



RESEARCH ARTICLE

Influence of new-generation herbicide-based weed management on growth and yield of direct-seeded rice (*Oryza sativa* L.) under coastal Cauvery delta zone

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Abstract

The present investigation was conducted during the samba cropping seasons of 2023 and 2024 at the Department of Agronomy Experimental Farm, Annamalai University, to evaluate selected new-generation herbicides for weed control and productivity enhancement in direct-seeded rice (DSR) using the cultivar TKM 13. The field experiment comprised of 10 treatments arranged in a randomised block design (RBD) with 3 replications. Treatments represented integrated weed management strategies involving herbicide applications at pre-emergence (PE), early post-emergence (EPOE) and post-emergence (POE) stages, applied alone or with hand weeding. These were compared with a weedy check and manual weed control through hand weeding twice at 15 and 30 days after sowing (DAS). PE treatments included pretilachlor, pyrazosulfuron-ethyl and a ready-mix formulation of pretilachlor + pyrazosulfuron-ethyl followed by hand weeding at 15 DAS. EPOE treatments consisted of metsulfuron-methyl, bispyribac-sodium and triafamone + ethoxysulfuron, each supplemented with hand weeding, while an additional treatment involved metsulfuron-methyl + chlorimuron-ethyl followed by hand weeding at 30 DAS. POE weed control was achieved through application of 2,4-dichlorophenoxyacetic acid (2,4-D). All herbicide-based treatments significantly improved crop growth parameters such as plant height, leaf area index (LAI) and dry matter production, along with yield attributes including productive tillers, filled grains per panicle and yield, compared with the weedy check. Although hand weeding was effective, adoption is constrained by labour scarcity. Among chemical options, EPOE application of triafamone + ethoxysulfuron at 40 g a.i. ha⁻¹ followed by hand weeding at 30 DAS proved most effective for improving crop growth, yield attributes and yield under DSR conditions.

Keywords: direct-seeded rice; herbicide combinations; rice productivity; weed infestation

Introduction

Rice (*Oryza sativa* L.) is one of the world's most important food crops, supplying a major share of dietary energy to more than half of the global population and forming the backbone of food security across Asia, including India (1–4). In India, rice production reached a record level of 137.82 Mt during 2023–24, with an average productivity of 2.8 t ha⁻¹, whereas Tamil Nadu records comparatively higher yields of about 3.5 t ha⁻¹. Rice is cultivated under diverse agro-ecological conditions and weed flora composition and dynamics are strongly influenced by crop establishment methods and water availability. Traditionally, puddled transplanted rice has been the dominant cultivation system in Asia, where continuous flooding and soil puddling effectively suppress early weed emergence (5). However, this system is increasingly constrained by escalating labour costs, high water requirements and substantial energy inputs, particularly under conditions of declining groundwater resources and increasing climatic variability. These challenges have necessitated the exploration of alternative rice establishment methods that are resource-efficient and economically viable.

Under these circumstances, direct-seeded rice (DSR) has emerged as a promising alternative, offering significant savings in labour, water and production costs while ensuring timely crop establishment (6). Despite these advantages, the absence of standing water during early crop growth in DSR creates favourable conditions for the simultaneous emergence of crops and weeds, making weed infestation the most serious biotic constraint. Yield losses ranging from 45 % to 95 % have been reported in DSR when weeds are not effectively controlled, particularly during the early growth period when crop competitiveness is low (7). Although manual weeding at 20 and 40 days after sowing (DAS) is effective, its practical feasibility at the farm level in Tamil Nadu is increasingly constrained by acute labour scarcity, rising wage rates and untimely availability of labour during critical crop growth stages. Consequently, chemical weed management has become an integral component of DSR systems because weed pressure is severe during the early crop growth stages, when rice and weeds emerge simultaneously. Unlike transplanted rice, DSR lacks standing water to suppress weeds, leading to intense crop-weed competition. Chemical control provides timely, effective and economical weed

