ISSN 2518–2021 (Print) 2415–4474 (Electronic)

Fundamental and Applied Agriculture

Journal home page: https://www.f2ffoundation.org/faa/index.php/home

Vol. 9(3), pp. 220 – 231: 2024, doi: https://doi.org/10.5455/faa.227330

CROP SCIENCE | ORIGINAL ARTICLE

Weed Response to Different Tank-Mix Herbicide Combinations and its Impact on Winter Rice Performance in Zero Till Non-Puddled Condition

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ARTICLE INFO

Article history

Received: 11 Jun 2024

Accepted: 28 Aug 2024

Published online: 30 Sep 2024

Keywords

Rice establishment method, Zero-till non-puddled, Tank-mix herbicides, Weed management, *Boro* rice

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ABSTRACT

Tank-mixture of two or more chemical groups of either pre- or post-emergence herbicide might play a vital role to manage weeds of a diversified community more effectively than their single or sequential application. Although some proprietary herbicides are available in the market, their number is very limited. The aim of this research was to evaluate the weed response to different tank-mix pre- or post- emergence herbicide combinations and its impact on winter rice performance in zero-till non puddled transplanted condition. Twenty-one treatments were used in each experiment (either pre- or post-emergence herbicide). Treatments comprised six pre-emergence herbicides with their 13 tank-mix combinations (at a ratio of 1:1), one proprietary pre-emergence herbicide and a season-long weedy plot as control. Similar treatments combination was also considered for post-emergence herbicide. Both the experiments were conducted under RCB design with three replications. Sole application of Triafamone pre-emergence herbicide performed as the best in terms of weed control efficiency (%) and yield increase over control (%) followed by Triafamone + Pretilachlor and Triafamone + Pendimethalin. In case of tank-mix post-emergence herbicide Pyrazosulfuron-ethyl+ Penoxsulam performed as the best in terms of weed control efficiency (%) and yield increase over control (%) followed by sole application of post-emergence Penoxsulam. Tank-mixture of Triafamone + Pretilachlor or Triafamone + Pendimethalin pre-emergence herbicide or Pyrazosulfuron-ethyl+ Penoxsulam post-emergence herbicide at a ratio of 1:1 might be the perfect alternative to sole or sequential application of herbicide for effective weed control and to obtain higher rice yield.

1. Introduction

Puddled transplanting is the most common rice production system in Bangladesh that consumes huge amount of water, time and energy (Rao et al., 2007; Gill and Walia, 2014). In addition, repeated puddling breaks down the soil aggregates and capillary pores, and form shallow plow pan (Ringrose-Voase et al., 2000). Recently, puddled transplanted (PT) rice establishment method in some Asian countries has been, or is being, replaced by dry direct seeded (DDS) system (Shekhawat et al., 2020). The DDS rice establishment method is conducive to mechanization, more rapidly and easily planted, required less labor and water, and has fewer methane emissions (Rahman, 2019). However, heavy weed infestations threaten the sustainability of DDS rice, and controlling them is especially difficult due to the diversity and severity of the weeds, the lack of a standing water layer to reduce weeds at the time of rice emergence, and the lack of a head start advantage (Farooq et al., 2011).

In this regard, zero-till non-puddled transplanted (ZT NPT) rice establishment method will emerge as the perfect technology from a conservation standpoint. Similar to puddled transplanting, rice seedlings can be transplanted in a non-puddled field by first preparing the soil with a single-pass shallow tillage, then strip tillage, bed formation, and finally, using a mechanical rice transplanter or even hand transplanting, rice seedlings can be placed into the softened land (Baldev et al., 2013; Haque et al., 2016). Non-puddled transplanted (NPT) rice has the ability to boost profit and energy efficiency without compromising yield. It also allows for little to no soil disturbance, lower tillage expenses, conserves water by eliminating the need

Cite This Article

Islam AKMM, Said MA, Rahman M, Jahan I, Yeasmin S, Hasan M, Motmainna M, Anwar MP. 2024. Weed Response to Different Tank-Mix Herbicide Combinations and its Impact on Winter Rice Performance in Zero Till Non-Puddled Condition. *Fundamental and Applied Agriculture*, 9(3): 220–231. https://doi.org/10.5455/faa.227330

for puddling (Haque et al., 2016; Islam et al., 2019; Gathala et al., 2020; Chaki et al., 2021). However, ZT NPT is considered as more advantageous over NPT because this system will save human labour and energy that required for ploughing in NPT system. However, there is still much to learn about this approach, particularly with regard to research presenting a methodological comparison of rice yield, weed infestation, and weed control effectiveness. We hypothesized that modifications in any crop management practice such as land preparation procedure and seedling establishment methods must have some effects on the floristic composition of weeds, their aggressiveness and responsiveness to control measures and ultimately rice productivity. Thus, further study is needed to develop a weed management strategy that keeps chemical control at the forefront and ensures the sustainability of the ZT NPT rice production system. It has been reported that NPT rice gives similar or higher yield than that of PT rice, but grain yield may sharply decline if appropriate weed management is not taken (Islam et al., 2014; Haque et al., 2016). Furthermore, tillage greatly affects the composition of weeds, and minimum tillage modifies the diversity of species; nevertheless, the ZT NPT system's definition of weed composition and management in wetland rice fields is still unclear (Murphy et al., 2006; Mishra and Singh, 2012).

Even though weed control techniques vary by nation, due to agricultural labor outflow, rising labor costs, and the arduous work needed, most weed management options these days rely on herbicides (Shrestha et al., 2021). Bangladesh saw a decline in agricultural labor availability (almost two times) from 70% in 1991 to 37% in 2022. This led to an increase in herbicide use (82 times) from 99 MT/kL in 1991 to 8050 MT/kL in 2022 (Islam et al., 2023). Herbicides are normally applied as single application or sequential application *e.g.*, pre- or post-emergence herbicide alone or pre- followed by post- or either one of them followed by mechanical or manual weeding by the farmers of Bangladesh. Although some proprietary herbicides (commercial mixture of two pre- or post-emergence herbicides) are available in the market, their number is very limited. A varied community's weeds may be better managed by tank-mixing two or more chemical groups of either pre- or post-emergence herbicide. There are two scenarios when using multiple herbicides in a tank mixture: (i) they might not work well together (antagonistic impact); (ii) they might work well together (synergistic effect).

The efficacy of weed control in a synergistic impact will be higher than in a single application. While literature does contain records of tank-mix herbicide treatment on some dryland crop fields (Younesabadi et al., 2013; Bhimwal et al., 2018; Ahmed et al., 2020; Ekhator et al., 2021), it is quite sparse in the context of rice fields, particularly under Bangladesh conditions. Considering all these issues, the present research was conducted to examine the weed response to different tank-mix pre- or post- emergence herbicide combinations and its effect on winter rice productivity under ZT NPT condition.

2. Materials and Methods

2.1. Description of the experimental site

The study was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh (24.719812 N latitude, 90.426944 E longitudes). The experimental field was medium high land belonging to the *Sonatola* Soil Series of Grey Floodplain soil under the agro-ecological zone of Old Brahmaputra Floodplain (AEZ-9). The region occupies the large area of Brahmaputra sediments which were laid down before the river shifted into its present Jamuna Channel about 200 years ago (Islam et al., 2011).

