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Dual-stage herbicide regimen for tackling weed menace in wheat under multiple crop establishment systems

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Transitioning to maize–wheat system (MWS) in conjunction with conservation agriculture has emerged as viable option to tackle the multiple challenges of yield stagnation, environmental threats, and resource depletion under conventional puddled-transplanted rice–wheat rotation in Indo-Gangetic Plains (IGP). However, efficient weed management and crop establishment strategies are critical to sustaining crop and resource productivity of MWS. To develop weed management options under diverse tillage systems, three crop establishment methods *viz.* elevated-bed + residue (EBRC), double zero-tillage + residue (DZRC), and conventional intensive tillage + residue (ITRI) in main plots and five weed management approaches, namely, pyroxasulfone (pyro; Pre-Emergence), Pyro (PE) fb metsulfuron + carfentrazone (MetCarf; Post-Emergence), sulfosulfuron + metsulfuron (SulfoMet; Post-Emergence), unweeded check (UWC), and weed-free check (WFC), were compared in a split-plot design. Reduced weed population and dry matter accumulation were noted with EBRC, relative to DZRC and ITRI. The growth and productivity of wheat remained higher in EBRC compared to DZRC, but it was at par to ITRI. Among diverse weed management options, dual-stage spray of Pyro–MetCarf substantially reduced the densities of sedges (36.7%), and narrow-leaved (64.1%) and broad-leaved (58.9%) weeds, compared to the UWC. Significantly higher weed control efficiency (80.3%), weed control index (79.4%), and lowest weed index were observed under Pyro–MetCarf combination compared to other herbicidal treatments. The same treatment also enhanced the wheat growth and yield (24.6%) over UWC and other herbicide applications. Conclusively, dual-stage herbicidal application of Pyro–MetCarf coupled with EBRC enhances wheat productivity by reducing the infestation of weeds substantially in IGP. The findings suggest that integrating dual-stage herbicidal application with EBRC offers a scalable and resource-efficient strategy for policymakers and practitioners for the wheat belt of IGP.

KEYWORDS

conservation agriculture, elevated bed planting, weed management, residue, zero tillage

1 Introduction

Wheat [*Triticum aestivum* (L.) emend Fiori & Paol] is the leading staple crop of the world grown over 215.9 mha area with production of 790.8 million tons and productivity of 3.54 t ha^{-1} (USDA, FAS, 2024). Globally, wheat is consumed by ∼2.5 billion people across ∼90 countries (CGIAR, 2020), with annual trade volumes of 207.3 million tons (USDA, 2024) and an estimated global trade value of approximately US $59 billion (IMF, 2024). In India, wheat accounts for 36% of its total foodgrain production, contributing 20% to the nation's protein intake and 19% to calorie consumption (Ramadas et al., 2019). Covering 31.4 million hectares, the largest wheat acreage globally, India produces ∼110.5 million tons of wheat, with a productivity of 3.52 t ha^{-1} (Annual Report, 2023-24, DFAFW, GOI).

Majority of wheat in South Asia is cultivated under cereal–cereal (after rice, maize, sorghum or pearl millet) rotation, with rice–wheat system (RWS) being the principal production system, covering more than one-third of the wheat acreage (Dhanda et al., 2022). Intensive tillage practices in prolonged RWS resulted in large-scale poor soil physical conditions, breaking down aggregates and creating hard pans (Kumari et al., 2011; Mondal et al., 2019), and hastening the degradation of organic matter (Lal, 2015; Roper et al., 2013; Das et al., 2014), in addition to environmental and water-related challenges. Present intensive-tillage practices transform soil into a source of atmospheric pollutants rather than a sink, threatening ecological and economic sustainability (Busari et al., 2015). In addition, the conventional crop establishment systems necessitate more labor and higher energy inputs and escalate production costs (Das et al., 2020; Kaur et al., 2020, 2023).