suppression, especially under labour scarcity, ensuring better crop establishment, resource use efficiency and yield stability. However, reliance on a single conventional herbicide often fails to provide adequate weed control due to diverse weed flora, staggered weed emergence patterns and the risk of herbicide resistance development (8). These limitations have necessitated a shift towards chemical-based integrated weed management strategies, involving the rational use of herbicides with different modes of action. In this context, sequential application of pre-emergence (PE) followed by early post-emergence (EPOE) herbicides, along with the use of premix or tank-mix formulations, has been shown to enhance weed control efficiency, expand the spectrum of weeds controlled and delay the development of herbicide resistance (9). In recent years, new-generation premixed herbicides have gained prominence in DSR, particularly in high-yielding varieties such as TKM 13. These formulations, containing active ingredients with complementary modes of action, provide effective control of grasses, sedges and broad-leaved weeds during critical crop growth stages. Compared to conventional herbicides applied individually, new-generation formulations offer improved selectivity, longer residual activity and superior weed suppression at lower application rates (10). By reducing early crop-weed competition, these herbicides enhance crop establishment, tillering, leaf area development and dry matter accumulation, ultimately contributing to higher yield potential. Furthermore, advancements in herbicide formulation technology, including improved solubility, stability and reduced active ingredient requirements, have enhanced efficacy while minimising crop phytotoxicity and environmental risks. When integrated with appropriate cultural practices such as optimum sowing methods and timely mechanical weeding, new-generation herbicides contribute to sustainable weed management in DSR systems. Thus, the adoption of DSR in combination with advanced herbicide formulations and suitable agronomic practices represents a sustainable, economically viable and climate-resilient strategy for enhancing rice productivity under emerging resource constraints.

Materials and Methods

Experimental site

A field experiment was conducted during the *Samba* seasons of 2023 and 2024 using the TKM 13 rice variety at Field A4, Experimental Farm, Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar, Tamil Nadu, India. The experimental location is situated at 11°24' N latitude and 79°44' E longitude, with an elevation of approximately 5.79 m above mean sea level. The region experiences a warm, humid tropical climate.

The experimental soil was classified as clay loam in texture, with an electrical conductivity of 0.89 dS m⁻¹ (measured in 1:2.5 soil-water suspension) and a slightly alkaline soil reaction (pH 8.0). Initial soil fertility analysis, carried out using standard procedures, indicated low available nitrogen (225 kg ha⁻¹, alkaline KMnO₄ method), medium available phosphorus (20.7 kg ha⁻¹, Olsen's method) and high available potassium (302 kg ha⁻¹, neutral normal ammonium acetate extraction). The soil organic carbon content was medium (0.02 %), estimated by the Walkley and Black wet oxidation method.

Climatic conditions

The climatic conditions prevailing during the experimental period are summarised to improve clarity. During the first year (2023), the weekly mean maximum and minimum temperatures ranged from 29.0 to 36.6 °C (mean 33.01 °C) and 19.0 to 23.8 °C (mean 21.57 °C), respectively. In the second year (2024), the corresponding maximum and minimum temperatures ranged from 28.6 to 37.2 °C (mean 32.90 °C) and 17.4 to 21.6 °C (mean 19.58 °C) respectively. Relative humidity varied between 64 % and 96 %, with mean values of 84.19 % in 2023 and 75.20 % in 2024. The total rainfall received during the *Samba* season was 983.3 mm in 2023 and 848.8 mm in 2024. Rainfall distribution was erratic in both years, with higher precipitation concentrated during the early crop growth period, which likely influenced weed emergence dynamics and the performance of applied herbicides.

Experimental treatments and design

The experiment consisted of 10 treatments laid out in a randomised block design (RBD) with 3 replications. To maintain a uniform plant stand, gap filling was carried out at 8 DAS. The treatment details are as follows:

T₁ – Pretilachlor 30 % emulsifiable concentrate (EC) 150 g a.i. ha⁻¹ on 3 DAS,

T₂ – Pyrazosulfuron ethyl 10 % wettable powder (WP) at 20 g a.i. ha⁻¹ on 3 DAS,

T₃ – Bisribac sodium 10 % suspension concentrate (SC) at 20 g a.i. ha⁻¹ on 14 DAS,

