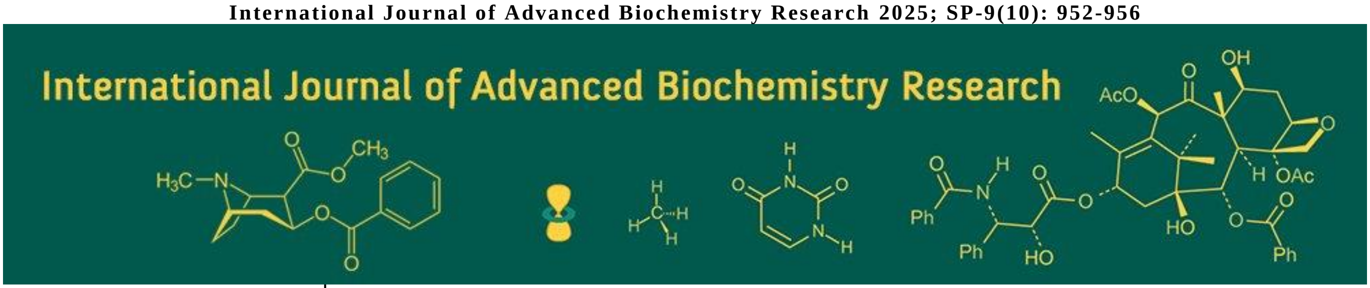

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(10): 952-956
www.biochemjournal.com
Received: 18-07-2025
Accepted: 21-08-2025

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Assessment of UAV-based herbicide spray volumes on physiological, phenological responses and biological yield of *rabi* maize under different irrigation methods

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DOI: https://www.doi.org/10.33545/26174693.2025.v9.i10Sl.5951

Abstract
The present field study was undertaken during the *rabi* seasons of 2023-24 and 2024-25 at Water Technology Centre, College Farm, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, to evaluate the interaction effects of irrigation methods and UAV-based herbicide applications on the Physiological, Phenological Responses and biological yield of *rabi* maize. The experiment employed on split-plot design with two irrigation methods as main plots and six weed management treatments as subplots. The study assessed parameters such as plant population, leaf area at 60, 90 DAS and biological yield. Results revealed that irrigation method had no significant impact on plant population, though surface drip irrigation (I_2) recorded slightly higher values. Significant effects of irrigation method were observed on leaf area 60 and 90 DAS with I_2 showing superior performance due to frequent and uniform moisture availability. Among weed control treatments, conventional spray (W_4) and followed by UAV-based applications at higher spray volumes W_3 (60 l ha^{-1}) and W_2 (40 l ha^{-1}) were showing results at par with W_5 weed-free in leaf area and biological yield. The unweeded control (W_6) consistently showed the poorest performance due to intense crop-weed competition. Surface drip irrigation combined with effective weed control due to localized application of water leads to less germination of weeds and reducing competition from weeds particularly UAV-based or conventional herbicide applications, which control weeds effectively and enhance maize productivity by improving water and nutrient availability.

Keywords: Rabi maize, surface drip irrigation, UAV herbicide application, plant growth parameters, weed management

Introduction

Maize (*Zea mays* L.) is one of the most versatile cereal crops, occupying a pivotal role in global food and fodder security. In India, maize is grown across various agro-ecological regions and is cultivated for multiple uses including food, feed and industrial raw material. However, the productivity of maize during the *rabi* season is often constrained by suboptimal water availability and intense weed competition, both of which severely impact plant growth, nutrient uptake and final yield (Kumar *et al*., 2017) [1]. Efficient irrigation management plays a crucial role in enhancing crop water productivity, especially in water-scarce regions. Traditional surface irrigation methods often result in non-uniform water distribution, leading to water stress or excess in parts of the field (Patel *et al*., 2022) [2]. In contrast, drip irrigation offers a promising alternative by delivering water directly to the root zone, thereby minimizing losses and improving water use efficiency (Sampathkumar and Pandian, 2010) [5]. Moreover, frequent and precise irrigation through drip systems creates a favorable soil moisture environment that supports better germination, root development, and nutrient availability (Durga *et al*., 2018) [3].