The soil of the experimental field was silty loam soil with pH 6.8. The particle size analysis was performed by hydrometer method (Bouyoucos et al., 1927) and the pH analysis was by glass electrode pH meter (Page et al., 1982). The soil of the field was low in organic matter content (0.93%) and its general fertility level (0.13% total N, 16.3 ppm available P, 0.28 ppm exchangeable K and 13.9 ppm available S). Soil organic matter and total nitrogen (N) contents were measured through the wet oxidation method of Walkley and Black (1934) and Kjedahl method (Bremner et al., 1995), respectively. While, phosphorus (P), potassium (K) and sulphur (S) of the soil were determined through spectrophotometry (Olsen, 1954), flame photometer (Warnkce and Brown, 1938) and spectrophotometry (Combs et al., 1938) techniques, respectively.

The mean maximum temperature rises in the month of April whereas, in winter, the mean temperature comes down to the lowest in January. Usually there is high temperature, high humidity and heavy rainfall (above 80% of the total rainfall) with occasional gusty winds during April to September (*Kharif* season) and scanty rainfall associated with moderately low temperature during October to March (*Rabi* season). The monthly average air temperature (°C) and relative humidity (%), and monthly total of rainfall (mm) during the experimental period have been presented in Table 1.

Table 1. Monthly temperature, rainfall and relative humidity of the experimental area during the experimentation

Years	Month	**Air temperature (°C)			*Rainfall (mm)	**Relative humidity (%)
		Maximum	Minimum	Average		
2022	November	30.4	18.3	24.4	0.0	81.6
	December	26.4	14.7	20.6	0.0	84.8
2023	January	24.4	12.3	18.3	0.0	83.5
	February	27.9	16.3	22.1	11	78.6
	March	29.9	19.8	24.8	110.2	76.7
	April	34.1	22.6	28.3	15.5	74.2
	May	36.3	25.9	31.1	242.1	93.0

*Monthly total; ** Monthly average; Source: Weather Yard, Department of Irrigation and Water Management, Bangladesh Agricultural University.

Table 2. Trade name, common name, doses, selectivity, mode of application of pre-emergence herbicides and their marketing company

#	Trade name	Common name	Doses (ha^{-1})	Selectivity	Marketing company
1.	Superhit 500 EC	Pretilachlor	1.0 L	Grass, broadleaf and sedge	ACI Crop Care Ltd.
2.	Sentry 25 EC	Oxadiazon	1.2 L	Grass and broadleaf	Haychem Ltd.
3.	Panida 33 EC	Pendimethalin	2.5 L	Grass, broadleaf and sedge	Auto Crop Care Ltd.
4.	Aimchlor 5G	Butachlor	25 kg	Grass, broadleaf and sedge	ACI Crop Care Ltd.
5.	Council Prime 20 SC	Triafamone	150 mL	Broadleaf and sedge	Bayer Crop Science BD
6.	Logran 75 WP	Triasulfuron	10 g	Broadleaf and sedge	Syngenta India Ltd.
7.	Super mix 18 WP	Acetachlor 14%+ Bensulfuron methyl 4%	750 g	Broadleaf and sedge	ACI Crop Care Ltd.

Table 3. Trade name, common name, doses, selectivity, mode of application of post-emergence herbicides and their marketing company

#	Trade name	Common name	Doses (ha-1)	Selectivity	Marketing company
1.	Super power 10WP	Pyrazosulforan ethyl	190 g	Grass, broadleaf and sedge	ACI Crop Care Ltd.
2.	Xtra Power 20WP	Bispyribac sodium	150 g	Grass, broadleaf and sedge	ACI Formulation Ltd.
3.	Granite 240 SC	Penoxsulam	93.7 mL	Grass, broadleaf and sedge	Auto Crop Care Ltd.
4.	Accurator 69EW	Fenoxaprop-p-Ethyl	500 mL	Grass, broadleaf and sedge	Haychem Ltd.
5.	Red Rise 15WDG	Ethoxysulfuron	100 g	Sedge	S I Agro International
6.	Fielder	2, 4- D Amine	2.8 L	Broadleaf and sedge	ACI Formulation Ltd.
7.	Council Active	Triafamone 20% + Ethoxysulfuron 10%	185 g	Broadleaf and sedge	Bayer Crop Science

2.2. Experimental treatments

2.2.1. Exp. 1 - Pre-emergence herbicides

A total of 21 treatments were used in this experiment. Treatments comprised single application of 06 (six) pre-emergence herbicides and their 13 tank-mix combinations (1:1 ratio) *viz.*, (i) Pretilachlor, (ii) Oxadiazon, (iii) Pendimethalin, (iv) Butachlor, (v) Triafamone, (vi) Triasulfuron, (vii) Pretilachlor + Oxadiazon, (viii) Pretilachlor + Pendimethalin, (ix) Pretilachlor + Butachlor, (x) Pretilachlor + Triafamone, (xi) Pretilachlor + Triasulfuron, (xii) Oxadiazon + Pendimethalin, (xiii) Oxadiazon + Butachlor, (xiv) Oxadiazon + Triafamone, (xv) Oxadiazon + Triasulfuron, (xvi) Pendimethalin + Butachlor, (xvii) Pendimethalin + Triafamone, (xviii) Pendimethalin + Triasulfuron, (xix) Triafamone + Triasulfuron, one proprietary (commercially ready mix) pre-emergence herbicide *viz*., (xx) Acetachlor 14% + Bensulfuron methyl 4%, and (xxi) season-long weedy plot as control. Table 2 provides a brief overview of the herbicides employed in the tests, including their trade name, common name, selectivity, application method, and marketing company. A randomized complete block design with three replications was used to set up the experiments. The unit plot size was 4.5 m × 2.0 m. The distance maintained between blocks was 1.0 m and unit plots were 0.5 m, respectively.

2.2.2. Exp. 2 - Post-emergence herbicides

Similar as Exp.#1, 21 treatments were also used in this experiment and the treatments comprised single application of 06 (six) post-emergence herbicides and their 13 tank-mix combinations *viz.*, (i) Pyrazosulfuron-ethyl, (ii) Bispyribac sodium, (iii) Penoxsulam, (iv) Fenoxaprop, (v) Ethoxysulfuron, (vi) 2,4-D amine, (vii) Pyrazosulfuron-ethyl+ Bispyribac sodium, (viii) Pyrazosulfuron-ethyl+ Penoxsulam, (ix) Pyrazosulfuron-ethyl+ Fenoxaprop, (x) Pyrazosulfuron-ethyl + Ethoxysulfuron, (xi) Pyrazosulfuron-ethyl + 2,4-D amine, (xii) Bispyribac sodium + Penoxsulam, (xiii) Bispyribac sodium + Fenoxaprop, (xiv) Bispyribac sodium + Ethoxysulfuron, (xv) Bispyribac sodium + 2,4 –D amine, (xvi) Penoxsulam + Fenoxaprop, (xvii) Penoxsulam + Ethoxysulfuron, (xviii) Penoxsulam + 2,4-D amine, (xix) Ethoxysulfuron + 2,4–D amine, one proprietary post-emergence herbicide (commercially ready mix) *viz*., (xx) Triafamone 20% + Ethoxysulfuron 10%, and (xxi) season-long weedy plot as control. Table 3 provides a brief summary of the herbicides employed in this experiment, along with information on their common name, commercial name, selectivity, application method, and marketing companies. The experimental design, number of replications and plot size all were same as experiment 1.