T₄ – Metsulfuron methyl 10 % WP at 4 g a.i. ha⁻¹ on 14 DAS,

T₅ – 2,4-Dichlorophenoxyacetic acid (2,4-D) sodium salt 80 % WP at 0.8 kg a.i. ha⁻¹ on 25 DAS,

T₆ – Triafamone 20 % + ethoxysulfuron 10 % water dispersible granules (WG) at 40 g a.i. ha⁻¹ on 14 DAS followed by hand weeding on 30 DAS,

T₇ – Pretilachlor 30 % at 150 g a.i. ha⁻¹ + pyrazosulfuron 0.75 % WG ethyl at 3.75 g a.i. ha⁻¹ on 3 DAS followed by hand weeding on 15 DAS,

T₈ – Metsulfuron methyl 10 % at 4 g a.i. ha⁻¹ + chlorimuron ethyl 10 % WP at 4 g a.i. ha⁻¹ on 14 DAS followed by hand weeding on 30 DAS,

T₉ – Two hand weeding (15 & 30 DAS),

T₁₀ – Weedy check.

To maintain a uniform plant stand, gap filling was performed at 8 DAS.

The crop received the recommended fertiliser dose of 120:40:40 kg N, P₂O₅ and K₂O per hectare. The statistical design used for research was RBD with 3 replications.

Herbicide application and weed control practices in DSR

Weed management in DSR was carried out through stage-wise herbicide applications, supported by manual weeding in relevant treatments. PE herbicides were uniformly sprayed at 3 DAS on moist soil to suppress the initial flush of weeds, followed by light irrigation to activate the herbicide. EPOE herbicides were applied between 12 and 15 DAS, coinciding with the early tillering stage of rice and the 2–3 leaf stage of weeds, using a calibrated knapsack sprayer fitted with a flat-fan nozzle at a spray volume of 500 L ha⁻¹

under optimum soil moisture conditions. POE herbicides, in relevant treatments, were applied at 20–25 DAS to control later-emerging weed flora. Irrigation was withheld for 24 hr before and after application. Manual weeding was carried out at 30 DAS in selected treatments to remove surviving weeds and to maintain weed-free conditions during critical crop growth stages. All herbicide applications were carried out by the same trained operator under calm weather conditions to ensure uniform spray coverage and to minimise spray drift.

Crop details

The rice variety TKM 13, a medium-duration (125–130 days) and high-yielding cultivar well adapted to the agro-climatic conditions of Tamil Nadu, was selected for this study. The variety exhibits stable performance under DSR.

Data collection and observations

Growth parameters (plant height, leaf area index (LAI) and dry matter production) and yield attributes (productive tillers, filled grains per panicle, grain yield and straw yield) final yields were assessed at the time of harvest. All observations were collected from a net plot area measuring 4.4 × 3.8 m.

Statistical analysis

The data collected were statistically analyzed by following standard procedures. Year-wise data were initially subjected to analysis of variance to test the significance of year and year × treatment interaction effects. As these effects were found to be non-significant, observations from both years were pooled for further analysis. Treatment effects were evaluated using analysis of variance (ANOVA) at a 5 % level of significance ($P \leq 0.05$). All statistical analyses were carried out using OPSTAT statistical software (CCS Haryana Agricultural University, Hisar, India). Observations from both years were pooled and treatment effects were evaluated using analysis of variance (ANOVA).