Diversifying the RWS with a more stable maize–wheat system (MWS) is a suggested pathway to address key soil, water, and environmental challenges associated with RWS (Bana et al., 2014; Yin et al., 2018; Venkatesh et al., 2017). Furthermore, conservation agriculture (CA) serves as a vital sustainable strategy for resource conservation, mitigating the adverse effects of climate change and enhancing profitability (Das et al., 2014). This crop establishment system also improves input use efficiency, sustains long-term productivity, and promotes carbon sequestration (Bhattacharyya et al., 2015; Sharma et al., 2012; Sharma, 2021). The CA with system diversification provides multiple benefits, including reducing soil erosion (Page et al., 2013), maintaining soil organic matter (Bhattacharyya et al., 2015; Lal, 2015; Qi et al., 2022), controlling weed growth (Baghel et al., 2020), retaining soil moisture, preventing soil compaction (Mondal et al., 2019), improving soil structure (Mondal et al., 2019; Qi et al., 2022), and enhancing both above- and below-ground biological processes and biodiversity (Ghosh et al., 2019).

Despite various challenges to the productivity, profitability, and sustainability of MWS, weeds remain a major obstacle due to their strong competition with crops for essential resources. Several studies reported differential losses owing to weed infestation in wheat crop ranging from 24.5% to as high as 55.7% (Kumar et al., 2013; Malik and Yadav, 2008; Kaur et al., 2017; Yadav et al., 2018) and nutrient loss due to weeds varies from 30 to 40% (Mundra et al., 2002). The presence of weeds diminishes the photosynthetic efficiency and photosynthate partitioning to the economical parts and thereby lowering sink capacity leading to poor and unstable yields (McKenzie-Gopsill et al., 2020). Critical period for weed control depends on the density, competitiveness, and emergence periodicity of the weed population (Das, 2008; Evans et al., 2003 and Bystro et al., 2012).

However, as tillage operations are enormously reduced in CA, weed infestation can become a prime limiting factor in crop production, particularly during early years of CA adoption (FAO, 2020; Bana et al., 2020). Overcoming these challenges necessitates a comprehensive weed management approach, incorporating zero tillage, soil residue coverage, diverse crop rotations, and the strategic application of herbicides. Being a rapid, more effective, time- and labor-saving option, chemical weed management is the most widely adopted method by the farmers (Nazari et al., 2013; Mehmeti et al., 2018). Despite the availability of numerous herbicides, no single herbicide has proven effective in managing the diverse weed flora present in arable crops. Moreover, the repeated use of a single herbicide, such as isoproturon, over the years has led to the development of herbicide resistance in *Phalaris minor* (due to target site resistance mutation in psbA gene) and several other grassy weeds in the IGP. Such scenario underscores the urgent need to identify novel herbicide molecules capable of providing season-long effective and sustainable weed control. Studies conducted by earlier researchers in USA, Canada, Australia, South Africa, and India opined that pre-emergence herbicide pyroxasulfone resulted in satisfactory weed control in maize (Odero and Wright, 2013; Kumar et al., 2021) and wheat (Kaur et al., 2019; Kumar and Kaur, 2024). However, there are reports of late-season weed infestation. Therefore, a dual-stage spray strategy of a combination of pre- and post-emergence herbicides application is obligatory for the effective management of multiple weed flora for season-long weed management in wheat.

This holistic approach is essential for mitigating weed interference and minimizing crop yield losses during the transitioning years of conservation agriculture (CA). Nevertheless, comparatively limited research has been conducted to examine the interactive effects of crop establishment methods, such as elevated-bed planting, residue recycling options, and tillage, in combination with strategic herbicide applications. Furthermore, category-wise (narrow leaved weeds, broad-leaved weeds, and sedges) and species-wise insights on weed dynamics under diverse herbicide–tillage–residue–year interactions have not been studied so far. To address this knowledge gap, the present study was undertaken to evaluate the impact of diverse crop establishment systems, residue recycling, and strategic herbicide application options on species-wise and category-wise weed dynamics and crop performance. Moreover, the experimentation also aimed to assess the combined and individual effects of study years, crop establishment systems, and herbicide applications on weed control efficacy, weed index, and crop productivity. We hypothesized that integrating CA-based crop establishment methods with use of dual-stage broad spectrum herbicide use will significantly reduce weed infestation while enhancing wheat productivity in the maize–wheat system, offering a sustainable alternative to conventional practices.