2.3. Plant material

BRRI dhan58, a popular high yielding *boro* rice variety was used in both experiments. Bangladesh Rice Research Institute (BRRI) developed and released this variety for cultivation in 2012. It can withstand lodging and grows to a maximum height of 105 cm. The variety may generate an average grain yield of 7.0-7.5 t ha^{-1} and matures in 150-155 days. Grains have a vivid hue and are long and thin.

2.4. Crop husbandry

Pre-planting non-selective herbicide Roundup® (glyphosate 41% SL-IPA salt) was administered at a rate of 75 mL 10 L^{-1} water (2.25 L ha^{-1}) two weeks prior to the transplanting of ZT NPT field. The land was submerged in standing water for 48 hours, at a depth of 3 to 5 cm, prior to transplanting. Forty-day-old rice seedlings were transplanted in accordance with the experimental guidelines after a hand-made furrow was created with a metallic rod. According to the BRRI recommendations, fertilizers were applied to the field @ 220 kg of urea, 120 kg of triple super phosphate, 75 kg of muriate of potash, 60 kg of gypsum, and 10 kg of zinc sulphate ha^{-1} (BRRI, 2022). All fertilizers were administered as basal, with the exception of urea. Three top dressings of urea were applied at 15, 30, and 45 days after transplantation (DAT). Two seedlings per hill were transplanted, with a spacing of 25 cm by 15 cm between each seedling. According to the treatment specification, the pre-emergence herbicide was administered at 6 DAT and the post-emergence herbicide at 14 DAT. Since there was no noteworthy insect or disease infestation during the experimentation, no crop protection measures were implemented to keep insects and diseases under control. Irrigation was provided when necessary. Except the herbicide application all other operations were same for both experiments.

2.5. Data recorded

The crop was harvested at maturity (when 90% of the seeds became golden yellow in color) from the central 2.0 m × 1.0 m of each plot to record data on grain and straw yield. Five hills were randomly collected from each plot to record data on plant parameters and yield contributing characters. The harvested crop of each plot was separately bundled, properly tagged, threshed and dried to 14% moisture level. Straws were sun dried properly. Final grain and straw yields plot^{-1} were recorded and expressed in t ha^{-1}. Weed species grown in the experimental field were identified and weed dry biomass were recorded time to time during crop growth stages. The summed dominance ratio (SDR) was calculated as per Islam et al. (2018). Weed control efficiency, yield increase over control were also calculated as per Anwar et al. (2012). The phytotoxic effects of herbicides mixtures on rice were evaluated based on visual observation scales as per Okafor (1986) at 3, 6 and 9 Days after application (DAA). Symptoms like leaf spot, yellowing, chlorosis and wilting are considered during visual observation.

2.6. Statistical analysis

All the data recorded during experimentation were compiled and tabulated for statistical analysis. The statistical analyses were performed with the help of Statistix 10.

3. Results

3.1. Floristic composition of the weeds in the experimental plots

Twelve weed species belonging to six families infested the experimental fields. Among the twelve species of weeds five were grasses, three sedges and four broad leaves. The scientific name, family, life cycle and sum dominance ratio (SDR) of those weeds of the experimental plot have been presented in Table 4.

In experiment 1, the most dominant weed was *Echinochloa crusgalli* (SDR 32.2) followed by *Leersia hexandra* (SDR 15.4), *Cynodon dactylon* (SDR 11.1) and the least dominant species was *Enhydra fluctuans* (SDR 0.5) followed by *Oxalis europea* (SDR 1) considering the SDR values (Table 4). Almost similar results were also observed in experiment 2, where *Echinochloa crusgalli* (SDR 38.3) followed by *Panicum repens* (15.4), *Monochoria vaginalis* (11.9) *and Leersia hexandra* (SDR 10.3) and the least dominant species was *Enhydra fluctuans* (SDR 0.5) followed by *Cyperus rotundus* (SDR 2.1) and *Scirpus juncoides* (2.2) (Table 4).

3.2. Weed dry biomass

The results showed that all the pre- and post- emergence herbicidal treatments have significant influence on the weed dry biomass under ZT NPT conditions (Table 5 and 6). In case of pre-emergence herbicide, the highest weed dry biomass (68.80, 90.63 and 123.12 g m^{-2} at 30, 45 and 60 DAT, respectively) was observed in season-long weedy treatment at all the measurement dates (Table 5). However, the lowest weed dry biomass was observed in the sole Triafamone applied plots at all DATs and the value was 10.96, 20.27 and 34.35 g m^{-2}, respectively followed by proprietary herbicide (Acetachlor 14% + Bensulfuron methyl 4%) treated plots (18.46, 29.67 and 39.53 g m^{-2} at 30, 45 and 60 DAT, respectively).

However, among the tank-mix pre-emergence herbicides Triafamone + Triasulfuron and Pendimethalin + Triafamone also showed better performance (Table 5). As like the pre-emergence herbicide, the highest weed dry biomass (92.48, 89.23 and 187.83 g m^{-2} at 30, 45 and 60 DAT, respectively) was also observed in season-long weedy treatment at all the measurement dates when post-emergence herbicide and their tank-mix combinations were applied (Table 6).

However, the lowest weed dry biomass was observed when tank-mix combination of Pyrazosulfuron-ethyl + Penoxsulam post-emergence herbicide was applied at all DATs and the value was 20.56, 36.69 and 60.50 g m^{-2} at 30, 45 and 60 DAT, respectively (Table 6).

Table 4. Sum dominance ratio of the infesting weed species in the experimental plots

#	Scientific Name	Family	Life cycle	Sum Dominance Ratio (SDR)	
				Exp.# 1	Exp.# 2
1	*Echinochloa crusgalli* (L.) Beauv.	Gramineae	Annual	32.2	38.3
2	*Eclipta alba* (L.) Hassk	Asteraceae	Annual	5.7	2.5
3	*Panicum repens* L.	Gramineae	Perennial	9.3	15.4
4	*Leersia hexandra* Sw.	Gramineae	Perennial	15.4	10.3
5	*Cynodon dactylon* L.	Gramineae	Perennial	11.1	4.5
6	*Cyperus rotundus* L.	Cyperaceae	Perennial	8.7	2.1
7	*Paspalum distichum* L.	Gramineae	Perennial	1.5	5.7
8	*Enhydra fluctuans* Lour.	Asteraceae	Annual	0.5	0.5
9	*Scirpus juncoides* Roxb.	Cyperaceae	Perennial	3	2.2
10	*Monochoria vaginalis* (Burm. F.) C. Presl.	Pontederiaceae	Perennial	9.4	11.9
11	*Alternanthera philoxeroides* (Mart.) Griseb	Amaranthaceae	Perennial	2.2	3.2
12	*Oxalis europaea* Jord.	Oxalidaceae	Annual	1	3.4