Results and Discussion

Growth attributes

Weed management practices significantly influenced rice growth attributes during both *Samba* seasons (2023 and 2024) (Table 1). Hand weeding performed at 15 and 30 DAS (T_9) resulted in the maximum plant height, higher number of tillers per hill, increased LAI and greater dry matter accumulation, indicating superior crop growth under effective weed control. At 25 DAS, the PE application of pretilachlor 30 % at 150 g a.i. ha^{-1} in combination with pyrazosulfuron 0.75 % WG at 3.75 g a.i. ha^{-1} applied at 3 DAS, along with hand weeding at 15 DAS, significantly improved plant height, LAI and dry matter production. The growth performance under this treatment was statistically comparable with hand weeding at 15 DAS, demonstrating efficient early-stage weed suppression and improved crop establishment. At 50 DAS and at harvest, the EPOE application of triafamone 20 % + ethoxysulfuron 10 % WG at 40 g a.i. ha^{-1} applied at 14 DAS, followed by hand weeding at 30 DAS (T_6), maintained higher plant height, LAI and crop dry matter accumulation by effectively controlling late-emerging weeds and enhancing the availability of growth resources during the later growth stages. This treatment remained statistically on par with hand weeding at 30 DAS, confirming its effectiveness in promoting sustained crop growth. Efficient weed management improved the growth of DSR by minimising crop-weed competition during the

critical early growth stages, thereby enhancing resource availability (nutrients, moisture and light) and leading to increased plant height, LAI and dry matter production (11). These growth attributes are closely associated with canopy development, photosynthetic efficiency and subsequent yield formation (12).

Hand weeding performed twice during the early vegetative to active tillering stage (15–30 DAS) produced superior growth responses by ensuring effective removal of weeds during the critical competition phase (13). Weed-free conditions allowed rice plants to utilise available resources more efficiently, resulting in enhanced nutrient uptake and biomass accumulation compared to weedy check plots (14).

Among herbicide treatments, the integrated weed management strategy involving triafamone + ethoxysulfuron at 40 g a.i. ha^{-1} followed by hand weeding at 30 DAS (T_6) produced growth responses comparable to manual weeding alone (15). Herbicide combinations with complementary modes of action effectively suppressed grasses, sedges and broad-leaved weeds during early crop growth, ensuring prolonged weed control and improved crop vigour (9). In contrast, uncontrolled weed growth significantly reduced plant height, LAI and dry matter accumulation due to severe competition for essential resources (16).

Yield attributes

In this study, weed management practices showed a significant influence on all major yield attributes of DSR during both years 2023 and 2024. Among the treatments evaluated, (T_9) hand weeding carried out at 15 and 30 DAS recorded the maximum number of productive tillers, grains per panicle and filled grains per panicle among all other treatments (Table 2). The superior yield performance observed under this treatment was due to the timely and effective removal of weeds during early tillering and panicle initiation, which are critical stages for yield formation.

Effective removal of weeds helped in maintaining a prolonged weed-free environment, thereby reducing competition for essential resources such as nutrients, soil moisture and solar radiation. This condition promoted better tiller initiation, higher tiller survival and effective panicle differentiation (17). According to earlier research, attaining greater tiller density and better panicle growth in DSR requires keeping the crop weed-free for the first 30 to 45 DAS (18, 19). Herbicide-based treatments performed similarly and were significantly better than the weedy check, even though hand weeding recorded the best yield attributes. Among the chemical treatments, EPOE application of triafamone + ethoxysulfuron at 40 g a.i. ha^{-1} followed by hand weeding at 30 DAS (T_6) showed superior performance and was statistically comparable to hand weeding at 30 DAS, resulting in significant improvement in yield parameters during both 2023 and 2024. The effectiveness of this treatment was attributed to the complementary modes of action of the premix herbicide. Both triafamone and ethoxysulfuron act as acetolactate synthase (ALS) inhibitors, disrupting the synthesis of branched-chain amino acids in weeds, leading to growth inhibition and eventual weed mortality. Triafamone effectively controls grassy weeds, while ethoxysulfuron targets sedges and broad-leaved weeds, ensuring broad-spectrum weed suppression during the early stages of crop growth. The timing of herbicide application in T_6 coincided with the active tillering stage, a phase when weed competition is most damaging. Effective weed control during this period reduced interspecific competition and improved nutrient uptake and

Table 1. Integration of new-generation herbicides on growth attributes of direct seeded rice (pooled data)