2 Materials and methods

2.1 Experimental sites and treatments

The experiment was conducted at the ICAR-Indian Agricultural Research Institute, New Delhi (28°64′ N latitude, 77°15′ E longitude, and an altitude of 228 meters above mean sea level) under triplicated split-plot design during the winter (*rabi*) seasons of 2021–22 and 2022–23. The main-plot treatments comprised of different crop establishment systems, while the sub-plot treatments included five weed management strategies (Table 1). The wheat crop was sown following the harvest of the preceding maize crop, maintaining a maize–wheat cropping system consistently applied on the experimental site for the past 5 years. Among the weed management treatments, the unweeded check (UWC) served as a control, allowing natural weed infestation without any intervention. The experimental field featured sandy loam soil (sand 58.6%, silt 22.8%, and clay 18.6%) with moderate water-holding capacity, an even topography, and a well-functioning drainage system. Soil analysis of the upper 150 mm layer revealed low organic carbon content (0.41%), low available nitrogen (221.3 kg ha^{-1}), medium levels of available phosphorus (18 kg ha^{-1}) and potassium (241.1 kg ha^{-1}), and a slightly alkaline reaction (pH 7.8).

The climatic conditions varied significantly during the 2 years of the study period (Figure 1). In the first year, higher rainfall was recorded during the early stages of crop growth, while the later stages experienced relatively lower rainfall. Conversely, in the second year, the rainfall was more pronounced during the later stages of crop ontogeny. Temperature trends also differed between the years, as a sudden rise in temperature was observed during the grain-filling stage of 2021–22, which contrasted with the second year, where temperatures during this critical stage remained fairly stable.

TABLE 1 Treatment details adopted in the experiment.

Treatments	Treatment abbreviations
Main plot (crop establishment systems)	
Elevated-bed + 3 t ha^{-1} residue-covered soil (M1)	EBRC
Double zero-tillage + 3 t ha^{-1} residue-covered soil (M2)	DZRC
Intensive tillage + 3 t ha^{-1} residue incorporation (M3)	ITRI
Sub-plot (weed management options)	
Pyroxasulfone 85WG at 0.15 kg/ha (pre-emergence) (S1)	Pyro
Pyroxasulfone at 0.15 kg/ha (pre-emergence) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (post-emergence) (S2)	Pyro–MetCarf
Sulfosulfuron + metsulfuron at 0.04 kg/ha (post-emergence) (S3)	SulfoMet
Unweeded check (S4)	UWC
Weed-free check (S5)	WFC

Pyroxasulfone ($C_{12}H_{14}F_5N_3O_4S$), metsulfuron methyl ($C_{14}H_15N_5O6S$), carfentrazone ethyl ($C_{15}H_{14}Cl_2F_3N_3O_3$), and sulfosulfuron ($C_{16}H_{18}N_6O_7S_2$).

2.2 Crop management practices

Wheat crop was sown in rows spaced 22.5 cm apart during both years of the study. For EBRC treatment, an elevated-bed planter was used (67.5 cm top and 30 cm furrow). Three rows of wheat variety "HD-3226" were sown on each bed keeping a row-to-row spacing of 22.5 cm using 100 kg seed ha^{-1} to ensure an optimal plant population. Prior to sowing, the seeds were treated with the carbendazim at 2 g kg^{-1} of seed to prevent fungal infections. The recommended fertilizer application of 150 kg N ha^{-1}, 60 kg P_2O5 ha^{-1}, and 40 kg K_2O ha^{-1} was done through urea, di-ammonium phosphate, and muriate of potash, respectively. Full doses of phosphorus and potassium, along with one third dose of the nitrogen, were applied at the time of sowing. The remaining nitrogen was top-dressed in two equal splits, once at the active vegetative stage (40 days after sowing, DAS) and second at the flowering stage (80 DAS). Herbicides were applied at recommended doses at 2 days after sowing as pre-emergence and 25 days after sowing as post-emergence for effective control of weeds.

