools and are an integral part of modern crop production systems. The strategic use of pre-emergence and post-emergence herbicides can effectively suppress weed growth, improve crop competitiveness and enhance resource-use efficiency (Mishra *et al.*, 2021). Pre-emergent herbicides such as atrazine and pendimethalin have been widely reported to control annual grasses and broad-leaf weeds effectively during the early growth stages of maize (Iqbal *et al.*, 2020).

The shortage of farm labour and rising labour cost have become major constraints to agricultural production,

especially in the critical period of weed management. The traditional methods, e.g. hand weeding, are effective but labour intensive, time consuming and often not economical under large scale farming conditions. The mechanical weed control is also limited by the availability of suitable machinery and operational difficulties in bad field conditions (Chauhan, 2020). Therefore, weed management practices based on herbicides have been widely adopted due to their operational efficiency and cost-effectiveness.

Herbicides have traditionally been applied with hand-carrying knapsack sprayers and tractor-mounted boom sprayers. However these methods require large volumes of water, involve considerable labour input and may result in uneven spray coverage and increased operator exposure to agrochemicals. Moreover, adverse weather conditions can limit field access for herbicide application in a timely manner and reduce weed control effectiveness (Faïçal *et al.*, 2014). Recent advances in precision agriculture have created new opportunities for the use of unmanned aerial vehicles (UAVs), or drones, in crop production systems (Huang *et al.*, 2013).

The drone technology has evolved as an effective tool for precision pesticide application because of its ability of delivering agrochemicals in a precise, uniform and effective manner with less water requirement. UAV spraying allows site-specific application, reduces crop damage from ground equipment, reduces operator exposure, and improves operational efficiency under a variety of field conditions (Hunter *et al.*, 2020). The technology allows for more flexibility in the timing of spraying, and effectively covers fields that are difficult to reach with conventional equipment. Besides, UAV-based spraying is reported to improve the spray deposition and coverage, and reduce the labour requirement and application cost (Zhang *et al.*, 2024). Hence, the integration of drone technology in weed management programmes is gaining more attention as a sustainable and resource efficient approach of crop protection.

Though the use of pesticides with drone support has shown an encouraging result in many field crops, the information regarding the effectiveness of the same for herbicide application and weed management in maize

under Indian conditions is still limited. Therefore, the present investigation was carried out to find out the feasibility of drone mediated herbicide application in maize and its effect on weed dynamics, weed control efficiency, crop growth, productivity and economics.

Materials and Methods

Location of the experimental site

The experiment was conducted at Agronomy Field Unit, Zonal Agricultural Research Station, University of Agricultural Sciences, Bangalore, Gandhi Krishi Vignana Kendra, Bengaluru which is situated at 13° 05' North latitude and 77° 34' East longitude with an altitude of 924 m above mean sea level and which comes under Eastern Dry Zone, agro-climatic zone (ACZ-5) of Karnataka.

Soil properties of the experimental site

The soil of the experimental site was red sandy loam in texture, classified under the order *Alfisol*. The composite soil sample from 0-15 cm depth was collected randomly in experimental site before sowing. Analysis was done for various physical and chemical properties of the soil. The textural class of the experimental site soil was red sandy loam, consisting of 52.40 per cent coarse sand, 22.10 per cent fine sand, 13.20 per cent silt and 12.20 per cent clay. The soil pH was 6.85 with an electrical conductivity of 0.40 dS m⁻¹. The organic carbon content was 0.42 per cent. The soil was medium in available Nitrogen (258.43 kg ha⁻¹), Phosphorus (21.82 kg ha⁻¹) and Potassium (206.86 kg ha⁻¹).

Actual climatic condition during the crop growth period from July 2022 to November 2022, total rainfall of 894.2 mm was received, which was 243.3 mm higher compared to the normal. The highest monthly rainfall was obtained in October 2022 (361 mm) and no rainfall was received in February 2022. The actual rainfall was less than normal in the months of September and November 2022 and higher than normal from April to August, October and December 2022. The average maximum air temperature ranged from 26°C in November 2022 to 27.7°C in September 2022. The mean minimum temperature also ranged from 16.6°C in November to 18.7°C in July. The

mean maximum temperature is lesser than normal from July to November 2022. The mean minimum temperature was also lesser than normal from July to November 2022. The mean monthly relative humidity ranged from 87 per cent in July to 91 per cent in August (2022). The average relative humidity was more than normal in all months of the cropping period. The mean monthly daily bright sunshine hours ranged from 3.4 hours in July (2022) to 5.3 hours in November (2022).

