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Formulating an appropriate herbicide sequence for direct seeded rice using UAVs

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Abstract
The experimental study was conducted during the summer 2023 at a farmer's field in Appanthirupathi village of Madurai East block, Madurai to evolve a suitable herbicide sequence for DSR crop using UAVs with 16 treatments and three replications using strip plot design. The treatment involving M3-Penoxsulam 97% + Butachlor 38.83% (2 L ha^{-1}) combined with S3-Triafomone 20% + Ethoxysulfuron 10% WG (225 g ha^{-1}) was administered using a drone at a spray height of 1.5-2.0 meters, moving at a speed of 4.5 meters per second, with an effective spray width of 3.5 meters over the crop canopy. This approach effectively reduced weed density and weed biomass while achieving higher weed control efficiency. The combination successfully managed various types of weeds including grasses like *Echinochloa crusgalli* and *Echinochloa colona,* sedges such as *Cyperus rotundus* and *Cyperus difformis*, as well as broadleaf weeds like *Bergia capensis, Ammannia baccifera,* and *Ludwigia parviflora*. Throughout the study, separate plots were maintained for comparison, including a weedy check and a weed-free check.

Keywords: Direct seeded rice, UAVs, weed, herbicides, weed control efficiency

1. Introduction
Rice (*Oryza sativa* L.) holds significant importance as a staple food in Asia, accounting for over 90% of global production and consumption. Cultivated across 161 million hectares of land, it yields around 509.87 million metric tons of milled rice annually (Statista 2021) [2]. In India, the average rice yield stood at 2.7 t/ha, resulting in a total production of 116.42 million tons from a 43 million-hectare area (Shahbandeh 2021) [10]. In Tamil Nadu Rice is grown in 22.17 lakh ha area with an annual production of about 71.72 lakh MT, Average yield of rice was 3.56 t/ha (Indiastat, 2021-2022) [2]. Transplanting and direct seeding are the most common cultivation methods in rice. Transplanting rice involves multiple tasks such as puddling, nursery preparation, transplanting labor, and extensive irrigation, leading to high labor expenses and labor scarcity during crucial crop growth periods. However, Direct Seeded Rice (DSR) requires less water and labor while maintaining grain yield comparable to transplanted rice, along with a shorter crop duration. Utilizing a drum seeder for direct seeding also enhances productivity and profitability under puddled conditions. Weeds pose a significant challenge for adopting aerobic direct-seeded rice, especially during the critical 15 to 45 days after sowing (DAS) period, where uncontrolled weeds can cause yield losses ranging from 50 to 90 percent. Chemical weed management in DSR has gained traction due to its efficiency, quickness, and cost-effectiveness compared to manual weeding. The recent trend involves employing herbicides with lower doses and higher efficacy, reducing overall herbicide volume, simplifying application, and making it more economical. A combination of pre-emergence and post-emergence herbicides provides flexibility in controlling specific or mixed weed types. Overcoming the limitations of knapsack sprayers, drones equipped with pre-programmed GPS systems are now being used to apply agrochemicals like herbicides, pesticides, and fertilizers. These unmanned aerial vehicles (UAVs) deliver chemicals precisely, reducing manual labor, minimizing wastage, lowering environmental impact, and optimizing resource utilization. The research's focus was to assess and determine an effective herbicide sequence for pre and postemergence stages, suited for UAV application, to manage weeds in DSR.

2. Materials and Methods
An experimental trial was conducted in the Farmer's field of Appanthirupathi village in the

Madurai East block. The coordinates of the location are 10°02' N latitude and 78°19' E longitude, with an altitude of 139 meters above MSL. The goal was to find a suitable herbicide sequence for Direct Seeded Rice (DSR) using Unmanned Aerial Vehicles (UAVs). The soil had a sandy loam texture with a pH of 7.9. It had medium levels of nitrogen and phosphorus and high levels of potassium. The trial conducted in strip plot design with 16 treatments and three replications. The treatments consisted of both pre-emergence and post-emergence herbicide applications. Pre-emergence herbicides include Pyrazosulfuron Ethyl 10 WP @ 20 g a.i/ha, Pretilachlor 50% EC @ 750 g a.i./ha, Penoxsulam + Butachlor mixture @ 820 g a.i./ha, and Bensulfuron Methyl + Pretilachlor mixture @ 660 g a.i/ha. These were applied on the 8th day after sowing (DAS). Post-emergence herbicides include Bentazone 48% SL @ 960 g a.i./ha, 2,4-D Sodium Salt 80% WP @ 1250 g a.i./ha, Triafamone + Ethoxysulfuron mixture @ 60 g a.i./ha, and Penoxsulam + Cyhalofop-butyl mixture @ 75 g a.i./ha. These were applied on the 30th DAS. Separate plots were maintained for weed-free checks and weedy checks.