Treatments	Plant height (cm)			LAI		Dry matter production (kg ha ⁻¹)			
	25 DAS	50 DAS	At harvest	25 DAS	50 DAS	25 DAS	50 DAS	Harvest	Harvest
T ₁ – Pretilachlor 30 % EC 150 g a.i. ha ⁻¹ on 3 DAS	41.37	69.04	80.20	3.41	4.78	3168	5132	9239	9239
T ₂ – Pyrazosulfuron ethyl 10 % WP at 20 g a.i. ha ⁻¹ on 3 DAS	38.69	66.81	78.08	3.21	4.45	2953	4812	8816	8816
T ₃ – Bispybac sodium 10 % SC at 20 g a.i. ha ⁻¹ on 14 DAS	35.82	72.94	83.68	2.98	5.45	2746	5467	9689	9689
T ₄ – Metsulfuron methyl 10 % WP at 4 g a.i. ha ⁻¹ on 14 DAS	31.46	62.18	74.53	2.56	4.23	2324	4467	8356	8356
T ₅ – 2,4-D sodium salt 80 % WP at 0.8 kg a.i. ha ⁻¹ on 25 DAS	26.57	56.72	69.22	1.87	3.54	1890	4135	7906	7906
T ₆ Triafamone 20 % + ethoxysulfuron 10 % WG at 40 g a.i. ha ⁻¹ on 14 DAS followed by hand weeding on 30 DAS	43.72	84.31	93.71	3.62	6.66	3436	6461	10989	10989
T ₇ – Pretilachlor 30 % at 150 g a.i. ha ⁻¹ + pyrazosulfuron 0.75 % WG ethyl at 3.75 g a.i. ha ⁻¹ on 3 DAS followed by hand weeding on 15 DAS	46.60	76.82	87.08	3.82	5.87	3639	5811	10135	10135
T ₈ – Metsulfuron methyl 10 % at 4 g a.i. ha ⁻¹ + chlorimuron ethyl 10 % WP at 4 g a.i. ha ⁻¹ on 14 DAS followed by hand weeding on 30 DAS	41.37	80.62	90.42	2.79	6.26	3051	6137	10561	10561
T ₉ – Two hand weeding (15 & 30 DAS)	48.25	86.62	96.71	3.98	6.87	3789	6785	11389	11389
T ₁₀ – Weedy check	25.58	50.32	63.77	1.69	2.66	1754	3775	7256	7256
S.Ed	1.06	1.75	1.48	0.09	0.14	96.14	151.35	199	199
C.D. (p = 0.05)	2.23	3.69	3.12	0.18	0.32	202	318	420	420

Abbreviations: DAS: days after sowing; LAI: leaf area index; EC: emulsifiable concentrate; WP: wettable powder; SC: suspension concentrate; WG: water dispersible granules.

Table 2. Integration of new-generation herbicides on yield attributes of direct seeded rice (pooled data)

Treatments	No. of tillers hill ⁻¹	Number of productive tillers m ⁻²	Filled grains panicle ⁻¹	Test weight (g)
T ₁ – Pretilachlor 30 % EC 150 g a.i. ha ⁻¹ on 3 DAS	10.61	339	92.36	13.40
T ₂ – Pyrazosulfuron ethyl 10 % WP at 20 g a.i. ha ⁻¹ on 3 DAS	10.06	326	89.05	13.38
T ₃ – Bispybac sodium 10 % SC at 20 g a.i. ha ⁻¹ on 14 DAS	11.23	354	95.70	13.42
T ₄ – Metsulfuron methyl 10 % WP at 4 g a.i. ha ⁻¹ on 14 DAS	9.47	312	85.69	13.44
T ₅ – 2,4-D sodium salt 80 % WP at 0.8 kg a.i. ha ⁻¹ on 25 DAS	8.83	299	82.29	13.34
T ₆ Triafamone 20 % + ethoxysulfuron 10 % WG at 40 g a.i. ha ⁻¹ on 14 DAS followed by hand weeding on 30 DAS	12.96	397	105.68	13.49
T ₇ – Pretilachlor 30 % at 150 g a.i. ha ⁻¹ + pyrazosulfuron 0.75 % WG ethyl at 3.75 g a.i. ha ⁻¹ on 3 DAS followed by hand weeding on 15 DAS	12.38	383	102.35	13.46
T ₈ – Metsulfuron methyl 10 % at 4 g a.i. ha ⁻¹ + chlorimuron ethyl 10 % WP at 4 g a.i. ha ⁻¹ on 14 DAS followed by hand weeding on 30 DAS	11.83	369	99.03	13.43
T ₉ – Two hand weeding (15 & 30 DAS)	13.52	410	109.00	13.50
T ₁₀ – Weedy check	8.13	270	77.00	13.16
S. Ed	0.24	5.71	1.00	–
C.D. (p = 0.05)	0.54	12.0	2.12	NS