Experimental details

The experimental site was left fallow during preceding *rabi* season (2021). The experiment was conducted in Kharif 2022. The design followed was Randomized Complete Block Design with factorial concept with 6 treatments and 4 replications. The maize variety used was MAH-14-5. The gross plot and net plot was 21 m × 21 m and 19.8 m × 20.4 m, respectively. Recommended dose of fertilizers (150:75:40 kg N: P₂O₅: K₂O ha⁻¹) was applied during the crop season. The treatment details are mentioned here. Factor-1 consisting of Herbicide (H) factor at two levels i.e., H₁: Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ (PE) and H₂: Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹ (PE). Factor-2 was Spray volume (V) at three levels i.e., V₁: 78 l ha⁻¹, V₂: 52 l ha⁻¹, V₃: 26 l ha⁻¹ and there was an control plot having Manual application i.e., C₁: H₁ @ 750 l ha⁻¹ (T₇) and C₂: H₂ @ 750 l ha⁻¹ (T₈). Hence total six treatment combinations were there receiving following treatment combinations viz., T₁: Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ @ 78 l ha⁻¹, T₂: Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ @ 52 l ha⁻¹, T₃: Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ @ 26 l ha⁻¹, T₄: Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹ @ 78 l ha⁻¹, T₅: Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹ @ 52 l ha⁻¹ and T₆: Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹ @ 26 l ha⁻¹.

Drone and its characteristics

The technical sections of drones are given in table 1. The unmanned aerial vehicle (UAV) used in the present study was a quadcopter-type drone with four fixed-pitch propellers in a vertical orientation. Each propeller was driven by its own electric motor with variable speed control allowing for stable flight and movement in any direction. The drone chassis was designed to find the

best compromise between structural strength and weight so that it can generate lift efficiently and maintain flight stability.

The propellers produced thrust by converting the rotational energy into an aerodynamic force. Two propellers spun clockwise and the other two spun anticlockwise, balancing rotational torque for stable hovering and manoeuvrability. The propulsion system used brushless DC motors that were rated in kilovolt (kV) which is the speed of the motor in revolutions per minute (RPM) per volt with no load on the motor. Higher motor speeds gave more lift and flight power, but the batteries drained faster.

The drone was powered by rechargeable lithium-polymer (Li-Po) batteries due to their high energy density and lightweight. The power supplied to each motor was controlled by an electronic speed controller (ESC) and the motor speed was controlled according to commands received from the flight controller. The flight controller served as the primary onboard processor, taking in input signals from the radio receiver and generating control commands to keep the flight steady and on course. The drone was controlled and communicated through a 2.4 GHz radio frequency (RF) remote controller with control sticks, switches and variable rotary controls for accurate manoeuvring and operation.

Sprayer Module

The sprayer module was composed of a spray tank, pump, nozzle assembly, controller unit and remote-control transmitter. The system was built for the aerial application of herbicides and other crop protection chemicals. The spray solution was carried in the spraying unit and the controller controlled the function of the pump and nozzle system. Spraying was activated and deactivated remotely by a radio-frequency transmitter operated by the user. The controller unit on the reception of the command from the remote controller actuated the spraying mechanism which helped in the release of the spray solution exactly through the nozzle assembly. This arrangement allowed for a controlled and targeted application of herbicides, reduced operator exposure to chemicals and improved spraying efficiency in field conditions.

Droplet density analysis

White coloured hydrophobic polythene sheets were spread at random spots in all plots of different spray volumes. The drone when passed over in those plots the herbicide solution was fallen on those randomly

distributed white polythene sheets and those sheets were collected separately in order to know the difference in droplet density in different spray volumes. Later, those sheets were taken into lab and observed under microscope and photographs of droplet density were captured under mobile camera.

Table 1: Technical specifications of spraying drone

Drone specification	Particulars
Structure	Quadcopter
Max. take-off weight (kg)	45
Maximum speed (m/s)	3-5
Spray width / swath (m)	2-3 m
Nozzle type	Flat jet nozzle
Number of nozzles	Four
Spray height from ground	2-4 m
Capacity (liter)	10
Maximum height (m)	20

Biometric observations and data collection

Observation on weeds

Species wise weed count

Species wise weed counts (number 0.25 m²) were recorded at 10, 20 and 30 DAS at two spots in net plot area. These weeds were categorized as sedge, grasses and broad leaf weeds and expressed as number m⁻² and averaged over two random spots per plot.