Weed competition is another major constraint in maize cultivation, especially during early growth stages. Uncontrolled weeds compete with the crop for nutrients, light and moisture, leading to significant yield losses. The conventional practice of hand weeding or the use of knapsack sprayers was labor-intensive and inconsistent in large-scale operations. Recent advancements in Unmanned Aerial Vehicle (UAV) technology have revolutionized crop protection practices by enabling precise, timely, and uniform application of herbicides with lower labor requirements and operational costs (Jeevan *et al*., 2024) [4]. Incorporating site-specific herbicide applications using UAVs with varying spray volumes can optimize herbicide efficacy, especially in pre-and post-emergence phases. The integration of efficient irrigation strategies with UAV-based herbicide applications is expected to significantly influence the growth dynamics of *rabi* maize by improving physiological processes such as leaf area expansion and biological yield. However, scientific understanding of their interactive effects under field conditions remains limited. Therefore, the present study was undertaken to evaluate the impact of different irrigation strategies and UAV-based herbicide application techniques on the growth parameters of *rabi* maize.

Material and Methods

The field experiment was performed at Water Technology Centre, College Farm, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad for two seasons. The farm was geographically located at 17°32'16.4" N latitude and 78°40'43.7" E longitude, with an altitude of 542.6 meters above mean sea level. The mean weekly maximum temperature during the crop growth period ranged from 27.57 °C to 38.57 °C and 27.44 °C to 37.7 °C, while the mean weekly minimum temperature varied from 13.71 °C to 22.50 °C and 13.33 °C to 21.10 °C in 2023-24 and 2024-25, respectively. There was rainfall of 16 mm on 2 rainy days during 2023-24 and 16.4 mm on 2 rainy days during 2024-25 during crop period of planning. The soil of experimental field was fairly levelled and sandy loam in texture, low in available N 180.1 and 195.6 kg ha^{-1}, high in P_2O_5 32.64 and 31.82 ha^{-1} and high in K_2O 342.30 and 355.28 ha^{-1}, medium in organic carbon content 1.01 and 1.16% during 2023-24 and 2024-25. The experiment was laid out in split plot design with two main plots and six sub plots which are replicated thrice which consisted of two irrigation methods as main plot treatments I_1 surface ridge and furrow irrigation at 1.0 IW/CPE ratio (50 mm), I_2 Surface drip irrigation at 1.0 Epan (at two days interval) and six weed management practices as subplot treatments. W_1-Aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE (@ 20 l ha^{-1} spray fluid*), W_2-Aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE (@ 40 l ha^{-1} spray fluid*), W_3-Aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE (@ 60 l ha^{-1} spray fluid*),W_4-Conventional spray of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE through knapsack sprayer (@ 500 l ha^{-1} spray fluid), W_5-Weed free (hand weeding at 20 and 40 DAS) and W_6-Unweeded control. Maize variety DHM 117 was sown with spacing of 60 x 20 cm for surface ridge and furrow irrigation and 80/40 x 20 cm for Surface drip irrigation at 1.0 Epan (at two days interval) in paired row system. The recommended dose of fertilizer 240: 80: 80 kg NPK ha^{-1} was applied to crop. The initial and final plant population per hectare was calculated based on the no. of seedlings from each plot immediately after seedling emergence and before harvest, respectively and expressed as plant ha^{-1}. Leaf area measures photosynthetically active area and measured leaf area with a leaf area meter 60 and 90 DAS and expressed in cm^2 plant^{-1}. The biological yield calculated at harvest and expressed as (kg ha^{-1}).

Results and Discussion

Initial and final plant population

Table 1: Initial and final plant population, Leaf area (cm^2 plant^{-1}) , 50% Tasseling and 50% silking influenced by irrigation methods and weed management practices.