The rice variety used was CO 55, sown directly using a paddy drum seeder on May 6, 2023. Standard crop management practices were followed as recommended. The herbicides were mixed according to recommended dosages and sprayed using a UAV with a 10-liter tank capacity. The spraying heights were 1.5 meters for pre-emergence and 2 meters for post-emergence, with a speed of 4.5 meters per second and an effective spray width of 3.5 meters.

Data on weed density and dry weight were collected randomly from two locations within each plot on 15, 30, 45, and 60 days after sowing, using 0.25 m² quadrates. Weeds were uprooted, dried, and the square root transformation ($\sqrt{(x+0.5)}$) was applied to the data before performing the analysis of variance. Statistical comparisons were made using the transformed values.

2.1. Weed control efficiency by Mani *et al.*, (1973) [4] were calculated using standard formulae.

$$\text{WCE (\%)} = \frac{DMC - DMT}{DMC} \times 100$$

Where,
WCE = Weed control efficiency (%)
DMC = Dry matter of weeds in unweeded control plot
DMT = Dry matter of weed in treated plots

2. 2. Uniformity coefficient of the spray

The spray's uniformity coefficient of UAVs was calculated using a formula by Kailashkumar *et al.* (2023) [3].

$$\text{Uniformity coefficient} = 1 - \sum_{i=0}^{n} \bar{x} - x1$$

The formula utilizes variables such as x1 (volume collected in each beaker in ml), n (number of beakers), and x (average spray volume collected across all beakers in ml).

3. Result and Discussion

3.1 Weed flora

During the study, the weed species observed in the experimental trail comprised *Echinochloa crusgalli, Echinochloa colona, Cyperus difformis, Cyperus rotundus, Bergia capensis, Ammannia baccifera,* and *Ludwigia parviflora.*

3.2 Herbicide effect on weeds

The weed control treatments significantly reduce weed density and dry weight of total weeds as compared to weedy check on 15, 30, 45, 60 DAS respectively.

3.2.1 Effect on Weed Density

Among the various treatments, the combination of Penoxsulam 0.97% + Butachlor 38.83% SE at 820 g.a.i./ha (M3) demonstrated the lowest weed density at different intervals (1.91, 3.09, 3.64, 4.23 g/m2), followed by Bensulfuron methyl 0.6% + Pretilachlor 6% G at 660 g/ha (M4) with weed density (2.17, 3.43, 4.16, 4.72) on 15, 30, 45, and 60 days after sowing (DAS) respectively (Table 1a, 1b & 2a, 2b). The application of Penoxsulam 0.97% w/w + Butachlor 38.8% w/w 41% SE at 820 g/ha as a pre-emergence treatment showed effective weed control in transplanted rice with a thin film of water. This result is in line with a study by Duary *et al.* in 2015 [1].

Similarly, the combination of Triafamone 20% + Ethoxysulfuron 10% WG at 60 g a.i./ha (S3) and 2,4-D Sodium salt WP at 1250 g a.i./ha (S2) exhibited comparable lower weed density (2.09, 3.33, 4.03, 4.59) and (2.12, 3.33, 4.05, 4.61) respectively on 15, 30, 45, and 60 DAS (Table 1a, 1b & 2a, 2b). The combination of triafamone and ethoxysulfuron was effective against some weed types but less so against *E. crusgalli*. This aligns with Menon *et al*.'s findings in 2016 [5].

Contrarily, the application of Bentazone 48% SL at 960 g a.i./ha (S1) resulted in higher weed density (2.28, 3.64, 4.47, 4.96) at 15, 30, 45, and 60 DAS (Table 1a, 1b & 2a, 2b).

In terms of interactions, the combination of Penoxsulam 0.97% + Butachlor 38.83% SE followed by Triafamone 20% + Ethoxysulfuron 10% WG (M3S3) showed the lowest weed density (1.49, 2.51, 2.94, 3.49), while Bensulfuron methyl 0.6% + Pretilachlor 6% G followed by 2,4-D Sodium salt WP (M4S2) exhibited weed density (1.96, 3.18, 3.74, 4.37) at 15, 30, 45, and 60 DAS respectively (Table 1a, 1b & 2a, 2b). Sequential herbicide application was effective in controlling complex weed species and reducing weed dry weight, leading to higher weed control efficiency. This outcome was also supported by Sairamesh *et al*. in 2015 [8] and Yadav *et al*. in 2018 [12].