Weed dry weight

Out of two random spots in net plot area, one of sampled spot was selected for recording weed dry weight. After sorting grasses, sedges and broad leaf weeds, these weeds were dried in hot air oven at 65 °C, till constant dry weight was recorded. The dry weight of weeds was expressed separately for sedge, grasses and broad leaf weeds as gram (g m⁻²) at 10, 20 and 30 DAS.

Relative weed control efficiency (RWCE)

Weed control efficiency was calculated by using the following formula,

$$RWCE (\%) = \frac{X - Y}{X} \times 100$$

Where,

X : Weed dry weight in manual applied plot

Y : Weed dry weight in drone applied plot

Relative weed index (RWI)

Weed index was calculated by using the following formula,

$$RWI (\%) = \frac{X - Y}{X} \times 100$$

Where,

X : Yield obtained from manual applied plot

Y: Yield obtained from drone applied plot

Operational efficiency (OE)

Operational efficiency (OE) is used to work out the efficiency of herbicide application by drone over manual application with respect to time using the following formula.

$$OE (\%) = \frac{\text{One hectare of land}}{\text{Time taken by drone/man to apply herbicide}} \times 100$$

Phytotoxicity rating on crop

Phytotoxicity rating on crop are given in table 2. Qualitative description of visual phytotoxicity ratings on crop from 1-10 was recorded at 7, 14 and 21 days after spraying of herbicide.

Table 2: Phytotoxicity rating on crop

Effect	Score	Phytotoxicity symptoms (crop)
None	0	No injury, normal
	1	Slight stand loss, stunting or discoloration
Slight	2	Some stand loss, stunting or discoloration
	3	Injury more pronounced but not persistent
	4	Moderate injury, recovery not possible
Moderate	5	Injury more persistent, recovery possible
	6	Near sever injury, no recovery possible
	7	Sever injury, stand loss
Severe	8	Almost destroyed, a few plants surviving
	9	Very few plants are alive
Complete	10	Complete destruction

Statistical analysis and interpretation of data

The experimental data collected on plant growth parameters, yield components and weed parameters were subjected to Fisher's method of "Analysis of Variance" (ANOVA) as outlined by Panse and Sukhatme (1954). Wherever F- test was significant, for comparison between the treatment means, an appropriate value of critical difference was worked out. All the data were analyzed and the results are presented and discussed at a probability level of five per cent.

Results and Discussion

Effect of drone mediated herbicide application on operational parameters in maize

Droplet density

The higher droplet density was observed in treatments with herbicide spray volume 78 l ha⁻¹ followed by 52 l ha⁻¹ whereas lower droplet density was observed in treatments with 26 l ha⁻¹ spray volume (Fig. 1). When the spraying operation was performed at a lower flight velocity, the droplet density was higher. Spray volume of 78 l ha⁻¹ recorded higher deposits per unit area with low flight velocity. This was followed by the spray volume 52 l ha⁻¹ when speed of drone increases, the area of liquid covered

testers and the density of drops that settle on them reduced (He *et al.*, 2012). There was no significant difference were observed in droplet size of all the three spray volumes studied. It might be due to no change in nozzle type. Droplet size was not affected by spray volume and also number of passes over the research plot did not change the droplet size (Esehaghbeygi *et al.*, 2011; Sanagi *et al.*, 2012 and Martin *et al.*, 2020).

Operational time

Herbicide application by using a drone recorded lesser time (37.79 min ha⁻¹) when compared to manual application of herbicide by using a power operated knapsack sprayer. This was due to greater forward speed of the drone (Hensh *et al.*, 2018 and Ahirwar *et al.*, 2019).

Operational efficiency

Herbicide application through drone recorded higher operational efficiency (2.65%) whereas manual application of herbicide by using a power operated knapsack sprayer recorded lower operational efficiency (0.27 %). The drone completed spraying of herbicide for the entire plot within less time when compared to traditional manual spraying which required more time to complete the spraying of herbicide to the same plot (Giles *et al.*, 2016; Hensh *et al.*, 2018 and Ahirwar *et al.*, 2019).