2.3 Weed dynamics

A quadrat measuring 0.5 m × 0.5 m was thrown randomly at four different locations within each plot for sampling at 40 DAS, and weeds were counted species-wise, and collected and categorized into sedges, and narrow-leaved and broad-leaved weeds, which were later summed up as total number of weeds. After air drying, the categorized weed species were dried in oven at a temperature of 65°C for 48 h to record the dry matter accumulation by different weed flora. Moreover, the different indices of weeds were calculated to evaluate the efficiency of different herbicides. These indices are mentioned as follows:

2.3.1 Weed index (WI)

The weed index (WI) was calculated for quantifying reduction in wheat productivity across studied herbicidal weed management strategies, relative to WFC. To estimate WI, Equation 1 was used (Gill and Vijaykumar, 1969).

$$WI(\%) = \frac{Y_{WF} - Y_T}{Y_{WF}} \times 100 \quad (1)$$

where Y_{WF} is the wheat productivity (t ha^{-1}) in WFC, and Y_T is the wheat productivity (t ha^{-1}) in treated plot.

2.3.2 Weed control efficiency

As per Equation 2, weed control efficiency (WCE) was calculated to assess the efficacy of various weed control treatments based on their effect on weed control (Das, 2008):

$$WCE(\%) = \frac{WP_C - WP_T}{WP_C} \times 100 \quad (2)$$

where WP_C is weed population (No. m^{-2}) in UWC plot, and WP_T is weed population (No. m^{-2}) in herbicide applied plot.

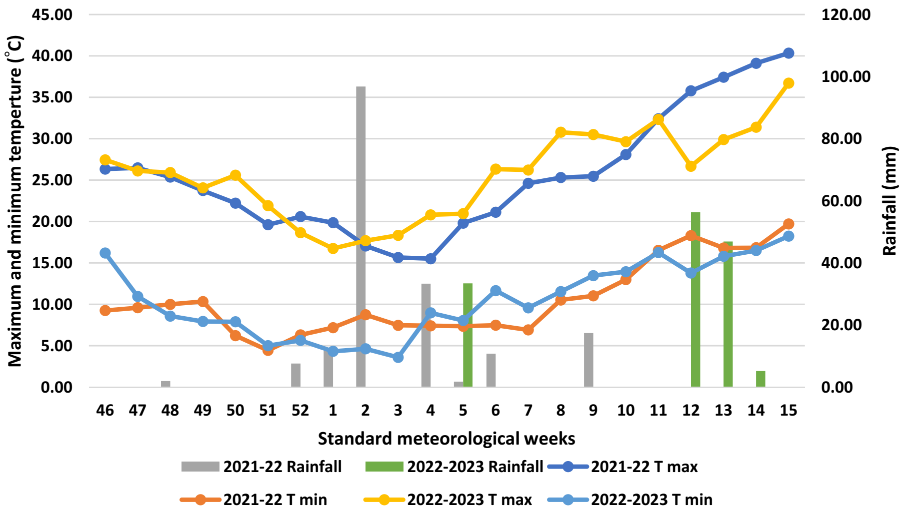

FIGURE 1
Standard meteorological weeks during experimentations.

2.3.3 Weed control index

Weed control index (WCI) was computed as per the Equation 3 to analyze the comparability of the efficacy of various treatments based on dry weight (Das, 2008).

$$\text{WCI}(\%) = \frac{WDM_C - WDM_T}{WDM_C} \times 100 \quad (3)$$

where WDM_C is the oven-dried weight of weeds (g m^{-2}) in UWC, and WDM_T is the oven-dried weight of weeds (g m^{-2}) in herbicide applied plot.

2.4 Growth and yield parameters

Numerous growth indices, such as leaf area index (LAI), crop growth rate (CGR), relative growth rate (RGR), and net assimilation rate (NAR), were computed using the following standard equations:

2.4.1 Leaf area index (LAI)

The leaf area index (LAI) was measured using a leaf area meter (LI COR-3100) at regular interval in the crop. The leaf area index (LAI) was calculated by dividing total leaf area by land area using the formula given by Watson (1952).

$$\text{LAI} = \frac{Total\ LeafArea\ (sq.cm.)}{Total\ ground\ area\ (sq.cm).} \quad (4)$$

2.4.2 Crop growth rate

The crop growth rate was worked out following the Equation 5 (Watson, 1958).

$$\text{CGR}(\text{gm}^{-2}\text{day}^{-1}) = \frac{W2 - W1}{T2 - T1} \times \frac{1}{P} \quad (5)$$

where W_1 and W_2 are dry weight (g) of wheat plants at time T_1 (0 days) and T_2 (40 DAS), respectively. T_1 and T_2 are the growth stages of wheat; P is land area (m^2) occupied by number of tillers under sampling.