The combination of Pretilachlor 50% EC followed by Bentazone 48% SL (M2S1) resulted in higher weed density (2.50, 4.03, 5.09, 5.44) at 15, 30, 45, and 60 DAS (Table 1a, 1b & 2a, 2b). The application of bentazone as post-emergence in paddy crop did not effectively control weeds in directly seeded rice, which contrasts with the findings of Narolia *et al*. in 2019 [6].

Table 1a: Impact of methods for controlling weeds on the overall weed presence after 15 days of sowing (DAS).

	M1	M2	M3	M4	Mean
S1	2.33	2.50	1.99	2.28	2.28
S2	2.16	2.27	2.11	1.96	2.12
S3	2.20	2.37	1.49	2.30	2.09
S4	2.18	2.35	2.04	2.13	2.18
Mean	2.22	2.37	1.91	2.17	

	M	S	M×S
Sed	0.047	0.020	0.039
CD (P=0.05)	0.111	0.047	0.068

Table 1b: Impact of methods for controlling weeds on the overall weed presence after 30 days of sowing (DAS).

	M1	M2	M3	M4	Mean
S1	3.70	4.03	3.24	3.57	3.64
S2	3.39	3.55	3.33	3.18	3.36
S3	3.45	3.77	2.51	3.60	3.33
S4	3.42	3.74	3.27	3.36	3.45
Mean	3.49	3.77	3.09	3.43	

Pre-emergence	M1- Pyrazosulfuron Ethyl 10% WP	M2- Pretilachlor 50% EC
	M3- Penoxsulam 0.97% + Butachlor 38.83% SE,	M4- Bensulfuron methyl 0.6% + Pretilachlor 6% G.
Post- emergence:	S1- Bentazone 48% SL,	S2- 2,4-D Sodium salt WP,
	S3- Triafamone 20% + Ethoxysulfuron 10% WG,	S4 - Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD.

Table 2a: Impact of methods for controlling weeds on the overall weed presence after 45 days of sowing (DAS).

	M1	M2	M3	M4	Mean
S1	4.57	5.09	3.79	4.44	4.47
S2	4.04	4.43	3.98	3.74	4.05
S3	4.08	4.65	2.94	4.45	4.03
S4	4.05	4.62	3.86	4.01	4.14
Mean	4.19	4.70	3.64	4.16	

	M	S	M×S
Sed	0.105	0.051	0.090
CD (P=0.05)	0.248	0.119	0.158

Table 2b: Impact of methods for controlling weeds on the overall weed presence after 60 days of sowing (DAS).

	M1	M2	M3	M4	Mean
S1	5.05	5.44	4.42	4.94	4.96
S2	4.63	4.91	4.54	4.37	4.61
S3	4.70	5.18	3.49	4.98	4.59
S4	4.66	5.10	4.49	4.58	4.71
Mean	4.76	5.16	4.23	4.72	

	M	S	M×S
Sed	0.093	0.042	0.078
CD (P=0.05)	0.218	0.099	0.136

Pre-emergence	M1- Pyrazosulfuron Ethyl 10% WP	M2- Pretilachlor 50% EC
	M3- Penoxsulam 0.97% + Butachlor 38.83% SE,	M4- Bensulfuron methyl 0.6% + Pretilachlor 6% G.
Post- emergence:	S1- Bentazone 48% SL,	S2- 2,4-D Sodium salt WP,
	S3- Triafamone 20% + Ethoxysulfuron 10% WG,	S4 - Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD.

3.2.2 Effect on Weed Dry Weight

Different herbicide combinations were tested in the field to control weed growth. One combination, Penoxsulam 0.97% + Butachlor 38.83% SE, applied at a rate of 820 g.a.i./ha (M3), resulted in lower weed dry weights (1.82, 2.80, 1.99, 2.99) followed by Bensulfuron methyl 0.6% + Pretilachlor 6% G @ 660 g /ha (M_4) which also showed reduced weed dry weights of (2.30, 3.42, 2.46, 3.62) at 15,30,45,60 DAS respectively**.** On the other hand, applying Pretilachlor 50% EC at 750 g a.i./ha (M2) led to higher weed dry weights across the same time points. (Table 3a, 3b & 4a, 4b)