Treatments	Initial and final plant population				Leaf area (cm^2 plant^{-1})				50% Tasseling		50% silking	
	2023-24		2024-25		60 DAS		90 DAS					
	Initial	Final	Initial	2023-24	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
Main plots												
I_1	82832	82600	83025	82755	4262	4370	4153	4311	54	53	59	58
I_2	82938	82861	83063	82861	4904	5141	4871	5187	53	52	58	57
SEm±	80.4	100.9	89.4	65.1	99.1	90.6	93.6	122.6				
CD (P = 0.05)	NS	NS	NS	NS	603.3	551.3	569.3	746.0				
Sub plots												
W_1	82784	82668	82986	82755	3963	4577	3851	4456	54	53	59	58
W_2	82928	82697	83015	82784	5005	5114	4962	5145	53	52	58	57
W_3	82899	82755	83044	82813	5058	5184	5058	5262	53	52	58	57
W_4	82928	82813	83073	82957	5236	5304	5191	5334	53	52	58	57
W_5	83015	82870	83218	82986	5337	5382	5313	5423	52	51	57	56
W_6	82755	82581	82928	82552	2900	2972	2697	2876	57	56	62	61
SEm±	79.4	107.2	95.7	145.45	127.9	112.6	122.4	125.4				
CD (P = 0.05)	NS	NS	NS	NS	377.4	332.2	361.0	369.8				
Interaction												
W x I												
SEm±	112.3	151.6	135.3	205.7	181.0	159.3	173.1	177.3				
CD (P = 0.05)	NS	NS	NS	NS	533.8	469.9	510.6	523.1				
IXW												
SEm±	130.3	171.3	152.5	198.7	192.7	171.4	183.6	203.1				
CD (P = 0.05)	NS	NS	NS	NS	728.3	655.7	691.2	831.1				

Effect of irrigation methods

In 2023-24 and 2024-25, irrigation methods had non-significant impact on initial and final plant population of *rabi* maize. Whereas higher initial and final plant population was observed in I_2 surface drip irrigation at 1.0 Epan (at two days interval) (82938 & 82861 and 83063 & 82861 plants ha^{-1} during 2023-24 and 2024-25) than I_1 surface ridge and furrow irrigation at 1.0 IW/CPE ratio (82832 & 82600 and 83025 & 82755 plants ha^{-1} during 2023-24 and 2024-25 respectively). The plant population under drip irrigation was marginally higher from initial to final population in the range of 0.13% to 0.32% and 0.05% to 0.13% during 2023-24 and 2024-25, respectively. Compared to surface irrigation and drip indicating better germination and plant establishment under frequent and uniform moisture availability (Durga *et al*., 2019) [6].

Effect of weed management practices

Weed management practices had non-significant influence on the initial and final plant population. W_5 weed free plots recorded maximum initial and final plant population (83015 & 82870 plants ha^{-1} and 83218 & 82986 plants ha^{-1} in 2023-24 and 2024-25 respectively). W_6 unweeded control had lower initial and final plant population (82755 & 82581 and 82928 & 82552 plants ha^{-1} during 2023-24 and 2024-25). The decrease in final population from the weed-free plot to the unweeded plot was 0.35-0.53% during 2023-24 to 2024-25.

Leaf Area (cm^2 plant^{-1})

Leaf area is a critical growth indicator that signifies the photosynthetic potential of a plant. It plays a pivotal role in light interception, accumulation of biological yield. The leaf area of *rabi* maize was measured at 60 and 90 DAS. The data related to leaf area (cm^2 plant^{-1}) are detailed in Table no.1

Effect of irrigation methods

Irrigation methods had a significant impact on the leaf area of maize at 60 and 90 DAS during 2023-24 and 2024-25. At 60 DAS, leaf area with I_2 surface drip irrigation at 1.0 Epan (at two days interval) was 4904.4 & 5141.0 cm^2 plant^{-1} during 2023-24 and 2024-25 respectively. This was significantly higher than I_1 surface ridge and furrow irrigation (1.0 IW/CPE) 4261.8 & 4370.1 cm^2 plant^{-1} during 2023-24 and 2024-25. At 90 DAS, similar pattern continued with I_2 surface drip irrigation (1.0 Epan) (at two-day interval) produced leaf area of 4870.7 and 5187.4 cm^2 plant^{-1} in 2023-24 and 2024-25, respectively and I_1 surface ridge and furrow irrigation (1.0 IW/CPE). The larger leaf area under drip irrigation can be attributed to the steady and efficient water supply that fosters better vegetative growth (Durga *et al*., 2019 and Mohanpuria *et al*., 2024) [6, 7]