2.4.3 Mean relative growth rate [RGR; mg g^{-1} (dry matter) day^{-1}]

The mean relative growth rate was worked out using the Equation 6 (Blackman, 1919):

$$RGR = \frac{\text{LnW2} - \text{LnW1}}{T2 - T1} \quad (6)$$

where W_1 and W_2 are plants dry weight (g) at time T_1 and T_2, respectively. T_1 and T_2 are wheat growth stages. Ln is natural logarithm.

2.4.4 Mean net assimilation rate [NAR, g m^{-2} (leaf area) day^{-1}]

Equation 7 was used for computing mean net assimilation rate (Gregory, 1917).

$$\text{NAR} = \frac{W2 - W1}{LA2 - LA1} \times \frac{LnLA2 - LnLA1}{T2 - T1} \quad (7)$$

where W_1 and W_2 are plants dry weight (g) at time T_1 and T_2, respectively; T_1 and T_2 are growth stages of crop. Ln is natural logarithm; LA_1 and LA_2 are the leaf area (m^{-2}) of plants at time T_1 and T_2, respectively.

Dry matter accumulation (g m^{-2}) in wheat was determined using a destructive sampling technique. Plant samples were collected from 1 m^2 area, air-dried for 2–3 days, and then oven-dried at 105°C for 48 h. Yield attributes such as ear length and the number of seeds per ear were recorded manually from 10 randomly selected representative ears per plot in each replication. Grain yield and biological yield (grain + straw) were estimated based on the net plot area (5 m × 4 m) under each treatment, adjusted to moisture contents of 12.5% and 18%, respectively.

2.5 Statistical analysis

Data on weeds and wheat crop were analyzed by the analysis of variance (ANOVA) technique for a split-plot design using PROC GLM in SAS 9.3 (SAS Institute, Cary, NC). Weed populations were transformed through the square-root transformation method $[(x + 0.5)^{½}]$ before ANOVA to reduce higher variation and for more precision. The species-wise populations of weeds, wheat grain yield, were subjected to Levene's test for homogeneity of variance. The error variances for almost all parameters (i.e., weed and wheat grain yield) were homogeneous over the years, indicating that the uniformity in error variance was significant. The significance of treatment means was appraised using Tukey's honest significant difference (HSD) test at $p \leq 0.05$. The genotype + genotype by environment (GGE) biplot analysis was carried out to determine the effects of treatment combinations in controlling the weed population across both the years (Yan and Kang, 2011).

3 Results

3.1 Weed dynamics

The predominant weed flora at the experimental site consisted of two narrow-leaved weed (NLW) species, four broad-leaved weed (BLW) species, and sedges, as detailed in Table 2. A pooled ANOVA over 2 years revealed 3.6% lower *Chenopodium murale* population in the second year compared to the first year of investigation. However, the densities of other weed species showed no statistically significant variation between the 2 years.

Across different crop establishment systems (Table 2), densities of *Phalaris minor*, *Avena ludoviciana*, and *Coronopus didymus* were 11.8, 10.8, and 11.0% lower under the elevated-bed system (EBRC) compared to double zero-tillage (DZRC), respectively. The densities of *A. ludoviciana* and *Chenopodium album* were statistically comparable between EBRC and conventional intensive tillage with residue incorporation (ITRI) treatments. No significant differences were noticed in the populations of *Anagallis arvensis* and *Medicago indica* across the crop establishment systems.

Among weed management options, the lowest populations of four dominant BLW species, namely, *C. didymus*, *C. album*, *C. murale*, and *M. indica,* were recorded under treatment WFC, followed by Pyro-MetCarf, while the population densities of two major narrow-leaved weed species, namely, *P. minor* and *A. ludoviciana*, were 67.6% and 46.5% lesser in WFC compared to SulfoMet, respectively, although the differences between WFC and Pyro-MetCarf treatments were non-significant. Furthermore, the

TABLE 2 Species-wise density of weeds as influenced by crop establishment methods and weed management options (pooled data of 2 years) [data are square-root transformed $(x + 0.5)^{1/2}$]*.

