Research Article

Assessment of Herbicide Effectiveness in Weed Suppression and Agronomic Output in Dry Direct-Seeded Rice

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Abstract | Dry direct seeded rice (DDSR) is highly susceptible to weeds because it lacks an early advantage over weeds and does not involve standing water to suppress weeds. To evaluate the weed control efficacy (WCE), yield potentialities, and cost-effectiveness of rice under direct dry seeding conditions, an experiment was conducted during the 2020 and 2021 *boro* seasons at Bangladesh Agricultural University to assess five herbicides (pretilachlor, acetochlor (14%) plus bensulfuron methyl (4%), pyrazosulfuron ethyl, triafamone, and penoxsulam) along with season-long weedy and weed-free for weed suppression and yield improvement in DDSR. The results indicate that the weedy plot was predominantly infested with three grasses (*Echinochloa crus-galli*, *Paspalum scrobiculatum*, *Cynodon dactylon*) and one sedge (*Schoenoplectiella juncoides*). All evaluated herbicides significantly reduced weed density and biomass measured at 30 and 60 days after seeding. The application of acetochlor plus bensulfuron methyl achieved 100% WCE, followed by triafamone (94–96%), pyrazosulfuron ethyl (88–95%), and pretilachlor (80–93%). Compared to the unweeded plots, acetochlor plus bensulfuron methyl resulted 46% and 31% yield increase in 2020 and 2021, respectively, with yields of 4.40 and 4.98 t ha^{-1}. The results also showed that the acetochlor (14%) plus bensulfuron methyl (4%) applied at 6 DAS gave the highest net income (BDT 69,845 in 2020 and 95,415 in 2021) and the highest benefit-cost ratio (1.65 in 2020 and 1.87 in 2021). The findings provide valuable insights into the selection of effective herbicide strategies to improve rice production in dry seeding systems, contributing to sustainable and cost-efficient rice cultivation practices.

Received | February 12, 2026; **Accepted** | April 28, 2026; **Published** | July 21, 2026
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Citation | Jahan, I., A.K.M.M. Islam, M.M. Rana, T.K. Roy, S. Yeasmin, M.P. Anwar and M. Rahman. 2026. Assessment of herbicide effectiveness in weed suppression and agronomic output in dry direct-seeded rice. *Sarhad Journal of Agriculture,* 42(3): 1264-1275.
DOI | https://dx.doi.org/10.17582/journal.sja/2026/42.3.1264.1275
Keywords | Dry seeding, Herbicides, Summed dominance ratio, Weed species, *Boro* rice, Yield

Introduction

Rice (*Oryza sativa* L.) is the most significant staple food for 650 million hungry and 80% of world undernourished people worldwide (Saha *et al*., 2021) and the main source of nutrition for approximately half of the world's population (Mohidem *et al*., 2022). Among the rice growing countries of the world, Bangladesh ranked 3rd on rice cultivation and 5th on area under production where total production of rice has been estimated 39.095 million tones under 28.754 million acres of cultivable land during 2022-23 cropping season (BBS, 2024). The soil and climate of Bangladesh is favorable for rice cultivation but the production didn't meet our food demand due to rapid increasing rate of population, low yield of food crops and also loose roughly 225 ha of land due to urbanization (Timsina *et al*., 2018). Therefore, closing the yield gap in rice cultivation is vital for ensuring food security. The primary cause of the yield gap is poor management practices in rice farming, which also contribute to soil infertility. To meet the needs of a growing population, Bangladesh must focus on improved crop establishment methods and adopt scientific approaches to the efficient use of natural resources. Effective management options are essential to increase rice yields and bridge the existing gap, thereby ensuring sustainable food production for the country (Das *et al*., 2021).

In Bangladesh, transplanting rice in irrigated puddled fields is the predominant and most widely practiced method of rice cultivation (Chaki *et al*., 2021). The sustainability of rice production during the boro season under the puddled transplanted system is threatened by factors such as labor shortages, rising labor expenses, and water scarcity. Additionally, boro rice cultivation relies entirely on irrigation because of the minimal rainfall typically experienced in this period in Bangladesh. Therefore, direct dry-seeded rice (DDSR) has been evolved as an alternate water–wise rice cultivation technology that offers saving about 50–60% irrigation compared with puddle systems (Chaudhary *et al*., 2023). In addition, DDSR saves up to 60% of labor and 35% water with 92% reduction of methane emission and 32% reduction of cultivation cost which saving about US$50 ha^{-1} while DDSR systems need only 35–57% water compared to PTR method (Kumar and Ladha, 2011).