Abbreviations: DAS: days after sowing; EC: emulsifiable concentrate; WP: wettable powder; SC: suspension concentrate; WG: water dispersible granules.

assimilate accumulation, resulting in enhanced tiller production and better tiller retention (18). Continued weed suppression during panicle initiation further promoted efficient assimilate translocation towards reproductive structures, leading to higher numbers of grains and filled grains per panicle.

Similar improvements in yield attributes under ALS-inhibiting herbicide treatments have been reported in earlier studies (18, 19). Additionally, reduced weed pressure under T6 improved canopy structure and light interception, enhancing photosynthetic efficiency during the reproductive stage. Improved source-sink relationships during grain filling contributed to better grain set and reduced spikelet sterility, as also observed (20). Improved source-sink relationships during grain filling contributed to better grain set and reduced spikelet sterility, as also observed in earlier reports (21). In contrast, the weedy check T10 recorded the lowest values for all yield parameters due to severe weed infestation throughout the crop growth period. Intense competition for nutrients, moisture and light resulted in poor tiller establishment, increased tiller mortality, reduced panicle size and inferior grain filling, leading to substantial yield losses. Similar reductions under unweeded conditions in DSR have been widely documented (22). Overall, the findings in both years (2023–2024) demonstrate that effective, stage-specific weed management is the key determinant of improved yield attributes in DSR. While manual weeding ensured maximum weed suppression, the integration of new-generation herbicide premixes with limited mechanical intervention provided comparable benefits by efficiently controlling diverse weed flora, reducing early-season competition and enhancing yield formation with reduced labour dependency.

Yield

The pivotal role of effective weed management in enhancing grain and straw yields of DSR is illustrated in Fig. 1. Among the treatments evaluated, hand weeding twice T₉ proved to be the most effective practice, recording the highest grain yield (5080 kg ha⁻¹) and straw yield (7472 kg ha⁻¹). The superior performance of this treatment can be attributed to sustained weed suppression throughout the critical crop growth stages, particularly during early establishment and tillering. Maintaining a weed-free environment during these stages reduces interspecific

competition, enabling the rice crops to utilise available nutrients, moisture and light more efficiently (23). This ultimately promotes better root proliferation, higher LAI and enhanced photosynthetic activity during the reproductive phase, resulting in improved yield components and final productivity. These findings agree with earlier reports which emphasise that keeping rice fields weed-free during the critical period of crop-weed competition (15–45 DAS) significantly enhances crop growth and yield (24).

Manual weeding, although labor-intensive, remains one of the most effective methods for controlling diverse weed flora in DSR systems, particularly where herbicide escapes or resistant weeds are prevalent (25). Closely following hand weeding twice, the EPOE herbicide treatment T6 involving triafamone + ethoxysulfuron at 40 g a.i. ha⁻¹ followed by hand weeding at 30 DAS also recorded significantly higher grain and straw yields compared to other chemical treatments and the weedy check. The effectiveness of this integrated approach lies in its ability to suppress early weed flushes during the most sensitive phase of crop establishment and tiller initiation. Early reduction in weed density and biomass between 10 and 30 DAS minimises competition for growth resources, thereby allowing the rice plants to develop a higher number of productive tillers, larger panicles and improved grain filling. The present results corroborate the findings that the combined application of triafamone + ethoxysulfuron followed by manual weeding resulted in crop growth and yield parameters comparable to, or even exceeding, those obtained under conventional hand-weeding practices (26). Similar observations have also highlighted that integrating EPOE herbicides with limited manual weeding offers an effective and economically viable alternative to repeated hand weeding in DSR (27, 28).