Effect of weed management practices

Weed management strategies significantly influenced maize leaf area at (60 and 90 DAS) during *rabi* 2023-24 and 2024-25. W_5 weed free plots consistently produced the greater leaf area was 5336.6 & 5312.8 cm^2 plant^{-1} during 2023-24 and 5381.9 & 5423.1 cm^2 plant^{-1} during 2024-25 at 60 and 90 DAS, respectively and it was at par with W_4 conventional spray of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 500 l ha^{-1} (5235.9 & 5191.1 cm^2 plant^{-1} during 2023-24 and 5304.3 & 5333.5 cm^2 plant^{-1} during 2024-25 at 60 and 90 DAS, respectively), W_3 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 60 l ha^{-1} spray fluid (5058.3 & 5057.5 cm^2 plant^{-1} during 2023-24 and 5184.0 & 5261.6 cm^2 plant^{-1} during 2024-25 at 60 and 90 DAS, respectively) and W_2 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 40 l ha^{-1} spray fluid (5005.0 & 4962.1 cm^2 plant^{-1} during 2023-24 and 5114.0 & 5144.7 cm^2 plant^{-1} during 2024-25 at 60 and 90 DAS respectively). W_6 the unweeded control significantly lesser leaf area and values 2900.0 & 2696.9 cm^2 plant^{-1} in 2023-24 and 2972.2 & 2876.0 plant^{-1} in 2024-25 at 60 and 90 DAS respectively. The lower leaf area found in weedy plots may be attributed to high crop weed competition for the growth resources, which is reflected in poor growth of maize (Kavya *et al*., 2025 and Bhavitha *et al*., 2022) [8, 9].

Interaction effect

The interaction between irrigation methods and weed management practices on leaf area was significant at 60 and 90 DAS. At 60 and 90 DAS the greater leaf area was found in I_2 surface drip irrigation (1.0 Epan) (at two-day interval) joined with W_5 weed free treatment (5780.83 & 5905.83 cm^2 plant^{-1} at 60 DAS and 5812.45 & 6006.16 cm^2 plant^{-1} at 90 DAS in the year of 2023-24 and 2024-25, respectively) and it was at par with W_4 conventional spray of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 500 l ha^{-1}, W_3 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 60 l ha^{-1} spray fluid and W_2 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 40 l ha^{-1} and statistically significant lower leaf area found in W_6 unweeded control coupled with I_1 surface ridge and furrow irrigation (1.0 IW/CPE) (2884.19 & 2863.75 cm^2 plant^{-1} at 60 DAS 2643.39 & 2776.26 at 90 DAS in the year of 2023-24 and 2024-25 respectively) Enhanced leaf area in well-managed plots diminishes crop-weed competition, which enables maize to more effectively utilize resources like sunlight, water and nutrients.

Days to 50% Tasseling and 50% Silking

The timing of tasseling and silking is a critical phenological milestones that mark the shift from vegetative to reproductive growth in maize. This were not analysed statistically and tabulated in table.

Effect of Irrigation Methods

Earliness of days to 50% tasseling (53 & 52 days during 2023-24 and 2024-25) and 50% silking (58 & 57 days during 2023-24 and 2024-25) was observed in I_2 surface drip irrigation (1.0 Epan) (at two-day interval) due to improved and consistent soil moisture availability promoting faster vegetative and reproductive development when compared to I_1 surface ridge and furrow irrigation (1.0 IW/CPE) the similar results were observed with Du *et al*. (2024) [10].

Table 2: Leaf area (cm^2 $plant^{-1}$) at 60 and 90 DAS influenced by irrigation methods and weed management practices

Treatments	60 DAS						90 DAS					
	2023-24			2024-25			2023			2024		
	I_1	I_2	mean	I_1	I_2	mean	I_1	I_2	mean	I_1	I_2	mean
W_1	3914	4011	3963	4384	4769	4577	3914	4011	3963	4384	4769	4577
W_2	4521	5489	5005	4581	5647	5114	4521	5489	5005	4581	5647	5114
W_3	4567	5549	5058	4690	5678	5184	4567	5549	5058	4690	5678	5184
W_4	4832	5640	5236	4844	5765	5304	4832	5640	5236	4844	5765	5304
W_5	4892	5781	5337	4858	5906	5382	4892	5781	5337	4858	5906	5382
W_6	2844	2956	2900	2864	3081	2972	2844	2956	2900	2864	3081	2972
Mean	4262	4904	4583	4370	5141	4756	4262	4904	4583	4370	5141	4756
Interaction	W X I	I x W		W X I	I x W		W X I	I x W		W X I	I x W	
S.Em	180.96	192.68		159.31	171.36		180.96	192.68		159.31	171.36	
CD	533.76	728.28		469.91	655.66		533.76	728.28		469.91	655.66	