However, weeds are the most significant barrier to DDSR performance but yields are comparable to regular transplanting (Khaliq *et al*., 2021). In the absence of weed control, rice yield losses due to weeds ranged from 40–100% in direct–seeded rice (Ahmed *et al*., 2021). Therefore, efforts are being made to develop effective and sustainable weed management strategies for this system (Shekhawat *et al*., 2020). Manual or hand weeding is most common practice of weed control in rice (Ahmed *et al*., 2020) and are effective in Bangladesh but manual weed control progressively less attractive due to the rising of labor cost and scarcity of labor at critical times (Paul *et al*., 2025).

Therefore, the use of herbicides for weed management has gained increasing popularity, primarily because it can lower overall expenses by reducing the need for labor-intensive practices (Hakim *et al*., 2021). Over the past thirty years, herbicides have played a significant role in Bangladesh's agriculture sector, with their usage increasing by approximately 37 times (Ahmed *et al*., 2021). While recent registrations of herbicides such as acetochlor plus bensulfuron methyl, pyrazosulfuron ethyl, triafamone, and penoxsulam have expanded weed management options for irrigated puddled rice in Bangladesh, their efficacy in dry direct-seeded rice systems remains unassessed. Currently, there is a lack of empirical data evaluating the weed control efficiency, phytotoxicity, and crop safety of these herbicides under dry direct seeding conditions. Given the distinct weed flora, soil moisture regimes, and crop establishment methods in dry direct seeding compared to puddled systems, it is uncertain whether these herbicides will perform effectively. Systematic evaluation of these recently registered herbicides in dry direct seeded rice is essential to identify optimal weed control options.

Therefore, this study was conducted to evaluate the weed control efficacy, yield potentialities, and cost-effectiveness of rice under direct dry seeding conditions using five different herbicides.

Material and Methods

Experimental site and season

The experiments were carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh during the 2020 and 2021 *boro* seasons. The location is approximately 18 meters above sea level, situated at 24.719890 °N latitude and 90.426928 °E longitude. The research site falls within the Old Brahmaputra Floodplain, Agro-Ecological Zone (AEZ-9). The soil in the experimental area is silty loam, moderately fertile, with a pH of 6.8 and low organic matter content (1.29%). Overall, the soil exhibits poor fertility, with 1% total nitrogen, 26 ppm available phosphorus, and 0.14% exchangeable potassium.

Plant material

BRRI dhan58, a high-yielding boro rice variety developed and released by Bangladesh Rice Research Institute (BRRI) in 2012, was utilized in this study as

Table 1: *Details of the herbicidal treatment.*

Sl. No.	Name of herbicide	Trade name	Dose	Application time (DAS)	Manufacturer
1	Pretilachlor	Commit 500EC	1.0 L ha^{-1}	6	Auto crop care Ltd.
2	Acetochlor (14%) plus Bensulfuron methyl (4%)	Clean master 18WP	500 g ha^{-1}	6	Haychem Bangladesh (Pvt.) Ltd.
3	Pyrazosulforan ethyl	Super power 10WP	125 g ha^{-1}	14	Macdonald Bangladesh (Pvt.) Ltd.
4	Triafamone	Council prime 20SC	1.5 L ha^{-1}	14	Bayer crop Science BD
5	Penoxsulam	Granite 240SC	93.7 mL ha^{-1}	14	Auto crop care Ltd.

a test crop. Under optimal conditions, BRRI dhan58 can produce up to 7.2 t ha^{-1}, making it a highly productive rice variety. BRRI dhan58 is a medium duration variety that requires approximately 155 days from planting to harvest. The plant height of BRRI dhan58 is about 100 centimeters, which helps reduce the risk of lodging during growth.

Herbicide treatments and applications

This experiment comprised seven treatments that include a season-long weedy (T_1) and season-long weed-free (T_2) condition, application of two pre-emergence herbicides; pretilachlor (T_3), acetochlor (14%) plus bensulfuron methyl (4%) (T_4), and three post-emergence herbicides; pyrazosulfuron ethyl (T_5), triafamone (T_6), and penoxsulam (T_7). Table 1 provides a description of the herbicidal treatments. Herbicides were applied using a hand-operated plastic knapsack sprayer fitted with a flat-fan nozzle. The sprayer was calibrated to deliver a spray volume of 300 L ha^{-1} at a constant pressure of 0.3 MPa. During application, the operator maintained a uniform walking speed (approximately 8 km h^{-1}, depending on the required spray volume) to ensure consistent herbicide distribution. The nozzle was held at a height of approximately 50 cm above the weed canopy to achieve proper spray overlap and uniform coverage of the target weeds.

Experimental design

The experiment employed a Randomized Complete Block Design with three replications. A total of 21 plots were used, each measuring 4 meters by 2.5 meters (10 m^2). The plots were spaced 0.5 meters apart. Treatments were randomly assigned to the plots to ensure unbiased results.