Table 5. Effect of pre-emergence herbicide and their tank-mix combinations on the weed dry biomass under ZT NPT conditions

Treatments	Weed dry biomass (g m^{-2})		
	30 DAT	45 DAT	60 DAT
Pretilachlor	41.30f	55.81g	67.52d
Oxadiazon	40.30g	48.54k	69.45d
Pendimethalin	36.39l	62.72c	74.84c
Butachlor	38.63i	52.42i	68.90d
Triafamone	10.96u	20.27s	34.35h
Triasulfuron	42.96e	61.41d	77.53c
Pretilachlor + Oxadiazon	32.41n	45.48m	58.61e
Pretilachlor + Pendimethalin	21.84q	48.50k	66.07d
Pretilachlor + Butachlor	29.86o	45.50m	58.55e
Pretilachlor + Triafamone	33.12m	39.21o	50.34f
Pretilachlor + Triasulfuron	29.12p	48.24l	60.62e
Oxadiazon + Pendimethalin	43.64c	66.82b	86.68b
Oxadiazon + Butachlor	38.92h	60.36e	78.44c
Oxadiazon + Triafamone	37.93j	43.33n	53.49f
Oxadiazon + Triasulfuron	47.26b	58.53f	68.60d
Pendimethalin + Butachlor	43.41d	55.57h	66.46d
Pendimethalin + Triafamone	20.94s	32.34p	39.91g
Pendimethalin + Triasulfuron	37.48k	51.35j	58.56e
Triafamone + Triasulfuron	21.45r	31.42q	42.32g
Acetachlor 14% + Bensulfuron methyl 4%	18.46t	29.67r	39.53g
Season-long weedy	68.80a	90.63a	123.12a
Level of significance	***	***	***
CV (%)	0.37	0.29	4.02
SE (±)	0.10	0.11	2.09

In column, means followed by different letters are significantly different, ***means significant at 0.1% level of probability

Table 6. Effect of post-emergence herbicide and their tank-mix combinations on the weed dry biomass under ZT NPT conditions

Treatments	Weed dry biomass (g m^{-2})		
	30 DAT	45 DAT	60 DAT
Pyrazosulfuron-ethyl	33.51j	53.73i	63.97ij
Bispyribac sodium	39.35h	81.32b	66.73i
Penoxsulam	26.53k	45.85j	80.00gh
Fenoxaprop-p-Ethyl	33.47j	72.46de	98.27d
Ethoxysulfuron	23.93l	75.46c	76.73h
2,4-D Amine	35.66ij	70.18e	78.20gh
Pyrazosulfuron-ethyl + Bispyribac sodium	22.32lm	65.43f	80.77g
Pyrazosulfuron-ethyl + Penoxsulam	20.56m	36.69k	60.50j
Pyrazosulfuron-ethyl + Fenoxaprop-p-Ethyl	42.00g	63.17fg	92.33ef
Pyrazosulfuron-ethyl + Ethoxysulfuron	36.08i	58.66h	93.50e
Pyrazosulfuron-ethyl + 2,4-D Amine	50.82e	74.26cd	88.80f
Bispyribac sodium + Penoxsulam	42.07g	53.89i	81.50g
Bispyribac sodium + Fenoxaprop-p-Ethyl	58.33d	58.93h	93.40e
Bispyribac sodium + Ethoxysulfuron	57.53d	75.19c	108.33c
Bispyribac sodium + 2,4 –D Amine	75.63b	81.52b	66.13i
Penoxsulam + Fenoxaprop-p-Ethyl	45.25f	80.10b	90.83ef
Penoxsulam + Ethoxysulfuron	35.77ij	79.96b	90.80ef
Penoxsulam + 2,4-D Amine	49.017e	62.19g	92.03ef
Ethoxysulfuron + 2,4 –D Amine	42.76g	72.08de	133.50b
Triafamone 20% + Ethoxysulfuron 10%	70.38c	71.38e	108.37c
Season –long weedy	92.48a	89.23a	187.83a
Level of significance	***	***	***
CV (%)	3.34	2.42	2.50
SE (±)	1.21	1.33	3.79

In column, means followed by different letters are significantly different, ***means significant at 0.1% level of probability

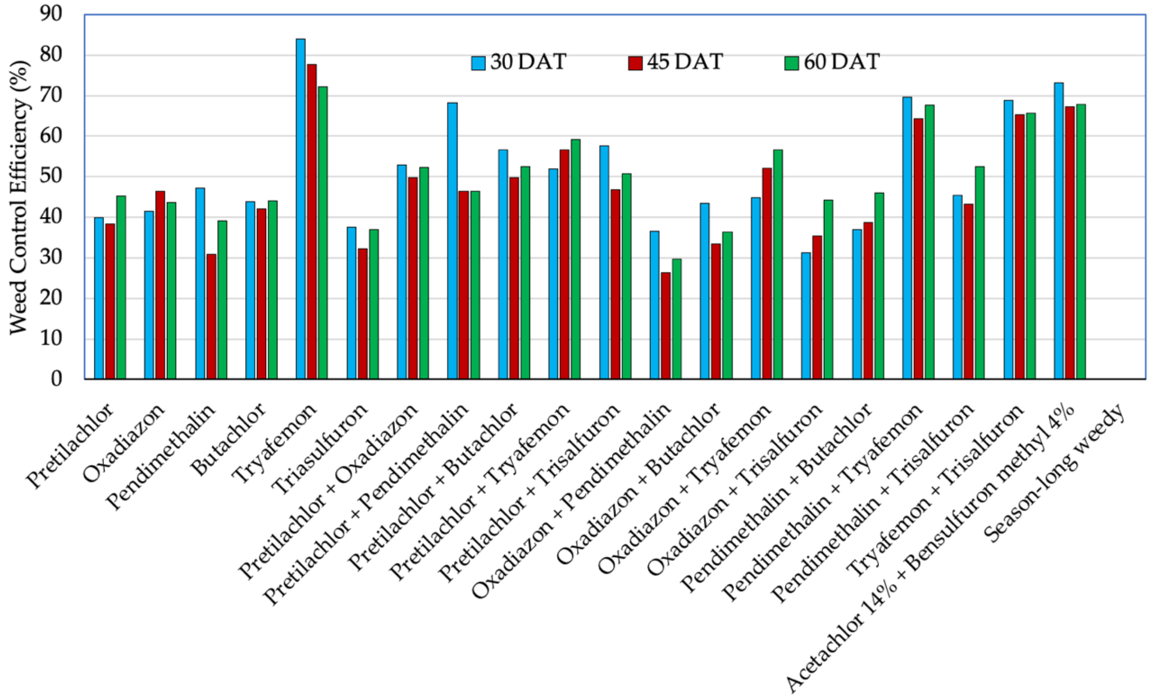

Figure 1. Effect of different pre-emergence herbicides and their tank-mix combinations on Percent weed control efficiency at three different dates of measurements