Effect of Weed Management Practices

Days to 50% tasseling and 50% silking were shortest under W5 weed free treatment (52 & 57 days and 51 & 56 days during 2023-24 and 2024-25, respectively) whereas, the weedy check required more days to reach these phenological stages (57 & 62 days and 56 & 61 days during 2023-24 and 2024-25, respectively). This delay can be attributed to increased crop-weed competition for essential resources such as nutrients, water, light and space, which suppressed early vegetative growth in maize. These findings are in agreement with the reports of Swetha *et al*. (2018) and Ganapathy *et al*. (2022), who also observed delayed crop development under unchecked weed competition.

Biological yield (kg ha^{-1})

Effect of Irrigation Methods

The biological yield under I_2 surface drip irrigation (1.0 Epan) (at two-day interval) with 15467 kg ha^{-1} in 2023-24 and 16068 kg ha^{-1} in 2024-25 was recorded and which was significantly higher than I_1 surface ridge and furrow irrigation (1.0 IW/CPE) 13621 & 13896 kg ha^{-1} during 2023-24 and 2024-25 respectively.

Table 3: Interaction effect of irrigation methods and weed management practices on biological yield of *rabi* maize crop at harvest in 2023 and 2024

Treatment	2023			2024		
Weed management practices	I_1	I_2	mean	I_1	I_2	mean
W_1	13173	13747	13460	13389	14492	13940
W_2	14653	17034	15843	14885	17572	16228
W_3	14684	17151	15917	14950	17645	16297
W_4	14760	17451	16105	15079	17731	16405
W_5	14848	17652	16250	15075	18537	16806
W_6	9611	9768	9690	9997	10435	10216
Mean	13621	15467	14544	13896	16068	14982
Interaction	W X I	I x W		W X I	I x W	
S.Em	495.037	531.46		385.34	428.93	
CD	1460.14	2028.99		1136.59	1705.33	

Effect of Weed Management Practices

Biological yield was significantly affected by weed management practices during 2023-24 and 2024-25. W5 weed free treatment consistently recorded the superior with 16250 and 16806 kg ha^{-1} during 2023-24 and 2024-25. It was statistically at par with the W_4 conventional spray of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 500 l ha^{-1} (16105 and 16405 kg ha^{-1} during 2023-24 and 2024-25 respectively), W_3 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 60 l ha^{-1} spray fluid (15917 and 16297 kg ha^{-1} during 2023-24 and 2024-25, respectively) and W_2 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 40 l ha^{-1} spray fluid (15843 and 16228 kg ha^{-1} during 2023-24 and 2024-25, respectively). While W_6 unweeded control produced significantly inferior biological yield (9690 and 10216 kg ha^{-1} during 2023-24 and 2024-25). Taller plants and higher leaf area apart from better light interception and assimilation promoted higher biological yield in lower weed dry matter plots. (Kavya *et al*., 2024) [11].

Interaction effect

The irrigation methods significantly affected biological yield across the years of 2023-24 and 2024-25. The elevated biological yield achieved with the combination of I_2 surface drip irrigation (1.0 Epan) (at two-day interval) coalesced with W_5 weed free (17652 & 18537 kg ha^{-1} during 2023-24 and 2024-25) and at par with W_4 conventional spray of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 500 l ha^{-1}, W_3 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 60 l ha^{-1} spray fluid and W_2 aerial spray (UAV) of pyroxasulfone 85% w/w WG 127.5 g ha^{-1} as PE and mesotrione 2.27% w/v + atrazine 22.7 w/w SC 875 g ha^{-1} as PoE @ 40 l ha^{-1}. Lower biological yield was recorded under I_1 surface ridge and furrow irrigation (1.0 IW/CPE) combined with W_6 unweeded control. The increase in biological yield production under drip irrigation indicates that the combination of effective weed control and sustained soil moisture created favourable environment for crop growth.

Conclusion

Based on the above investigation, it is concluded that the herbicide application with knapsack, UAV with 60 l ha^{-1} and 40 l ha^{-1} achieved at par with weed-free in surface drip irrigation improved maize biological yield.

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