Crop husbandry

Tillage operations were carried out to create a favorable soil structure for dry direct-seeded rice, and weeds along with stubbles were removed from the field. Rice seeds were hydro–primed by soaking in water for 24 hours at room temperature, followed by 30 hours of incubation at 32°C. Then those seeds were directly sown on 15 February in 2020 and 2021 to dry cultivated land as per experimental specification at 25 cm × 15 cm in 3-5 cm depth allocating 5–6 seeds hill^{-1}. The soil was enriched with fertilizers including urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum, and zinc sulfate at application rates of 300, 100, 120, 60, and 10 kg ha^{-1}, respectively (BRRI, 2020). The complete amounts of TSP, MoP, gypsum, and zinc sulfate were incorporated during the final land preparation stage. Urea was applied in three equal installments at 15, 30, and 45 days after planting. Consistent intercultural practices were carried out to promote healthy crop development.

Data collection

Weed data

In each plot, three quadrats (0.25 m × 0.25 m) were randomly placed for weed sampling. All weeds within each quadrat were clipped at ground level, identified to species level, and counted. The collected weed samples were oven-dried at 70 °C until constant weight to determine weed dry biomass, and the data from the three quadrats were averaged for each plot. The relative density, dry weight, and summed dominance ratio of weeds were determined with the formula described by Janiya and Moody (1989):

$$RD\,(\%) = \frac{\text{Density of a given weed species}}{\text{Total weed density}} \times 100$$

$$RDW\,(\%) = \frac{\text{Dry weight of a given weed species}}{\text{Total weed dry weight}} \times 100$$

$$SDR\ of\ a\ weed\ species = \frac{[\text{Relative density (RD) + Relative dry weight (RDW)}]}{2}$$

Weed control efficiency (WCE) was determined by the formula stated in Mani *et al.* (1973):

$$Weed\ control\ efficiency\ (\%) = \frac{\text{DWC - DWT}}{\text{DWC}} \times 100$$

Where,
DWT = dry weight of weeds in treated plots
DWC = dry weight of weeds in weedy check plots

Crop data

The crop was harvested when the majority of the grains had ripened to a golden yellow hue approximately 90% maturity. Before harvest, five hills were randomly selected from each unit plot (excluding border hills) and uprooted to collect data on yield metrics. The central 2.5 m × 2.0 m area (5.0 m^2) was used to determine grain and straw yield. The harvested material from each plot was bundled, tagged, and taken to the threshing floor. After sun-drying the grains and straw, grain yield was recorded at a 14% moisture basis and converted to t ha^{-1}. Yield increase over control (YOC) was calculated using the following formula:

$$YOC\ (\%) = \frac{\text{Treatment yield - weedy yield}}{\text{Weedy yield}} \times 100$$

Cost-benefit analysis

Individual expenditure items were documented, and a partial budget analysis was conducted. The budget encompasses variable costs, total income, net income, and the benefit-cost ratio.

Statistical analysis of data

The data collected for various parameters were organized into well-structured tables detailing different plant traits and were analyzed statistically using the Statistics 10 software. The differences among treatment means were tested for significance using both DMRT and LSD at the 5% probability level (Gomez and Gomez, 1984).

Results and Discussion

Weed composition

In 2020, the experimental field harbored a naturally occurring weed community dominated by grasses, with three weed species belonging to the Poaceae family (Table 2). Grasses accounted for 100% of both relative density (RD) and relative dry biomass (RDB). According to the summed dominance ratio (SDR) measurements, *Echinochloa crus-galli* exhibited the highest dominance in the season-long weedy plot (SDR=40.18), while *Paspalum scrobiculatum* was the least dominant (SDR=16.67). In 2021, the field was once more infested by a native weed assemblage comprising grasses and sedges, including four species from two families-three grasses and one sedge. (Table 2). Grasses contributed 86.28% RD and 76.90% RDB, followed by sedge species at 13.72% RD and 23.10% RDB. Based on SDR, *Echinochloa crus-galli* remained the most dominant (SDR=36.45), while the least dominant weed was the sedge *Schoenoplectiella juncoides* (SDR=18.41). These findings suggest that the weedy plot was predominantly dominated by grasses instead of sedges.