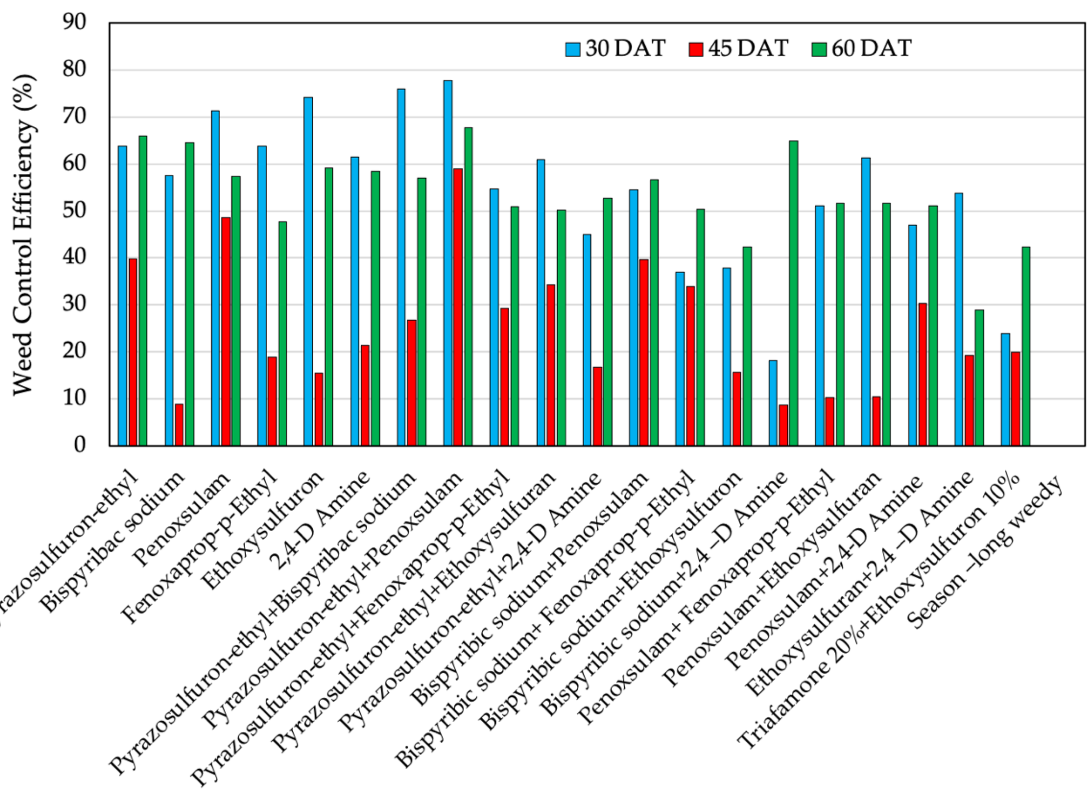

Figure 2. Effect of different post-emergence herbicides and their tank-mix combination on Percent weed control efficiency at three different dates of measurements

3.3. Weed control efficiency (%)

In case of pre-emergence herbicide, the percent weed control efficiency (%WCE) ranged from 0.0- 84% (at 30 DAT), 0.0 – 78% (at 45 DAT) and 0.0- 72% (at 60 DAT) (Figure 1). The highest %WCE was always observed in the sole Triafamone treated plots and the lowest is season-long weedy plots. At 30 DAT, second highest %WCE was observed in the proprietary pre-emergence herbicide Acetachlor 14% + Bensulfuron methyl 4% (73%), followed by tank-mix Pendimethalin + Triafamone (70%) and Triafamone + Triasulfuron (69%), while at 45 DAT, second highest %WCE was observed in the proprietary pre-emergence herbicide Acetachlor 14% + Bensulfuron methyl 4% (67%), followed by tank-mix Triafamone + Triasulfuron (65%) and Pendimethalin + Triafamone (64%). However, 65 DAT showed the similar pattern as like 30 DAT (Figure 1).

In case of post-emergence herbicide, the percent weed control efficiency ranged from 0.0- 78% (at 30 DAT), 0.0 – 59% (at 45 DAT) and 0.0- 68% (at 60 DAT) (Figure 2). The highest %WCE was always observed in the tank-mix combination of Pyrazosulfuron-ethyl + Penoxsulam treated plots, and the lowest is in season-long weedy plots. At 30 DAT, second highest %WCE was observed in the tank-mix combination of Pyrazosulfuron-ethyl+ Bispyribac sodium (76%), followed by sole application of Ethoxysulfuron (74%) and Penoxsulam (71%), while at 45 DAT, second highest %WCE was observed in the sole application of Penoxsulam (49%) followed by sole application of Pyrazosulfuron-ethyl (40%) and tank-mix application of Bispyribac sodium + Penoxsulam (40%). At 60 DAT, the second highest %WCE was observed in sole application of Pyrazosulfuron-ethyl (66%) followed by tank-mix application of Bispyribac sodium + 2,4 –D Amine (65%) and sole application of Bispyribac sodium (65%) (Figure 2).

3.4. Rice Phytotoxicity Rating

The phytotoxic effects of herbicides and their tank-mix combinations in ZT-NPT rice fields were evaluated based on visual observation at 3, 6 and 9 days after application (DAA) of each type of herbicides (Table 7). Plant treated with pre- or post-emergence herbicides and their tank-mix combination showed no/very slight injuries at all the observation dates (Table 7). The crop was constantly being monitored and it was found that phytotoxicity persisted only for a couple of days.

3.5. Yield attributes and yield

The results obtained from both experiments showed that all the herbicidal weed management practices (pre- or post-emergence herbicide and their tank-mix combinations) significantly influence the yield attributes and yield of BRRI dhan58 rice under ZT NPT condition (Table 8 and 9). In case of pre-emergence herbicide, highest number of effective tillers hill^{-1} (16.56), grains panicle^{-1} (154.17), 1000 grain weight (24.13 g), grain yield (7.13 t ha^{-1}) and straw yield (8.31 t ha^{-1}) was obtained when Triafamone herbicide was applied as sole (Table 8). Tank-mix application of pre-emergence herbicides Pretilachlor + Triafamone gave the second highest grain yield (6.86 t ha^{-1}) followed by tank-mix combination Pendimethalin + Triafamone (6.31 t ha^{-1}). The lowest number of effective tiller hill^{-1} (10.23) and grain yield (4.31 t ha^{-1}), was obtained from the season-long weedy condition, while lowest grains panicle^{-1} (115.73) was obtained from Oxadiazon + Pendimethalin, 1000 grain weight (20.60 g) from sole Oxadiazon, and straw yield (6.30 t ha^{-1}) from Pendimethalin + Butachlor application.

In case of post-emergence herbicide, highest number of effective tillers hill^{-1} (15.93), grains panicle^{-1} (157.23), 1000 grain weight (23.70 g), grain (7.90 t ha^{-1}) and straw (7.06 t ha^{-1}) yield were obtained from the tank-mix combination Pyrazosulfuron-ethyl + Penoxsulam (Table 9). While the second highest grain yield (7.13 t ha^{-1}) was obtained from the sole application of post- emergence herbicide Penoxsulam. On the other hand, the lowest number of effective tiller hill^{-1} (9.43), grain (3.59 t ha^{-1}) and straw (3.26 t ha^{-1}) yield, were obtained from the season-long weedy condition, while lowest grains panicle^{-1} (85.33) was obtained from sole application of 2, 4-D amine, 1000 grain weight (20.40 g) from Ethoxysulfuran + 2,4 –D Amine (Table 9).