Treatments	*Phalaris minor*	*Avena ludoviciana*	*Anagallis arvensis*	*Coronopus didymus*	*Chenopodium album*	*Chenopodium murale*	*Medicago indica*
Year							
2021–22	1.12[a]	1.15[a]	1.16[a]	1.36[a]	1.31[a]	1.74[a]	1.34[a]
2022–23	1.10[a]	1.15[a]	1.13[a]	1.33[a]	1.29[a]	1.68[b]	1.30[a]
Crop establishment methods (C)							
EBRC	1.02[b]	1.11[b]	1.06[a]	1.27[b]	1.19[a]	1.57[b]	1.28[a]
DZRC	1.14[a]	1.23[a]	1.19[a]	1.41[a]	1.36[a]	1.73[a]	1.33[a]
ITRI	1.17[a]	1.11[b]	1.18[a]	1.35[ab]	1.35[a]	1.84[a]	1.35[a]
Weed management options (W)							
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	0.93[c]	1.05[b]	0.99[b]	1.37[b]	1.28[c]	1.66[b]	1.19[b]
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	0.71[d]	0.93[c]	0.82[dc]	0.90[d]	1.07[d]	1.59[b]	0.90[c]
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	1.19[b]	1.04[b]	0.92[bc]	1.19[c]	1.50[b]	1.95[b]	1.29[b]
Unweeded check	2.01[a]	2.23[a]	2.28[a]	2.55[a]	1.95[a]	2.66[a]	2.52[a]
Weed-free check	0.71[d]	0.71[c]	0.71[d]	0.71[e]	0.75[e]	0.71[c]	0.71[d]

*Transformed data through square-root $(x + 0.5)^{½}$ method before analysis of variance (ANOVA); within a column, the means followed by different lowercase letters are significantly different at a *p*-value of ≤0.05 as per Tukey's HSD test. EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

TABLE 3 Category-wise density of weeds as influenced by crop establishment methods and weed management options (pooled data of 2 years) at 40 DAS (number m^{-2})*.

Treatments	NLWs	BLWs	Sedges	Total
Years (Y)				
2021–22	1.51^{a}	2.41^{a}	2.26^{a}	3.46^{a}
2022–23	1.36^{b}	2.33^{b}	2.12^{b}	3.26^{b}
Crop establishment methods (C)*				
EBRC	1.35^{a}	2.26^{b}	2.00^{b}	3.12^{b}
DZRC	1.47^{a}	2.42^{a}	2.26^{a}	3.46^{a}
ITRI	1.49^{a}	2.43^{a}	2.31^{a}	3.49^{a}
Weed management options (W)				
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	1.20^{c}	2.36^{b}	2.18^{c}	3.30^{c}
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	0.98^{d}	1.83^{c}	2.12^{c}	2.82^{d}
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	1.56^{b}	2.50^{b}	2.59^{b}	3.82^{b}
Unweeded check	2.73^{a}	4.45^{a}	3.35^{a}	6.14^{a}
Weed-free check	0.71^{e}	0.71^{d}	0.71^{d}	0.71^{e}

*Transformed data through square-root (x + 0.5)^{½} method before analysis of variance (ANOVA); within a column, the means followed by different lowercase letters are significantly different at a *p*-value of ≤0.05 as per Tukey's HSD test. NLWs, narrow leaf weeds; BLWs, broad leaf weeds; EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

TABLE 4 Category-wise dry matter of weeds as influenced by crop establishment methods and weed management options (pooled data of 2 years) at 40 DAS (g m^{-2})*.