Weed density

The analysis shows a highly significant effect of different treatments on weed density ($p < 0.001$) at both 30 days after sowing (DAS) and 60 DAS in both years (Table 3). Notably, acetochlor (14%) plus bensulfuron methyl (4%) (T_4) achieved complete weed suppression, recording 0.00 weeds m^{-2} across all four sampling points in 2020 and 2021 which was statistically similar to season-long weed free treatment. Across most herbicidal treatments, weed density

Table 2: *Floristic composition of the weed community with relative density (RD), relative dry weight (RDW) and summed dominance ration (SDR) of the experimental field at 30 and 60 DAS in 2020 and 2021.*

Local name	Scientific name	Family	Morphology	Life cycle	RD (%)	RDB (%)	SDR (%)
2020							
Shama	*Echinochloa crus-galli* (L.) P. Beauv	Poaceae	Grass	Annual	39.14	41.12	40.18
Angta	*Paspalum scrobiculatum* L.	Poaceae	Grass	Perennial	18.59	14.75	16.67
Durba	*Cynodon dactylon* L. Pers.	Poaceae	Grass	Perennial	42.27	44.13	43.15
2021							
Shama	*Echinochloa crus-galli* (L.) P. Beauv	Poaceae	Grass	Annual	34.12	38.78	36.45
Angta	*Paspalum scrobiculatum* L.	Poaceae	Grass	Perennial	19.46	21.78	20.62
Chechra	*Schoenoplectiella juncoides* (Roxb.) Lye	Cyperaceae	Sedge	Annual	13.72	23.1	18.41
Durba	*Cynodon dactylon* L	Poaceae	Grass	Perennial	32.7	16.34	24.52

RD=Relative density, RDB= Relative dry biomass, SDR= Summed dominance ratio declined from 30 DAS to 60 DAS within a given year, likely reflecting crop canopy development and ongoing management, but season–long weedy treatment remained very high at 60 DAS. In short, season–long weed free and acetochlor (14%) plus bensulfuron methyl (4%) provide the strongest weed suppression across dates and years, whereas the other treatments leave varying levels of weed pressure that could impact crop competition.

Weed dry biomass

The Table 3 shows that weed biomass in g m^{-2} is strongly influenced by herbicidal treatments and by year, with highly significant differences among treatments at both 30 and 60 days after sowing (DAS) in both 2020 and 2021. As expected, the season-long weedy control accumulates the most biomass (about 44.6–43.9 g m^{-2} at 30 DAS and 61.1–51.8 g m^{-2} at 60 DAS, across 2020/2021). The season-long weed free treatment completely suppresses weeds, yielding essentially zero biomass in all cases. Among herbicides, biomass generally declines relative to the weedy control, but efficacy varies. Pretilachlor and penoxsulam reduce biomass but do not achieve zero by 60 DAS in some years (at 60 DAS: 13.94 g m^{-2} in 2020 and 7.17 in 2021 for pretilachlor; 19.85 in 2020 and 8.87 in 2021 for penoxsulam). acetochlor (14%) plus bensulfuron methyl (4%) eliminates biomass, giving zero g m^{-2} at 30 and 60 DAS in both years (2020/2021). Pyrazosulfuron ethyl and triafamone (post-emergence herbicide) are particularly effective by 60 DAS, with low residual biomass (60 DAS: pyrazosulfuron ethyl about 4.99–8.42 g m^{-2}; triafamone about 3.68–4.24 g m^{-2} across years). The year-to-year pattern shows generally lower biomass in 2021 for the post-emergence herbicides (*e.g.*, pyrazosulfuron ethyl and penoxsulam). Overall, complete suppression is achieved by acetochlor (14%) plus bensulfuron methyl (4%), and substantial suppression by triafamone and pyrazosulfuron ethyl by 60 DAS.

Weed control efficiency (WCE)

The season-long weedy check provides zero (%) control, while the season-long weed free check provides 100% control, confirming the expected extremes. Among the herbicides, acetochlor (14%) plus bensulfuron methyl (4%) achieves complete weed control (100%), matching the weed-free standard and indicating excellent efficacy (Table 3). Triafamone applied at 14 DAS performs next best with about 67.9% control, followed by pretilachlor at 44.7% and penoxsulam at 42.9%, while pyrazosulfuron ethyl at 14 DAS is the least effective at about 29.8%. The acetochlor (14%) plus bensulfuron methyl (4%) combination delivering full suppression comparable to the weed-free control, whereas several single-herbicide options provide only partial control and may not prevent weed pressure later in the season.