Overall, the study underscores that while hand weeding twice remains the most effective weed management practice, integrated strategies combining EPOE herbicides with a single hand weeding can provide comparable yield benefits. Such approaches not only ensure effective weed control during the critical growth stages but also help reduce labor dependency, making them more suitable for large-scale adoption in DSR cultivation.

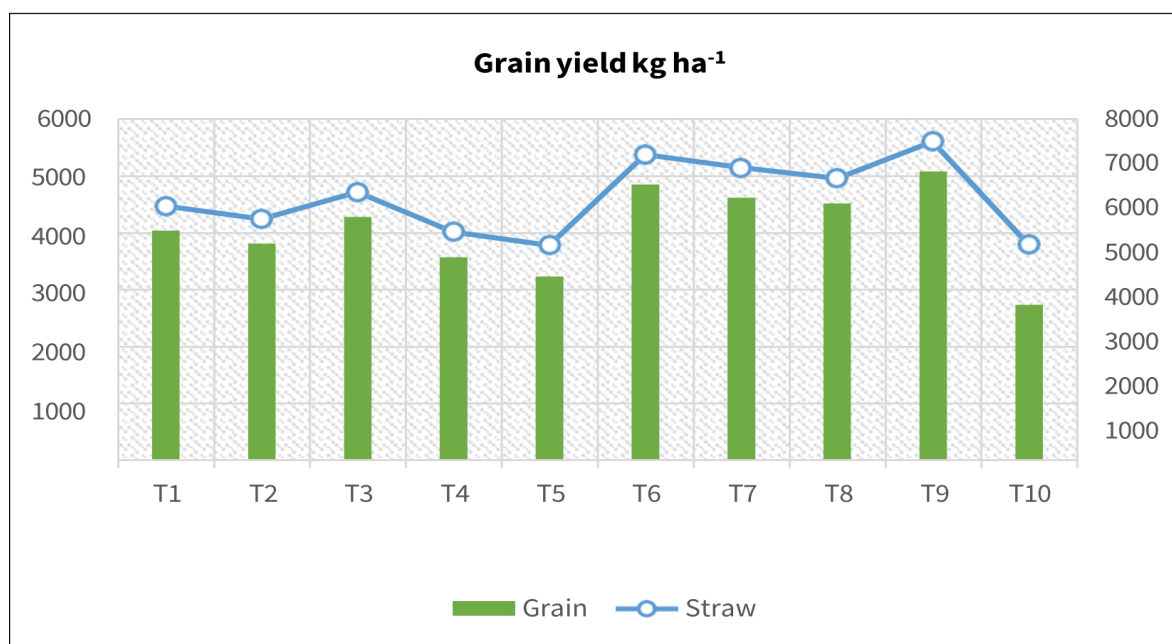


Fig. 1. Influence of new-generation herbicides on grain yield and straw yield increase over weedy check plot during 2023 and 2024.

Conclusion

The pooled results of the 2-year study highlight the critical role of timely weed management in enhancing growth and productivity of DSR. Although hand weeding twice at 15 and 30 DAS ensured effective weed control and maximum yields, its adoption is limited by high labour demand and cost. In contrast, EPOE application of triafamone + ethoxysulfuron at 40 g a.i. ha⁻¹ followed by a single hand weeding at 30 DAS provided effective broad-spectrum weed control during the critical growth period, resulting in yields comparable to manual weeding with reduced labour dependence. Consequently, integrating new-generation herbicide premixes with minimal mechanical intervention offers a practical and sustainable weed management strategy for DSR under labour-scarce conditions.

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Authors' contributions

VTM conceptualised the research, designed and conducted the field experiments, analysed the data and prepared the initial draft of the manuscript. PS provided overall supervision and key intellectual contributions to experimental design and results interpretation. SK and SM assisted in experiment planning, data analysis and manuscript review. KD offered technical guidance, performed critical revisions and finalised the editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used “Grammarly” in order to improve language for readability. After using this tool/service, authors carefully reviewed and edited the content as required and takes full responsibility for the content of the publication.

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