Relative weed control efficiency

In case of atrazine, drone mediated herbicide application at spray volume of 78 l ha⁻¹ has recorded higher relative weed control efficiency (39.05 %) compared to other two spray volumes in table 3. In case of oxyfluorfen, drone mediated herbicide application at spray volume of 78 l ha⁻¹ has recorded higher relative weed control efficiency (55.75 %) compared to other two spray volumes in table 3. Higher weed control efficiency was recorded with the recommended dose of herbicides with a spray volume of 78 l ha⁻¹. It was due to the uniform deposition of spray solution. This helped to improve the efficacy of herbicides against weed seeds, as it increased the probability of a spray droplet occupying under the surface of soil. The higher rate of uniformity was observed in 78 l ha⁻¹ and 52 l ha⁻¹ with the flight speed of 4 m / s. Qin *et al.* (2018) stated that when the flying speed of the drone was 4 m / s resulted in the best coverage and uniformity on the wheat canopy. The spray volume of 78 l ha⁻¹ was slightly superior to the recommended dose of herbicides with the spray volume of 750 l ha⁻¹. Wang *et al.* (2020) stated that the greater control on blast and leaf roller of rice by drone was similar to knap sack sprayer. Similar results were in congruency with the findings of

Giles and Billing, (2015); Qin *et al.* (2018) and Faical *et al.* (2017).

Relative weed index

In case of atrazine, drone mediated herbicide application at spray volume of 78 l ha⁻¹ has recorded lower relative weed index (-3.08 %) compared to other two spray volumes in table 3. In case of oxyfluorfen, drone mediated herbicide application at spray volume of 78 l ha⁻¹ recorded lower relative weed index (-5.07 %) compared to other two spray volumes in table 3.

The lowest yield reduction recorded in the recommended dose of herbicides with the spray volume of 78 l ha⁻¹ was comparable with the spray volume of 750 l ha⁻¹ by hand sprayer. The efficiency of herbicide application through drone recorded comparable results with hand sprayer. These findings were in line with Meng *et al.* (2020). The highest yield reduction was recorded in spray volume 26 l ha⁻¹. It might be due to more crop-weed competition in spray volume 26 l ha⁻¹ that led to poor growth and yield of crop. These results are in collaboration with Kakade *et al.* (2020) and Idziak and Woznica (2020).

Table 3: Relative weed control efficiency and Relative weed index as influenced by herbicide application in maize

Treatment	RWCE (%)	RWI (%)
T ₁ : Atrazine 50 % WP @ 1.25 kg <i>a.i.</i> ha ⁻¹ @ 78 l ha ⁻¹	39.05	-3.08
T ₂ : Atrazine 50 % WP @ 1.25 kg <i>a.i.</i> ha ⁻¹ @ 52 l ha ⁻¹	12.75	-0.3
T ₃ : Atrazine 50 % WP @ 1.25 kg <i>a.i.</i> ha ⁻¹ @ 26 l ha ⁻¹	-2.82	10.72
T ₄ : Oxyfluorfen 23.5 % EC @ 0.10 kg <i>a.i.</i> ha ⁻¹ @ 78 l ha ⁻¹	55.75	-5.07
T ₅ : Oxyfluorfen 23.5 % EC @ 0.10 kg <i>a.i.</i> ha ⁻¹ @ 52 l ha ⁻¹	33.77	-2.95
T ₆ : Oxyfluorfen 23.5 % EC @ 0.10 kg <i>a.i.</i> ha ⁻¹ @ 26 l ha ⁻¹	-14.30	2.65

Effect of herbicide application on weed density and weed dry weight

The data on weed density and weed dry weight is presented in table 4. The major weed flora observed in the experimental plots were *Cyperus rotundus* (sedge), *Digitaria marginata*, *Digitaria sanguinalis*, *Echinochloa colonum*, and *Eleusine indica* (grasses), *Borreria hispida*

and *Alternanthera sessalis* (broad leaved weeds). The predominant category of weed was grasses followed by board-leaved weeds and sedges. The lowest total weed density recorded in pre-emergent application of Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ with the spray volume 78 l ha⁻¹ (2.24, 3.60, 5.39 no. m⁻² at 10, 20 and 30 DAS, respectively). The lowest total weed dry weight recorded in pre-emergent application of Atrazine 50 % WP @ 1.25

kg *a.i.* ha⁻¹ with the spray volume 78 l ha⁻¹ (0.86, 1.34, 2.43 g m⁻² at 10, 20 and 30 DAS, respectively). Effective weed control resulted in reduced weed density and weed dry weight and provided a favourable environment to increase nutrient uptake by crops. The quantity of nutrient uptake by crops is the reflection of biomass production.