Table 3: *Effect of different weed management strategies on weed density, biomass, and control effectiveness at 30 and 60 DAS during 2020 and 2021.*

Treatments	Weed density (no. m^{-2})				Weed dry biomass (g m^{-2})				Weed control efficiency (%)			
	30 DAS		60 DAS		30 DAS		60 DAS		30 DAS		60 DAS	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
T_1	52.25^a	67.00^a	71.66^a	108.67^a	44.58^a	43.89^a	61.14^a	51.80^a	00	00	00	00
T_2	0.00^e	0.00^e	0.00^f	0.00^e	0.00^e	0.00^d	0.00^f	0.00^e	100	100	100	100
T_3	28.88^c	32.67^c	14.66^c	7.66^c	25.00^{cd}	34.48^b	13.94^c	7.17^{bc}	44.72	51.24	79.54	92.95
T_4	0.00^e	0.00^e	0.00^f	0.00^e	0.00^e	0.00^b	0.00^f	0.00^e	100	100	100	100
T_5	36.66^b	38.62^b	8.66^d	5.66^{cd}	32.52^b	38.34^d	8.42^d	4.99^{cd}	29.84	42.36	87.92	94.79
T_6	16.75^d	20.27^d	4.45^e	4.22^b	22.94^d	25.97^c	4.24^e	3.68^d	67.94	69.75	93.79	96.12
T_7	29.86^c	34.27^{bc}	21.34^b	11.66^d	30.06^{bc}	36.65^b	19.85^b	8.87^b	42.85	48.85	70.22	89.27
Level of sig.	***	***	***	***	***	***	***	***	-	-	-	-
CV (%)	12.82	10.82	9.73	8.53	13.45	11.63	10.94	15.38	-	-	-	-

Within the column, means assigned different letters indicate significant differences; three asterisks (***) denotes significance at the 0.1% probability level; T_1: Season–long weedy; T_2: Season–long weed free; T_3: Pretilachlor at 6 DAS; T_4: Acetochlor (14%) plus Bensulfuron methyl (4%) at 6 DAS; T_5: Pyrazosulfuron ethyl at 14 DAS; T_6: Triafamone at 14 DAS and T_7: Penoxsulam at 14 DAS

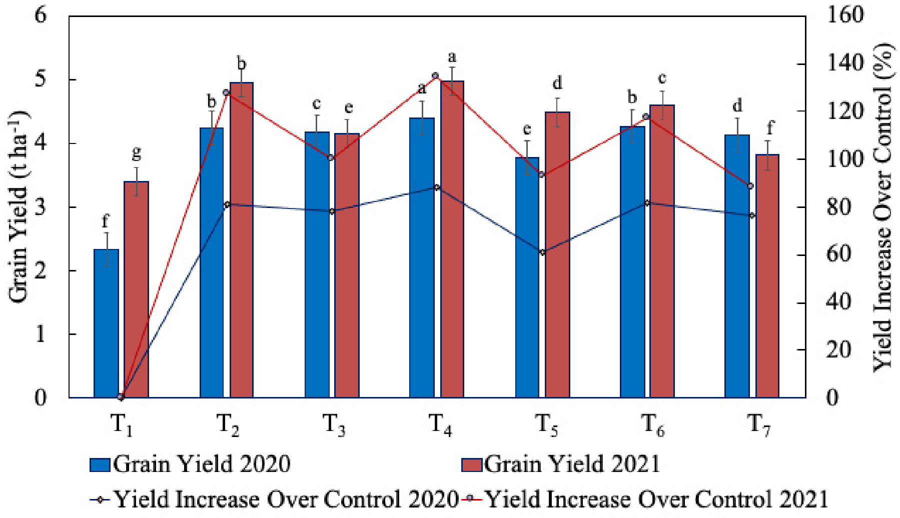

Figure 1: *Effect of different weed management practices on grain yield and yield increase over control in 2020 and 2021. T_1: Season–long weedy; T_2: Season–long weed free; T_3: Pretilachlor at 6 DAS; T_4: Acetochlor (14%) plus Bensulfuron methyl (4%) at 6 DAS; T_5: Pyrazosulfuron ethyl at 14 DAS; T_6: Triafamone at 14 DAS and T_7: Penoxsulam at 14 DAS.*

Table 4: *Effect of different weed management practices on yield related attributes during 2020 and 2021.*

Treatments	Effective tillers hill^{-1}(no.)		Non–effective tillers hill^{-1}(no.)		Grains panicle^{-1}(no.)		Weight of 1000–grain (g)	
	2020	2021	2020	2021	2020	2021	2020	2021
T_1	8.49^c	4.18^g	2.33^a	3.96^a	63.12^e	62.19^f	15.48^c	17.24^e
T_2	15.53^a	16.04^b	1.12^c	0.62^f	125.68^{abc}	133.12^a	22.07^a	21.03^b
T_3	13.76^{ab}	9.70^e	1.64^b	3.72^c	122.73^{bc}	98.66^d	21.50^a	18.50^d
T_4	16.59^a	16.62^a	0.74^d	0.47^g	128.35^a	134.36^a	22.39^a	22.71^a
T_5	10.80^{bc}	11.57^d	1.67^b	2.59^d	97.59^d	112.74^c	19.43^b	19.70^c
T_6	13.95^{ab}	13.36^c	0.98^c	1.97^e	126.03^{ab}	118.07^b	22.11^a	19.70^c
T_7	13.53^{ab}	7.93^f	1.21^c	3.82^b	120.45^c	74.17^e	22.19^a	17.15^e
Level of sig.	***	***	***	***	***	***	***	***
CV (%)	15.39	0.22	10.92	1.86	2.69	0.94	3.23	1.94