3.6. Yield increase over control (%)

In pre-emergence herbicide, the highest yield increase over control (%) was obtained from the sole application of pre-emergence herbicide Triafamone (65.4%) followed by tank-mix combination of Pretilachlor + Triafamone (59.2%) (Figure 3). On the other hand, the lowest yield increase over control (%) was obtained from season-long weedy condition (0.0%) followed by tank-mix combination of Oxadiazon + Butachlor (19.7%) (Figure 3).

In case of post-emergence herbicide, the highest yield increase over control (%) was obtained from the tank-mix application of Pyrazosulfuron-ethyl + Penoxsulam (120%) followed by sole application of Penoxsulam (98.6%) (Figure 4). Whereas, tank-mix combination of Pyrazosulfuron-ethyl + Fenoxaprop-p-ethyl and Pyrazosulfuron-ethyl + Ethoxysulfuron performed almost same yield increase over control *i.e.* 81.6 and 81%, respectively. The lowest yield increase over control (%) was obtained from season-long weedy condition (0.0%) followed by tank-mix combination of Bispyribac sodium + 2, 4 – D Amine (22.6%) (Figure 4).

4. Discussion

The current research evaluated the crop and weed response to tank-mix pre- or post-emergence herbicide combinations to control weeds of winter rice (*boro* rice) under zero-till non-puddled transplanted conditions. Tillage significantly impacts the composition of weeds, with minimum tillage causing changes in species diversity (Boscutti et al., 2015). Non-puddled transplanting is a new method that can be used to address these issues and decrease the expenses associated with rice production (Hossaina et al., 2021).

The results obtained from Experiment 1 (pre-emergence herbicide) showed that sole application of Triafamone provided on an average 78% WCE. Whereas, Acetachlor 14% + Bensulfuron methyl 4%, a proprietary pre-emergence herbicide exhibited 70% WCE followed by Pendimethalin + Triafamone and Triafamone + Triasulfuron (67%).

Table 7. Rice phytotoxicity rating for different herbicides using 1 to 5 scales

Experiment 1 (Pre-emergence herbicide)	Phytotoxicity rating Days after application (DAA)			Experiment 2 (Post-emergence herbicide)
	3	6	9	
Pretilachlor	1	1	1	Pyrazosulfuron-ethyl
Oxadiazon	1	1	1	Byspyribac sodium
Pendimethalin	1	1	1	Penoxsulam
Butachlor	1	1	1	Fenoxaprop
Tryafemon	1	1	1	Ethoxysulfuron
Triasulfuron	1	1	1	2,4-D Amine
Pretilachlor + Oxadiazon	1	1	1	Pyrazosulfuronethyl + Bispyribac sodium
Pretilachlor + Pendimethalin	1	1	1	Pyrazosulfuron-ethyl+ Penoxsulam
Pretilachlor + Butachlor	1	1	1	Pyrazosulfuron-ethyl+ Fenoxaprop
Pretilachlor + Tryafemon	1	1	1	Pyrazosulfuron-ethyl+ Ethoxysulfuran
Pretilachlor + Triasulfuron	1	1	1	Pyrazosulfuron-ethyl + 2,4-D Amine
Oxadiazon + Pendimethalin	1	1	1	Bispyribic sodium + Penoxsulam
Oxadiazon + Butachlor	1	1	1	Bispyribic sodium+ Fenoxaorop
Oxadiazon + Tryafemon	1	1	1	Bispyribic sodium+ Ethoxysulfuron
Oxadiazon + Triasulfuron	1	1	1	Bispyribic sodium + 2,4 –D Amine
Pendimethalin + Butachlor	1	1	1	Penoxsulam + Fenoxaorop
Pendimethalin + Tryafemon	1	1	1	Penoxsulam + Ethoxysulfuran
Pendimethalin + Triasulfuron	1	1	1	Penoxsulam + 2,4-D Amine
Tryafemon + Triasulfuron	1	1	1	Ethoxysulfuran + 2,4 –D Amine
Acetachlor 14% + Bensulfuron methyl 4%	1	1	1	Triafamone 20% + Ethoxysulfuron 10%

Phytotoxicity rating: 1= No/ very slight injury, 2= slight injury, 3= phytotoxic, 4= severely phytotoxic and 5= 100% killed.

Table 8. Effect of pre-emergence herbicide and their tank-mix combinations on the yield contributing characters and yield of BRRI dhan58

Treatments	No. of effective tiller $hill^{-1}$	Grains $panicle^{-1}$	1000 grain weight (g)	Grain yield ($t\ ha^{-1}$)	Straw yield ($t\ ha^{-1}$)
Pretilachlor	14.73de	136.53g	22.76d	6.04efg	7.34fg
Oxadiazon	11.90k	130.50i	20.60i	5.23jk	7.52e
Pendimethalin	13.26h	121.57n	22.20e	5.68hi	7.32g
Butachlor	14.10f	126.37k	21.40gh	6.12ef	7.48e
Triafamone	16.56a	154.17a	24.13a	7.13a	8.31a
Triasulfuron	12.40j	132.13h	21.73f	5.21jk	8.12c
Pretilachlor + Oxadiazon	13.73g	142.30f	21.66f	5.96g	8.18bc
Pretilachlor + Pendimethalin	14.06f	142.33f	22.73d	5.96g	7.53e
Pretilachlor + Butachlor	13.26h	122.83m	22.63d	6.14de	7.46ef
Pretilachlor + Triafamone	15.26c	151.37b	23.30bc	6.86b	7.27g
Pretilachlor + Triasulfuron	13.10h	127.73j	22.60d	5.55i	7.24gh
Oxadiazon + Pendimethalin	11.31l	115.73q	22.26e	5.33j	6.49i
Oxadiazon + Butachlor	10.80m	124.60l	21.16h	5.16k	7.27g
Oxadiazon + Triafamone	14.20f	141.60f	23.16c	5.77h	7.77d
Oxadiazon + Triasulfuron	11.46l	119.87o	22.13e	5.80h	7.27g
Pendimethalin + Butachlor	11.83k	118.60p	21.60fg	6.26cd	6.30j
Pendimethalin + Triafamone	14.50e	145.63e	23.43b	6.31c	8.25ab
Pendimethalin + Triasulfuron	12.73i	135.77g	22.10e	6.00fg	7.50e
Triafamone + Triasulfuron	14.96d	147.70d	22.70d	6.15de	8.24abc
Acetachlor 14% + Bensulfuron methyl 4%	15.96b	150.43c	23.16c	6.39c	8.25ab
Season-long weedy	10.23n	120.57o	22.26e	4.31l	7.12h
Level of significance	***	***	***	***	***
CV (%)	1.33	0.41	0.69	1.36	1.06
SE (±)	0.14	0.45	0.12	0.065	0.055