Among the drone spraying treatments, application of the recommended dose of herbicides with the spray volume of 78 l ha⁻¹ recorded the highest nutrient uptake. This might be due to reduced competition by weeds and thus better crop growth and increased dry matter production (Kumar *et al.*, 2017).

Table 4: Total weed biomass (g m⁻²) and Weed density at 10, 20 and 30 days after sowing as influenced by herbicide application in

Treatment	Weed Dry Weight			Weed density		
	10	20	30	10	20	30
Herbicide (H)						
H ₁ :	0.92(0.34)	1.44(1.57)	2.80(7.34)	2.81(7.39)	4.35(18.42)	5.93(34.66)
H ₂ :	0.97(0.44)	1.52(1.81)	3.21(9.80)	3.29(10.32)	5.12(25.71)	6.69(44.25)
SEm±	0.02	0.05	0.14	0.17	0.26	0.26
CD at 5%	NS	NS	NS	NS	NS	NS
Spray volume (V)						
V ₁ : 78 l ha ⁻¹	0.89(0.29)	1.36(1.34)	2.49(5.70)	2.70(6.79)	4.09(16.22)	5.49(29.64)
V ₂ : 52 l ha ⁻¹	0.93(0.36)	1.49(1.72)	2.98(8.38)	2.98(8.38)	4.84(22.92)	5.98(35.26)
V ₃ : 26 l ha ⁻¹	1.00(0.5)	1.59(2.02)	3.55(12.10)	3.46(11.47)	5.27(27.27)	7.46(55.15)
SEm±	0.03	0.06	0.17	0.21	0.32	0.32
CD at 5%	NS	NS	0.50	NS	NS	0.93
Interaction (Herbicide x Spray volume)						
H ₁ x V ₁	0.86(0.23)	1.34(1.29)	2.43(5.40)	2.24(4.51)	3.60(12.46)	5.39(28.55)
H ₁ x V ₂	0.90(0.31)	1.49(1.72)	2.87(7.73)	2.75(7.06)	4.40(18.86)	5.82(33.37)
H ₁ x V ₃	1.00(0.5)	1.48(1.69)	3.10(9.11)	3.45(11.40)	5.04(24.90)	6.57(42.66)
H ₂ x V ₁	0.92(0.34)	1.37(1.37)	2.55(6.00)	3.17(9.54)	4.58(20.47)	5.59(30.74)
H ₂ x V ₂	0.97(0.44)	1.49(1.72)	3.08(8.98)	3.21(9.80)	5.29(27.48)	6.13(37.07)
H ₂ x V ₃	1.01(0.52)	1.70(2.39)	4.00(15.5)	3.48(11.61)	5.50(29.75)	8.35(69.22)
SEm±	0.04	0.09	0.71	0.29	0.46	0.45
CD at 5%	NS	NS	NS	NS	NS	NS
Control (Manual application)						
C ₁ : H ₁ @ 750 l ha ⁻¹	0.86(0.23)	1.30(1.19)	3.06(8.86)	2.43(5.40)	4.84(22.92)	6.53(42.14)
C ₂ : H ₂ @ 750 l ha ⁻¹	0.95(0.40)	1.63(2.15)	3.75(13.56)	2.98(8.38)	5.56(30.41)	7.58(56.95)
SEm±	0.02	0.05	0.13	0.16	0.24	0.23
CD at 5%	NS	NS	NS	NS	NS	NS

Note: H₁: Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹, H₂: Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹, V₁: 78 l ha⁻¹, V₂: 52 l ha⁻¹, V₃: 26 l ha⁻¹, C₁: H₁ @ 750 l ha⁻¹, C₂: H₂ @ 750 l ha⁻¹

Effect of herbicide on growth, yield parameters and yield of maize

Between the two different herbicides, numerically higher plant height, leaf area and leaf area duration (170.91 cm, 6027.66 cm² plant⁻¹, 46.86 days at 90 DAS, respectively) was recorded in pre-emergent application of Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ which was on par with pre-emergent application of Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹. Among the different spray volumes, numerically higher plant height, higher leaf area and leaf area duration (173.52, 6682.31 cm² plant⁻¹, 52.10 days at 90 DAS, respectively) was recorded with the spray volume of 78 l ha⁻¹ which was on par with 52 l ha⁻¹ at 90 DAS.