Within the column, means assigned different letters indicate significant differences; three asterisks (***) denotes significance at the 0.1% probability level; T_1: Season–long weedy; T_2: Season–long weed free; T_3: Pretilachlor at 6 DAS; T_4: Acetochlor (14%) plus Bensulfuron methyl (4%) at 6 DAS; T_5: Pyrazosulfuron ethyl at 14 DAS; T_6: Triafamone at 14 DAS and T_7: Penoxsulam at 14 DAS

Yield related attributes and grain yield

Across both years, season-long weed-free plots produced the highest values for tillers (15.53 in 2020 and 16.04 in 2021) and for grains per panicle (125.68 in 2020 and 133.12 in 2021), with 1000-grain weight of 22.07 g and 21.03 g, indicating the strong benefit of complete weed suppression on these components (Table 4). Among herbicide treatments, Acetochlor (14%) plus bensulfuron methyl (4%) performed best, yielding 128.35 grains panicle^{-1} in 2020 and 134.36 in 2021, that closely approached the weed free level and were not significantly different from it in many cases. Triafamone applied at 14 DAS also gave high grains per panicle (126.03 in 2020 and 118.07 in 2021) and the highest 1000-grain weight in 2020 (22.11 g), but its 2021 grain weight fell to 19.70 g. The pre-emergence herbicide pretilachlor, and post-emergence herbicide pyrazosulfuron ethyl or penoxsulam were intermediate or lower in performance, with penoxsulam showing particularly strong in 2020 (120.45 grains) but a marked decline in 2021 (74.17 grains). Overall, the best outcomes for yield components were achieved by season-long weed free management and by the acetochlor (14%) plus bensulfuron methyl (4%) combination, which largely matched weed-free performance across both seasons. Figure 1 shows that grain yield and percent yield increase over control (% YOC) varied among

Table 5: *Economic efficiency of different weed control practices in 2020 and 2021.*

Treatments	Variable cost (Tk. ha^{-1})	Herbicide cost (Tk. ha^{-1})	Labour cost (Tk. ha^{-1})	Total cost (Tk. ha^{-1})	Gross income (Tk. ha^{-1})	Net income (Tk. ha^{-1})	BCR
2020							
T_1	105125	0	0	105125	106350	1225	1.01
T_2	105125	0	20900	126025	168460	42435	1.34
T_3	105125	1000	550	106175	172390	66215	1.62
T_4	105125	500	550	106675	176520	69845	1.65
T_5	105125	494	550	106169	149370	43201	1.41
T_6	105125	1020	550	106695	125740	19045	1.18
T_7	105125	2642	550	108317	165840	57523	1.53
2021							
T_1	108.620	0	0	108620	149810	41185	1.38
T_2	108620	0	20900	129520	202670	73140	1.56
T_3	108625	1000	550	110175	178100	67925	1.62
T_4	108625	500	550	109675	205090	95415	1.87
T_5	108625	235	550	109410	191290	81880	1.75
T_6	108625	494	550	109669	185840	76171	1.69
T_7	108625	2642	550	111817	168560	56743	1.51

T_1: Season–long weedy; T_2: Season–long weed free; T_3: Pretilachlor at 6 DAS; T_4: Acetochlor (14%) plus Bensulfuron methyl (4%) at 6 DAS; T_5: Pyrazosulfuron ethyl at 14 DAS; T_6: Triafamone at 14 DAS and T_7: Penoxsulam at 14 DAS. Tk.: Bangladesh Taka (BDT), 1 BDT = 0.00 82 USD.

weed-management practices. Relative to the weedy check, all weed control strategies improved grain yield, but the magnitude of the response differed among treatments. The highest grain yield (4.40 t ha^{-1} in 2020 and 4.98 t ha^{-1} in 2021) was observed with acetochlor (14%) + bensulfuron methyl (4%) followed by while triafamone in 2020 (4.26 t ha^{-1}) and season-long weed free in 2021 (4.96 t ha^{-1}). The untreated/ weedy check had the lowest grain yield (2.34 and 3.40 t ha^{-1}) at both seasons (2020/2021). The differences among treatments were statistically significant at $p<0.05$. Overall, the results suggest that effective weed suppression can markedly boost yield in both the year.