In column, means followed by different letters are significantly different, ***means significant at 0.1% level of probability

Table 9. Effect of post-emergence herbicide and their tank-mix combinations on the yield contributing characters and yield of BRRI dhan58

Treatments	No. of effective tiller hill^{-1}	Grains panicle^{-1}	1000 grain weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
Pyrazosulfuron-ethyl	13.73c	138.50d	23.16c	6.73c	6.42c
Bispyribac sodium	10.30j	98.37o	22.50de	5.27i	6.11d
Penoxsulam	14.20b	140.23c	23.53ab	7.13b	5.40g
Fenoxaprop-p-Ethyl	11.50h	117.47j	22.10g	6.41d	5.64f
Ethoxysulfuron	11.36hi	114.47k	23.10c	6.16e	5.40g
2,4-D Amine	10.43j	85.33q	22.76d	4.98j	4.58j
Pyrazosulfuron-ethyl + Bispyribac sodium	12.43f	110.47m	23.13c	6.12e	5.86e
Pyrazosulfuron-ethyl + Penoxsulam	15.93a	157.23a	23.70a	7.90a	7.06a
Pyrazosulfuron-ethyl + Fenoxaprop-p-Ethyl	12.70ef	129.97f	22.53de	6.52d	4.10l
Pyrazosulfuron-ethyl + Ethoxysulfuron	13.23d	134.63e	23.30bc	6.50d	6.79b
Pyrazosulfuron-ethyl + 2,4-D Amine	10.43j	112.37l	22.26efg	4.55l	4.53j
Bispyribac sodium + Penoxsulam	12.50f	148.43b	23.13c	5.93f	4.52j
Bispyribac sodium + Fenoxaprop-p-Ethyl	12.96de	121.17h	22.36efg	6.06e	5.20h
Bispyribac sodium + Ethoxysulfuron	11.96g	117.63j	22.30efg	5.41h	5.90e
Bispyribac sodium + 2,4 –D Amine	10.56j	99.53n	22.46ef	4.40m	3.71n
Penoxsulam + Fenoxaprop-p-Ethyl	13.60c	120.83h	22.20fg	5.44h	5.10i
Penoxsulam + Ethoxysulfuron	12.56f	140.30c	23.20c	5.92f	3.97m
Penoxsulam + 2,4-D Amine	12.43f	123.80g	22.36efg	5.65g	4.31k
Ethoxysulfuron + 2,4 –D Amine	11.13i	114.50k	20.40i	4.81k	5.13hi
Triafamone 20% + Ethoxysulfuron 10%	11.36hi	120.23i	21.03h	5.52h	4.06l
Season–long weedy	9.43k	92.40p	22.30efg	3.59n	3.26o
Level of significance	***	***	***	***	***
CV (%)	1.46	5.28	0.76	1.17	1.0
SE (±)	0.14	0.27	0.13	0.05	0.04

In column, means followed by different letters are significantly different, ***means significant at 0.1% level of probability

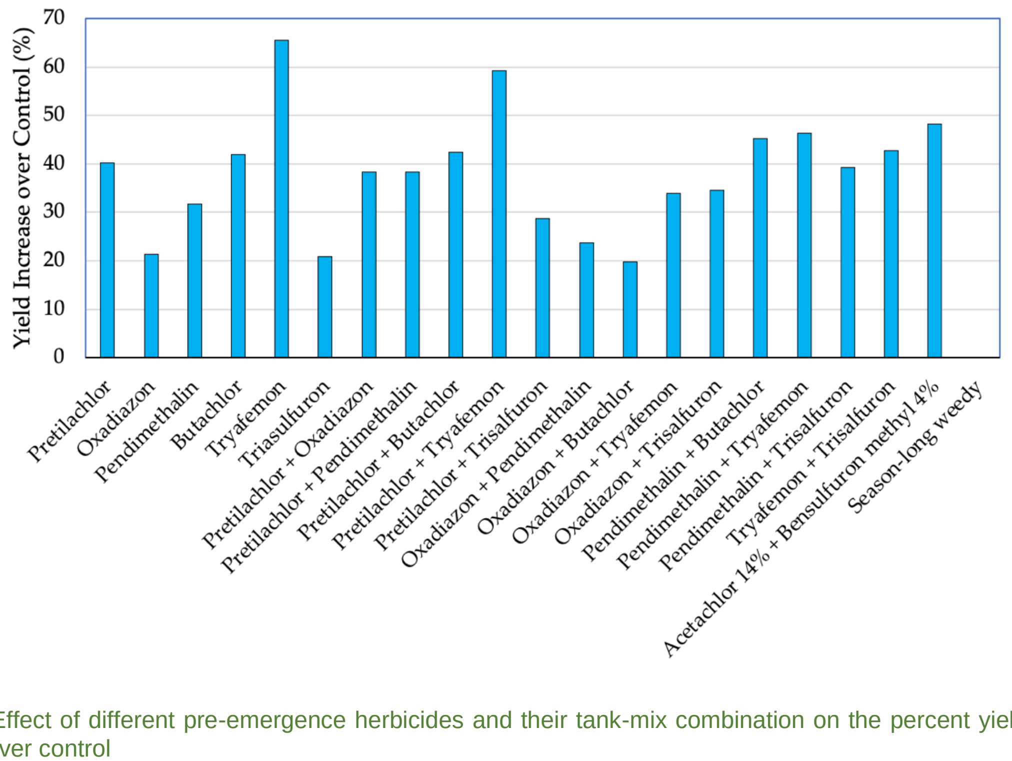

Figure 3. Effect of different pre-emergence herbicides and their tank-mix combination on the percent yield increase over control

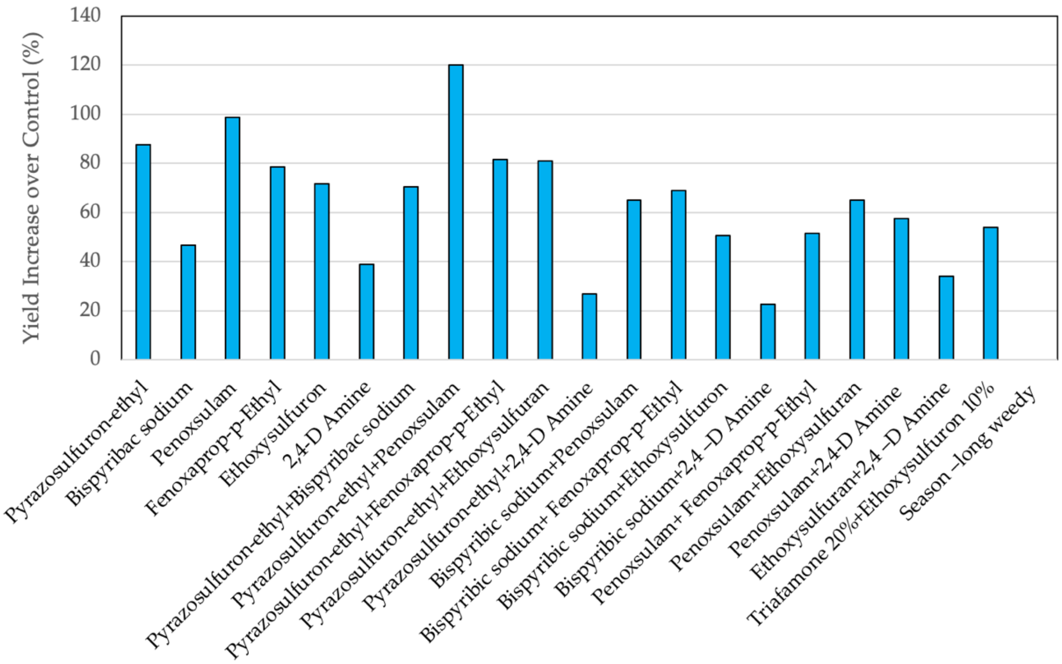

Figure 4. Effect of different post-emergence herbicides and their tank-mix combination on the percent yield increase over control