This might be due to removal of weeds resulting in reduced crop-weed competition during critical stages helped to timely availability of resources for rapid cell multiplication and cell elongation, which in turn helped in taller plants, a greater number of leaves and higher leaf area (Umesha and Sridhara, 2015, Nourmohammadi *et al.*, 2018 and Kaur *et al.*, 2020). Spray volume of 26 l ha⁻¹ resulted in shorter plants, as there was severe competition for resources throughout the cropping period and weeds drained all the nutrients, leaving behind crop in starving condition, leading to poor growth (Imoloame, 2020).

Between the two different herbicides, numerically higher total dry matter production (186.68 g plant⁻¹ at 90 DAS) was recorded in pre-emergent application of Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ which was on par with pre-emergent application of Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹. Among the different spray volumes, numerically higher total dry matter production (195.07 g plant⁻¹ at 90 DAS) was recorded with the spray volume of 78 l ha⁻¹ which was on par with 52 l ha⁻¹. Dry matter production of a crop reflects its efficiency to utilize solar radiation, moisture and nutrients from the existing environmental condition (Ehsas *et al.*, 2016). Again, weeds have been controlled and keeping them at lower densities throughout the crop growth (Kumar *et al.*, 2020). Significantly lower total dry matter production was observed in spray volume of 26 l ha⁻¹. Uncontrolled weed growth significantly removes nutrients resulting

in increased dry weight of weeds. This reduced the availability of resources to the crop and thus resulted in lower dry matter production of crops in plots received herbicide with a spray volume of 26 l ha⁻¹. These results were in line with earlier findings of Srivastava *et al.* (2018); Rasool and Khan, (2016) and Mitra *et al.* (2018).

The plots receiving pre-emergent application of Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ has shown numerically higher yield parameters *i.e.* cob length (17 cm), number of kernels per row (30) and seed index (31.87 g) and on par with pre-emergent application of Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹. The plots receiving herbicide dosage with the spray volume of 78 l ha⁻¹ has shown numerically higher yield parameters *i. e.* cob length (17 cm), number of kernels per row (32), and seed index (32.61 g) and on par with the spray volume 52 l ha⁻¹. Among the different spray volumes, pre-emergent application of herbicide with the spray volume of 78 l ha⁻¹ recorded numerically higher grain and stover yield of 6830 kg ha⁻¹ and 8576 kg ha⁻¹ respectively and which was on par with the spray volume 52 l ha⁻¹.

This increased yield attributes might be due to the fact that the weed free situation at early stages favoured rapid cell multiplication and elongation, leading to an increased yield attribute. A similar increase in yield attributes was registered with a spray volume of 78 l ha⁻¹. The lowest yield components due to heavy crop-weed competition throughout crop growth stages was recorded in spray volume of 26 l ha⁻¹ resulting in poor translocation of source into sink with poor yield. These results were in line with earlier finding of Hooda *et al.* (2017) and Nourmohammadi *et al.* (2018). Between the two different herbicides, pre-emergent application of Atrazine 50 % WP @ 1.25 kg *a.i.* ha⁻¹ recorded numerically higher grain yield of 6644 kg ha⁻¹ and which was on par with pre-emergent application of Oxyfluorfen 23.5 % EC @ 0.10 kg *a.i.* ha⁻¹. Recommended dose of herbicides with the spray volume of 78 l ha⁻¹ registered significantly higher grain yield (6830 kg ha⁻¹). This might due to less competition between crop and weed, which ultimately provided congenial atmosphere for efficient utilization of growth resources (Hakeem *et al.*, 2020 and Kumar *et al.*, 2020).