Similarly, another set of treatments was tested with different herbicide combinations. Triafamone 20% + Ethoxysulfuron 10% WG at 60 g a.i./ha (S3) resulted in lower weed dry weights (2.18, 3.17, 2.35, 3.52) comparable to 2,4-D Sodium salt WP at 1250 g a.i./ha (S2). (2.19, 3.30, 2.36, 3.53) at 15, 30,45,60 DAS respectively. In contrast, using Bentazone 48% SL at 960 g a.i./ha (S1) led to higher weed dry weights of (2.57, 3.68, 2.72, 3.88) at 15,30,45,60 DAS respectively (Table 3a, 3b & 4a, 4b).

Considering interactions between treatments, combining Penoxsulam 0.97% + Butachlor 38.83% SE (M3) with Triafamone 20% + Ethoxysulfuron 10% WG (S3) resulted in significantly lower weed dry weights of (1.10, 1.70, 1.31, 2.21) at 15,30,45,60 DAS respectively. Similarly, Bensulfuron methyl 0.6% + Pretilachlor 6% G (M4) combined with 2,4-D Sodium salt WP (S2) also showed reduced weed dry weights (1.85, 3.0, 2.10, 2.95) (Table 3a, 3b & 4a, 4b). Conversely, when Pretilachlor 50% EC (M2) was combined with Bentazone 48% SL (S1), higher weed dry weights were observed (3.13, 4.27, 3.30, 4.54) at 15, 30, 45, 60 DAS respectively.

All treatment plots were effective compared to weedy check plot.

Table 3a: Influence of Weed Management Methods on Total Weed Dry Weight at 15 Days After Sowing (DAS).

	M1	**M2**	**M3**	**M4**	**Mean**
S1	2.64	3.13	1.94	2.57	2.57
S2	2.21	2.55	2.14	1.85	2.19
S3	2.32	2.7	1.1	2.6	2.18
S4	2.28	2.67	2.1	2.18	2.31
Mean	2.36	2.76	1.82	2.30	

	M	**S**	**M×S**
SEd	0.095	0.045	0.080
CD (P=0.05)	0.223	0.105	0.141

Table 3b: Influence of Weed Management Methods on Total Weed Dry Weight at 30 Days After Sowing (DAS).

	M1	**M2**	**M3**	**M4**	**Mean**
S1	3.7	4.27	3.14	3.62	3.68
S2	3.43	3.58	3.2	3	3.30
S3	3.5	3.8	1.7	3.67	3.17
S4	3.46	3.75	3.17	3.4	3.45
Mean	3.52	3.85	2.80	3.42	

	M	**S**	**M×S**
SEd	0.107	0.054	0.093
CD (P=0.05)	0.252	0.127	0.163

Pre-emergence	M1- Pyrazosulfuron Ethyl 10% WP	M2- Pretilachlor 50% EC
	M3- Penoxsulam 0.97% + Butachlor 38.83% SE,	M4- Bensulfuron methyl 0.6% + Pretilachlor 6% G.
Post- emergence:	S1- Bentazone 48% SL,	S2- 2,4-D Sodium salt WP,
	S3- Triafamone 20% + Ethoxysulfuron 10% WG,	S4 - Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD.

Table 4a: Influence of Weed Management Methods on Total Weed Dry Weight at 45 Days After Sowing (DAS).

	M1	**M2**	**M3**	**M4**	**Mean**
S1	2.77	3.3	2.14	2.67	2.72
S2	2.4	2.65	2.27	2.1	2.36
S3	2.48	2.9	1.31	2.71	2.35
S4	2.43	2.85	2.25	2.36	2.47
Mean	2.52	2.93	1.99	2.46	

	M	**S**	**M×S**
SEd	0.094	0.042	0.079
CD (P=0.05)	0.220	0.100	0.138

Table 4b: Influence of Weed Management Methods on Total Weed Dry Weight at 60 Days After Sowing (DAS)."

	M1	**M2**	**M3**	**M4**	**Mean**
S1	4.01	4.54	3.04	3.91	3.88
S2	3.70	3.87	3.59	2.95	3.53
S3	3.77	4.14	2.21	3.95	3.52
S4	3.72	4.10	3.10	3.65	3.64
Mean	3.80	4.16	2.99	3.62	

	M	**S**	**M×S**
SEd	0.121	0.041	0.095
CD (P=0.05)	0.284	0.096	0.166

Pre-emergence	**M1-** Pyrazosulfuron Ethyl 10% WP	**M2-** Pretilachlor 50% EC
	M3- Penoxsulam 0.97% + Butachlor 38.83% SE,	**M4-** Bensulfuron methyl 0.6% + Pretilachlor 6% G.
Post- emergence:	**S1-** Bentazone 48% SL,	**S2-** 2,4-D Sodium salt WP,
	S3- Triafamone 20% + Ethoxysulfuron 10% WG,	**S4** - Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD.