This might be due to the synergistic effect of the mixture of Pendimethalin or Triasulfuron with Triafamone. On the other hand, the lowest %WCE was obtained from the tank-mix combination of Oxadiazon + Pendimethalin (31%). It might be due to antagonistic effect of Pendimethalin when mix with Oxadiazon, resulting in a more than 2-folds reduction of their %WCE compare to its tank-mixture with Triafamone. Similar types of %WCE was also observed when Triasulfuron mixed with Oxadiazon (37% WCE, 1.8-folds reduction). Antagonism refers to an unfavorable interaction that occurs when the control of weeds is lower than what would be expected if the herbicides were used individually (Barbieri et al., 2022). On the other hand, in Experiment 2 (post-emergence herbicide) tank-mix Pyrazosulfuron-ethyl+ Penoxsulam herbicide exhibited higher %WCE (68% on an average) than the sole application of Pyrazosulfuron-ethyl (57% on an average). This could be due to the broad-spectrum control of weeds provided by the combined application of Pyrazosulfuron-ethyl+ Penoxsulam with different modes of action. The findings align with Singh et al. (2018), who observed that using Pyrazosulfuron, Pretilachlor, Bispyribac-sodium, and Penoxsulam individually is less successful in minimizing weed growth compared to using a combination of herbicides through tank-mix or sequence. Mohapatra et al. (2021) reported that ready-mix post-emergence application of Triafamone + Ethoxysulfuron 60 g ha^{-1} are more effective in minimising total weed biomass (5 g m^{-2}), weed index (4%) and enhancing weed control efficiency (96%), grain yield (5.4 t ha^{-1}) and benefit cost ratio (1.9) than season-long weedy check. In our study, applying Pyrazosulfuron-ethyl alone and in combination with Penoxsulam recorded the lowest weed dry biomass at 30, 45, and 60 days after transplanting. The systemic and selective herbicide Pyrazosulfuron ethyl is useful for controlling annual grasses, sedges, and broadleaves in rice fields, whether they are grown in direct seed-sowing or transplanted (Mondal et al., 2019).

In this experiment, weedy check plots recorded the lowest values of effective tillers hill^{-1}, panicle length, grains panicle^{-1}, 1000 grain weight, grain yield and straw yield of rice. Among the pre-emergence herbicide treatments, Triafamone recorded a significantly higher grain yield. The high yield may be due to the high efficiency of suppressing weed seed germination and then reducing weed competition may have improved rice growth and production. The results align with the findings of other researchers (Alhammad et al., 2023; Rodenburg et al., 2022; Burgos et al., 2014), who also found that complex weed flora affected rice yield components, resulting in varying grain yields. In post-emergence application, tank-mix of Pyrazosulfuron-ethyl + Penoxsulam resulted in better rice yield performance than was achieved under the application of herbicides alone. Tank-mix herbicide treatment reduces crop-weed competition at important rice crop growth times by keeping weeds below a critical level, allowing that crop to use all resources and grow effectively (Mahajan and Chauhan, 2015; Ruzmi et al., 2017; Kaur et al., 2022). Yadav et al. (2020) and Pradhan et al. (2023) found that using a combination of herbicides resulted in a considerable reduction in weed biomass and optimized rice growing conditions, leading to the maximum rice yield. This was more effective than using a single herbicide application. Pradhan et al. (2023) also obtained highest weed control efficiency and higher grain yield in tank-mix combination of Pendimethalin fb fenoxaprop-p-ethyl + Ethoxysulfuron that reduced more 50% weeds compared to weedy check plot at 60 DAS which was statistically at par with season-long weed free condition.

In our study, the tank mix of pre-emergence herbicide application (Pendimethalin + Triafamone) was not as efficient as post-emergence (Pyrazosulfuron-ethyl + Penoxsulam) in comparison with others. The interaction among herbicides leads to notable alterations in weed control outcomes, either reducing or enhancing effectiveness. The efficacy of either of the two active substances may be enhanced or diminished when they are combined, as a result of alterations in their physical and chemical characteristics. Combinations of herbicides frequently have distinct mechanisms of action, and their mixtures can exhibit one of three responses: synergistic, antagonistic, or additive/neutral (Barbieri et al., 2023). Weed practitioners face a challenge in herbicide antagonism, which may lead to ineffective weed control and necessitate additional treatments to eradicate escaped weeds. For example, Triclopyr combined with Fenoxaprop was ineffective against barnyard vegetation (Zhang et al., 2005). Synergy is a concept that refers to any form of interaction or cooperation that results in an output that is larger than the combined effect of its individual components. Prior research has demonstrated that the combination of Bispyribac sodium and broadleaf herbicide resulted in more effective weed management compared to the use of Bispyribac sodium alone due to the fact that the composition can control both grassy and broadleaved weeds (Mitra et al., 2022 and Mahajan and Chauhan, 2015).

5. Conclusion

The findings of this research indicate that tank-mix application of pre- or post- emergence herbicide has a great potential to control weeds better than their sole application in some cases. Sole application of Triafamone pre-emergence herbicide performed as the best in terms of percent weed control efficiency, grain yield and percent yield increase over control. Tank-mix application of post-emergence herbicide Pyrazosulfuron-ethyl + Penoxsulam performed as the best in terms of percent weed control efficiency, grain yield and percent yield increase over control followed by sole application of post-emergence herbicide Penoxsulam. Based on the findings it can conclude here that tank-mixture of Triafamone + Pretilachlor or Triafamone + Pendimethalin pre-emergence herbicide or Pyrazosulfuron-ethyl+ Penoxsulam post-emergence herbicide at a ratio of 1:1 might be perfect alternative compare to their sole application or sequential application for effective weed control and to obtain higher rice yield. However, as these experiments have been conducted in a single season and location, it is not wise to draw a final conclusion based on these experimental results. Multi-location and multi-season trials considering different tank-mix ratios should be taken into account in future to draw a concrete conclusion.

Funding

The authors thankfully acknowledge the financial support provided by the Ministry of Science and Technology, The Government of the People's Republic of Bangladesh through the grant number ''SRG-221038''. The authors also acknowledge Bangladesh Agricultural University Research System (BAURES) for all kinds of logistic support to complete the research successfully.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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