Table 5: Growth parameters of maize as influenced by herbicide application

Treatment	Growth Parameters			
	Plant height (cm)	Leaf area (cm ² plant ⁻¹)	Dry matter (g plant ⁻¹)	Leaf Area Duration (Days)
Herbicide (H)				
H ₁ :	170.91	6027.66	186.68	46.86
H ₂ :	163.87	5504.36	164.78	42.93
SEm±	2.85	178.65	7.48	1.34
CD at 5%	NS	NS	NS	NS
Spray volume (V)				
V ₁ : 78 l ha ⁻¹	173.52	6682.31	195.07	52.10
V ₂ : 52 l ha ⁻¹	168.16	6117.58	181.48	47.49
V ₃ : 26 l ha ⁻¹	160.48	4498.14	150.65	35.11
SEm±	3.40	218.80	9.16	1.64
CD at 5%	9.98	641.73	26.85	4.82
Interaction (Herbicide x Spray volume)				
H ₁ x V ₁	175.05	6815.90	207.26	53.06
H ₁ x V ₂	172.12	6709.05	192.81	51.99
H ₁ x V ₃	165.55	4558.03	159.97	35.54
H ₂ x V ₁	171.98	6548.72	182.88	51.14
H ₂ x V ₂	164.21	5526.11	170.15	42.98
H ₂ x V ₃	155.41	4438.25	141.32	34.68
SEm±	4.94	309.44	12.95	2.32
CD at 5%	NS	NS	NS	NS
Control (Manual application)				
C ₁	174.02	6334.11	181.32	49.20
C ₂	169.91	5972.33	128.42	46.44
SEm±	2.47	154.72	6.48	1.17
CD at 5%	NS	NS	NS	NS

Note: H₁: Atrazine 50 % WP @ 1.25 kg a.i. ha⁻¹, H₂: Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹, V₁: 78 l ha⁻¹, V₂: 52 l ha⁻¹, V₃: 26 l ha⁻¹, C₁: H₁ @ 750 l ha⁻¹, C₂: H₂ @ 750 l ha⁻¹

Table 6: Yield parameters and yield of maize as influenced by herbicide application

Treatment	Growth Parameters			
	Cob length (cm)	No of kernels row ⁻¹	100 kernel weight (g)	Kernel yield (kg ha ⁻¹)
Herbicide (H)				
H ₁ :	14	30	31.87	6644
H ₂ :	13	28	29.70	6428
SEm±	0.32	1.16	0.76	165.23
CD at 5%	NS	NS	NS	NS
Spray volume (V)				
V ₁ : 78 l ha ⁻¹	15	32	32.61	6830
V ₂ : 52 l ha ⁻¹	14	30	30.55	6665
V ₃ : 26 l ha ⁻¹	13	27	29.21	6112
SEm±	0.39	1.42	0.92	202.36
CD at 5%	1.15	4.17	2.71	593.52
Interaction (Herbicide x Spray volume)				
H ₁ x V ₁	16	33	33.94	7025
H ₁ x V ₂	15	30	31.67	6829
H ₁ x V ₃	13	28	30.01	6078
H ₂ x V ₁	14	31	31.27	6635
H ₂ x V ₂	14	29	29.42	6501
H ₂ x V ₃	13	25	28.41	6147
SEm±	0.55	2.01	1.31	286.19
CD at 5%	NS	NS	NS	NS
Control (Manual application)				
C ₁	14	31	29.79	6808
C ₂	13	28	27.49	6315
SEm±	0.28	1.01	0.66	143.09
CD at 5%	NS	NS	NS	NS

Note: H₁: Atrazine 50 % WP @ 1.25 kg a.i. ha⁻¹, H₂: Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹, V₁: 78 l ha⁻¹, V₂: 52 l ha⁻¹, V₃: 26 l ha⁻¹, C₁: H₁ @ 750 l ha⁻¹, C₂: H₂ @ 750 l ha⁻¹

Effect of drone mediated herbicide application on economics of maize

Drone-mediated herbicide application had a significant effect on the economics of maize cultivation. Higher cost of cultivation was recorded with drone application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ (₹41,728 ha⁻¹) than Oxyfluorfen 23.5% EC @ 0.10 kg a.i. ha⁻¹ (₹41,583 ha⁻¹) due to higher quantity of atrazine required for

application. Additionally, the cost of cultivation for drone-based herbicide application was slightly higher than manual spraying because of higher operational charges associated with the use of drones. Pre-emergence application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ with spray volume of 78 L ha⁻¹ recorded the highest gross returns (₹1,38,704 ha⁻¹), net returns (₹96,976 ha⁻¹) and benefit-cost ratio (3.32) followed by the same herbicide with the spray volume of 52 L ha⁻¹ and 750 L ha⁻¹. The

improved economic performance of these treatments was attributed to the effective weed suppression which led to better crop growth and higher grain yield. In contrast, the lowest gross returns (₹1,20,135 ha⁻¹), net returns (₹78,407 ha⁻¹) and benefit-cost ratio (2.87) were obtained with

Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ applied at 26 L ha⁻¹ and were associated with relatively poor weed control and reduced crop productivity. The results suggested that the best weed management practice in maize cultivation was drone application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ at 78 L ha⁻¹.