Weed Control Efficiency (%)

The impact of various weed control methods during the summer of 2023 was assessed. Among the treatments, the PE application of Penoxsulam 0.97% + Butachlor 38.83% SE @ 820g.a.i./ha (M3) exhibited the highest weed control efficiency (WCE) at both 30 and 60 days after sowing (DAS), with values of 69.25% and 79% respectively. The second best treatment was Bensulfuron methyl 0.6% + Pretilachlor 6% G @ 660 g/ha (M4) with WCE of 55.50% at 30 DAS and 72.75% at 60 DAS. On the other hand, Pretialchlor 50% EC @750 g a.i./ha (M2) showed the lowest WCE of 43.5% at 30 DAS and 65% at 60 DAS. This information can be found in Table 5a.

Similarly, when considering the PoE application, Triafamone 20% + Ethoxysulfuron 10% WG @ 60 g a.i./ha (S3) demonstrated the highest WCE of 60% at 30 DAS and 74.25% at 60 DAS. The treatment 2,4-D Sodium salt WP @ 1250 g a.i./ha (S2) came next with WCE values of 58.75% at 30 DAS and 73.75% at 60 DAS. The least effective treatment in this category was Bentazone 48% SL @ 960 g a.i./ha, with a WCE of 47.75% at 30 DAS and 67.75% at 60 DAS. This data can be found in Table 5a as well.

Additionally, the interaction between the PE application of Penoxsulam 0.97% + Butachlor 38.83% SE @ 820g.a.i./ha and the PoE application of Triafamone 20% + Ethoxysulfuron 10% WG @ 60 g a.i./ha (M3S3) resulted in the highest combined WCE of 91% at both 30 and 60 DAS. Conversely, the interaction of PE Pretialchlor 50% EC @750 g a.i./ha and PoE Bentazone 48% SL @ 960 g a.i./ha (M2S1) showed the lowest WCE of 30% at 30 DAS and 58% at 60 DAS. All treatment plots performed better than the weedy check. You can refer to Table 5a for further details.

Table 5a: Impact of different methods for controlling weeds on the efficiency (%) of weed control at 30 days after sowing (DAS).

	M1	M2	M3	M4	Mean
S1	48	30	63	50	47.75
S2	57	51	61	66	58.75
S3	54	46	91	49	60.00
S4	55	47	62	57	55.25
Mean	53.50	43.50	69.25	55.50	

Table 5b: Impact of different methods for controlling weeds on the efficiency (%) of weed control at 60 days after sowing (DAS).

	M1	M2	M3	M4	MEAN
S1	67	58	76	70	67.75
S2	72	71	74	78	73.75
S3	72	65	91	69	74.25
S4	73	66	75	74	72.00
MEAN	71.00	65	79.00	72.75	

Pre-emergence	M1- Pyrazosulfuron Ethyl 10% WP	M2- Pretilachlor 50% EC
	M3- Penoxsulam 0.97% + Butachlor 38.83% SE,	M4- Bensulfuron methyl 0.6% + Pretilachlor 6% G.
Post- emergence:	S1- Bentazone 48% SL,	S2- 2,4-D Sodium salt WP,
	S3- Triafamone 20% + Ethoxysulfuron 10% WG,	S4 - Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD.

Drone Observation

The volume of spray fluid collected in each beaker (600 ml), the number of beakers used in the experiment (4), and the average volume of spray liquid collected across all beakers were used to compute the uniformity coefficient value for spray. Formula 2.2 was used to calculate the drone spray uniformity coefficient value. The coefficient value is unity.

Conclusion

Using Penoxsulam 0.97% + Butachlor 38.83% SE at a rate of 820 g.a.i/ha, followed by Triafamone 20% + Ethoxysulfuron 10% WG at 60 g.a.i/ha in sequence, resulted in decreased weed density and dry weight, while achieving higher efficiency in weed control. This combination outperformed other weed control methods, suggesting that employing drone-based application of this sequential treatment could be a recommended approach for effectively managing diverse weed species in rice fields.

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