Economic efficiency of different weed control practices

The study also estimated the cost effectiveness of different weed management practices related to herbicides for rice cultivation in dry direct seeded condition (Table 5). The results show a clear economic advantage to actively managing weeds, with weed-free and herbicide-based programs delivering much higher gross and net incomes than the season-long weedy control in both years. In 2020 the season-long weedy treatment produced the lowest net income (Tk. 1,225) and a modest BCR of 1.01, whereas the season-long weed free and chemical programs substantially increased both earnings and profitability (net incomes around Tk. 42,435–69,845 and BCRs of 1.34-1.65). The Acetochlor (14%) plus Bensulfuron methyl (4%) combination consistently gave the highest gross income (Tk. 176,520 in 2020; Tk. 205,090 in 2021) and the largest net income (Tk. 69,845 in 2020; Tk. 95,415 in 2021), with the highest BCRs (1.65 in 2020 rising to 1.87 in 2021), indicating the best economic return among treatments. Other effective options include pyrazosulfuron ethyl or triafamone applied at 14 DAS, which yielded strong net incomes and high BCRs, especially in 2021 (net incomes ≈ Tk. 81,880 and Tk. 76,171; BCRs ≈ 1.75 and 1.69).

Discussion

The dominance patterns and weed species composition observed in this study reflect the typical flora of tropical dry direct-seeded rice (DDSR) habitats. In 2020, only grasses (Poaceae) made up the weed flora; however, sedges (Cyperaceae) appeared in 2021. According to the summed dominance ratio (SDR), *Echinochloa crus-galli* was the most prevalent weed in both years. Earlier studies found that this species to be among the most competitive and aggressive weeds in direct-seeded systems because of its high capacity for tillering, quick germination, and phenological synchronization with rice (Chauhan, 2022). The findings suggest that the weedy plot was predominantly affected by grasses rather than sedge weeds. Juraimi *et al.* (2009) reported that variations in soil moisture or micro-environmental circumstances that promote sedge germination could be the cause of *Schoenoplectiella juncoides* sporadic appearance. Grasses tended to dominate in conditions with increased moisture levels (Bhagat *et al*., 1999). Based on SDR measurements, these grasses exhibited greater competitiveness throughout both studied years. The variations in the floristic composition and dominance pattern of weeds might be due to the differences in the agro-ecological conditions, cropping pattern, management practices and weed seed bank composition.

Season-long weedy plots had significantly higher weed density and biomass, especially at 60 DAS. This suggests that uncontrolled, early-season weed emergence leads to significant competition for resources like nutrient, water, light etc. Neglecting weed control resulted in the highest weed dry biomass across all crop development stages, primarily due to increased weed density and their competitive advantage in absorbing sunlight, nutrients, and moisture (Mishra *et al*., 2022). Similarly, Suryakala *et al*. (2019) found that the dry biomass of weeds was significantly affected by the varying application rates of Acetochlor (14%) combined with Bensulfuron methyl (4%). The excellent effectiveness of pre-emergence combination and demonstrates their effectiveness in mitigating this competition against both grasses and sedges is confirmed by the zero-weed density and dry biomass in plots treated with acetochlor (14%) plus bensulfuron methyl (4%) applied at 6 DAS. This supports previous findings that showed mixed-mode herbicides achieved near complete control in DDSR (Alptekin *et al*., 2023). Mahbub and Bhuiyan (2018) observed similar outcomes, noting that a combination of acetochlor (14%) and bensulfuron methyl (4%) achieved approximately 80% suppression of both annual and perennial weeds. This effectiveness was comparable to applying the herbicides separately and likely worked by preventing the germination of sensitive weed species and limiting the growth of those already sprouted through the inhibition of photosynthesis, similar to other herbicide strategies. On the other hand, Acharya and Bhattacharya (2013) also reported that application of acetochlor (14%) plus bensulfuron methyl (4%) is most effective against weed grown in field. Treatments like pyrazosulfuron ethyl or penoxsulam that were treated at 14 DAS had comparatively reduced weed control efficiency (WCE), which shows that delayed application permits early weed establishment and lowers overall control effectiveness (Alptekin *et al*., 2023). Anwar *et al*. (2012) described WCE as the proportion of weed dry biomass decrease resulting from a specific herbicide application relative to the untreated control. On the other hand, Acharya and Bhattacharya (2013) also found that the application of acetochlor (14%) plus bensulfuron methyl (4%) recorded maximum weed control efficiency and this treatment found most effective in controlling predominant weeds in comparison to other herbicides.