Table 24: Economics of weed management in maize as influenced by herbicide application

Treatments	Cost of cultivation (Rs. ha ⁻¹)	Gross returns (Rs. ha ⁻¹)	Net returns (Rs. ha ⁻¹)	B-C ratio (Rs. ha ⁻¹)
T ₁ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 78 l ha ⁻¹	41728	138704	96976	3.32
T ₂ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 52 l ha ⁻¹	41728	134894	93165	3.23
T ₃ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 26 l ha ⁻¹	41728	120135	78407	2.87
T ₄ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 78 l ha ⁻¹	41583	131150	89566	3.15
T ₅ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 52 l ha ⁻¹	41583	128535	86952	3.09
T ₆ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 26 l ha ⁻¹	41583	121442	79859	2.92
T ₇ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 750 l ha ⁻¹	41579	134679	93099	3.23
T ₈ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 750 l ha ⁻¹	41434	125019	83584	3.01

This was attributed to the efficiency and broad spectrum weed control achieved with the above herbicides. The favourable condition created through efficient weed management resulted in lesser weed competition between crops and weeds during the critical period of crop growth. This favoured the crop to producing more leaf area and plant dry matter production. The higher grain yield with the various treatments was due to the cumulative effect of increased levels of yield attributes combined with lesser crop weed competition, better light transmission for photosynthesis, reduced depletion of nutrients by weeds and increased nutrient uptake by crops (Nazreen and Subramanyam, 2017).

Visual phytotoxicity symptoms

The phytotoxicity effect on maize as influenced by drone mediated herbicide application is presented in table. The visual observations on crop phytotoxicity ratings

were recorded in pre-emergence application of Atrazine 50 % WP @ 1.25 kg a.i. ha⁻¹ and Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹ at 7, 14 and 21 DAT. There was no phytotoxic injury was observed (0.00) on crop at 7, 14 and 21 DAT with pre-emergence application of Atrazine. At 7 DAT, slight stunting injury or discoloration of the crop was observed in application of Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹ (1.00). At 14 DAT, slight stunting injury or discoloration of the crop was observed with application of oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹ (1.00). At 21 DAT, crop recovered from injury caused by application of Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹ (0.00). Application of low volume herbicide *i.e.* oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha⁻¹ causes phytotoxic effect on maize which slightly effects its growth during early stages and later on those phytotoxic symptoms got recovered then crop started to grow luxuriously. These results are in conformity with Chougala, (2013); Singh *et al.* (2014) and Patil, (2014).

Table 25: Phytotoxicity rating (0 – 10 scale) as influenced by herbicide application in maize

Treatments	7 DAT	14 DAT	21 DAT
T ₁ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 78 l ha ⁻¹	0	0	0
T ₂ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 52 l ha ⁻¹	0	0	0
T ₃ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 26 l ha ⁻¹	0	0	0
T ₄ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 78 l ha ⁻¹	1	1	0
T ₅ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 52 l ha ⁻¹	1	1	0
T ₆ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 26 l ha ⁻¹	1	1	0
T ₇ : Atrazine 50 % WP @ 1.25 kg a.i. ha ⁻¹ @ 750 l ha ⁻¹	0	0	0
T ₈ : Oxyfluorfen 23.5 % EC @ 0.10 kg a.i. ha ⁻¹ @ 750 l ha ⁻¹	1	1	0

Conclusion

The present study revealed that drone-mediated herbicide application is an effective and economic way for weed management in maize. Among the evaluated treatments, pre-emergence application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ with spray volume of 78 L ha⁻¹ was found superior in weed suppression with higher relative weed control efficiency (39.05%) and lower relative weed index (-3.08). Effective weed control improved crop growth and productivity, which was evident in increased kernel yield (7025 kg ha⁻¹) and stover yield (8747 kg ha⁻¹). The treatment also had the highest economic returns with a benefit-cost ratio of 3.32. Hence, drone-based application of Atrazine 50% WP @ 1.25 kg a.i. ha⁻¹ at 78 L ha⁻¹ can be recommended as an efficient, labour saving and profitable weed management strategy for maize cultivation under labour scarcity and increasing adoption of precision agriculture technologies.

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