The results of weed control were closely reflected in yield-related parameters. Effective tillers hill^{-1}, grains panicle^{-1}, and 1000-grain weight were significantly decreased by season-long weedy circumstances, demonstrating the competitive impact weeds exert throughout crucial crop growth stages. Strategic early weed suppression is adequate to sustain rice production in DDSR, as demonstrated by the fact that acetochlor (14%) plus bensulfuron methyl (4%) not only increased these yield components but also maintained performance comparable to the season-long weed-free treatment. Similar findings were reported by Yadav *et al*. (2018), who observed that the application of Acetochlor (14%) combined with Bensulfuron methyl (4%) enhanced the number of effective tillers in treated plots, comparable to weed-free conditions. Likewise, Jabran *et al*. (2012) found that the highest 1000-grain weight in rice occurred under weed-free conditions, while the lowest was recorded in weedy check plots. Their study also indicated that herbicide application significantly improved yield-related traits of direct-planted rice compared to untreated weedy plots. Teja *et al*. (2017) highlighted that timely and effective weed management through herbicides allowed crops to access sufficient space, light, nutrients, and moisture, leading to increased filled grains per panicle. Research by Bhuiyan *et al*. (2018), demonstrated that the highest grain yields were achieved with a combination of acetochlor (14%) and bensulfuron methyl (4%) WP at 750 g ha^{-1}, likely due to superior weed control efficiency and enhancement of yield attributes, comparable to weed-free treatments. Additionally, Suryakala *et al*. (2019) reported that a well-chosen herbicide mixture effectively suppressed a broad spectrum of weed species, reducing weed density more efficiently than single or less effective herbicide treatments, which in turn improved resource utilization and grain yield. The reported production increased over 30-75% in weedy circumstances is in line with other research that found 40–60% yield losses in DDSR due to uncontrolled weed development (Singh, 2017).

Acetochlor (14%) plus bensulfuron methyl (4%) is the most practical weed control solution, according to economic research. Its highest benefit-cost ratio (BCR) and net income in both years show that more profitability is a direct result of efficient weed management. Even though alternative herbicides like triafamone or pretilachlor also significantly increased yield, their marginally lower weed control effectiveness and financial returns make them less ideal for the particular production system. Crucially, the negligible yield differences between the weed-free manual control and acetochlor (14%) plus bensulfuron methyl (4%) indicate that this herbicide regimen can take the place of time-consuming weeding in situations where labor is limited.

Conclusions and Recommendations

Effective weed management is a crucial aspect of ensuring successful rice cultivation. Farmers of Bangladesh mainly practiced manual, mechanical weeding and now habituating chemical to manage the weeds. Moreover, before making the final choice of any weed control method, farmers' available resources *e.g.,* labour, have to be considered. Overall, the findings underscore that early-season weed management, particularly with broad-spectrum, pre-emergence herbicide combinations play a decisive role in sustaining yield and profitability in DDSR. Manual weeding can be time-consuming and labor-intensive; however, chemical weed control methods offer a highly effective and economical alternative. Of the herbicides evaluated, a combination of acetochlor (14%) and bensulfuron methyl (4%) applied at 6 days after sowing (DAS) demonstrates significant efficacy and cost savings for managing weeds in dry, direct-seeded rice.

Acknowledgements

The authors thankfully acknowledge Bangladesh Agricultural University Research System (BAURES) for all kinds of logistic support to complete the research successfully.

Funding

The Ministry of Education, The Government of the People's Republic of Bangladesh through the grant number 'LS2019959'.

Novelty statement

This study provides the first systematic evaluation of newly registered pre- and post-emergence herbicides under dry direct seeded rice (DDSR) conditions in Bangladesh, where empirical evidence on herbicide performance has been lacking. Unlike previous research focused mainly on puddled transplanted rice systems, this work uniquely identifies the dominant weed flora in DDSR and quantifies herbicide specific impacts on weed density, biomass, weed control efficiency, grain yield, and profitability across two consecutive boro seasons. The findings highlight the superior efficacy of acetochlor (14%) + bensulfuron methyl (4%) which achieved complete weed suppression (100% WCE), maximized yield improvement, and delivered the highest economic returns. This research introduces as cost-effective and sustainable weed management strategy that can serve as a practical alternative to labor-intensive manual weeding, thereby supporting the wider adoption of DDSR for water- and labor-saving rice production in Bangladesh.

Author's Contributions

A.K.M. Mominul Islam: Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, visualization, supervision, project administration, funding acquisition.
Md. Parvez Anwar: Conceptualization, methodology, validation, resources, writing—review and editing, supervision, project administration, funding acquisition.
Israt Jahan: Formal analysis, investigation, data curation, writing—original draft preparation, visualization,
Tapon Kumar Roy: Writing—original draft preparation.
Sabina Yeasmin: Conceptualization, methodology, validation, writing—review and editing
Md. Masud Rana: Writing—original draft preparation, visualization,
Md. Moshiur Rahman: Methodology, validation,

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All authors have read and agreed to the published version of the manuscript.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors declare no conflicts of interest.

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