Treatments	NLWs	BLWs	Sedges
Years (Y)			
2021–22	1.10^{a}	1.57^{a}	1.12^{a}
2022–23	1.03^{a}	1.56^{a}	1.11^{a}
Crop establishment methods (C)*			
EBRC	1.04^{a}	1.54^{a}	1.11^{a}
DZRC	1.08^{a}	1.58^{a}	1.12^{a}
ITRI	1.07^{a}	1.58^{a}	1.12^{a}
Weed management options (W)			
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	0.94^{c}	1.53^{b}	1.18^{bc}
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	0.85^{d}	1.34^{c}	1.12^{c}
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	1.09^{b}	1.58^{b}	1.21^{b}
Unweeded check	1.74^{a}	2.67^{a}	1.34^{a}
Weed-free check	0.71^{e}	0.71^{d}	0.71^{d}

*Transformed data through square-root (x + 0.5)^{½} method before analysis of variance (ANOVA); within a column, the means followed by different lowercase letters are significantly different at a *p*-value of ≤0.05 as per Tukey's HSD test. NLWs, narrow leaf weeds; BLWs, broad leaf weeds; EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

sequential application of Pyro-MetCarf consistently resulted in the lowest populations of *P. minor*, *A. ludoviciana*, *C. didymus*, *C. album*, *C. murale*, and *M. indica*, compared to standalone applications of Pyro or SulfoMet.

The category-wise weed density (Table 3) was significantly influenced by the year, crop establishment system, weed management options, and their interactions. In the second year of experimentation, the overall densities of NLWs (11.0 %), BLWs (3.4%), sedges (6.6%), and total weeds (6.1%) were significantly lower compared to the first year. Similarly, among the crop establishment systems, EBRC showed lower densities of BLWs (7.1%), sedges (11.5 %), and total weeds (10.9%) compared to DZRC. Contrarily, non-significant differences were observed in NLW population across the crop establishment systems. The Pyro-MetCarf treatment reduced the NLW, BLW, and sedges density by 178%, 143.2%, and 58% as compared to UWC, respectively. However, the best treatment was WFC, and it remained statistically superior to all other treatments. Notably, for controlling sedges population, Pyro alone and pyro-MetCarf were statistically at par. The Pyro-MetCarf treatment remained at par to WFC for controlling diverse weed flora.

For weed dry matter (Table 4), no significant differences were observed due to the years and crop establishment systems. However, numerically, the lowest total weed dry matter and dry matter of NLWs, BLWs, and sedges were recorded in the EBRC, compared to DZRC and ITRI. The weed-free check (WFC) exhibited the lowest dry matter accumulation (Tables 3, 4) among all treatments. Dual-stage spray treatment of Pyro-MetCarf resulted in the lowest dry matter of NLWs, BLWs, sedges, and total weeds, outperforming other herbicidal treatments. However, the WFC had resulted in lowest weed dry matter accumulation. The interaction effects for main plot × subplot (C × W), year × main plot (Y × C), and year × main plot × subplot (Y × C × W) were found to be non-significant.

Both weed control efficiency (WCE; 66.3%) and weed control index (WCI; 67%) were significantly higher during the first year of experimentation compared to the second year (60.6 and 60.3%, respectively). However, no significant differences in WCE and WCI were observed among the various crop establishment systems (Table 5). Among weed management options, the WFC achieved the highest WCE and WCI. However, out of the herbicidal treatments, the application of Pyro-MetCarf resulted in significantly higher WCE (80.3%) and WCI (79.4%), followed by sole pre-emergence application of Pyro, which recorded 72.7% WCE and 71.9% WCI. The next best treatment was SulfoMet, with WCE and WCI values of 64.3% and 66.95%, respectively.

3.2 Species diversity GGE biplot analysis

To have greater insights in interactive effects, four patterns of GGE biplot *viz.* "which won where/what," "mean vs. stability," "ranking genotypes," and "ranking environments" have been generated for weed density to identify best treatments, dominant weed species under specific treatments, average control of weed population, prevalent weed species, and best treatment combination for controlling weeds.

3.2.1 Which-won-where

Figure 2a depicts the which-won-where view of different population of weeds under various treatments. The total variation of 88.87% was captured by both principal components (PC) accounting 59.38% and 29.49% by PC1 and PC2, respectively. The polygon was divided into five sectors by six rays forming two major mega environments. The populations of *P. minor*, *R. dentatus*, *A. arvensis*, and *C. didymus* were in the vertices of each sectors indicating highest population in their distinctive mega-environment. The population of *P. minor* was not favored under any of the mega-environments and was in a different sector indicating distinctive performance irrespective of the environment (year × treatment). *C. album* was more favored under M3S3 treatment combination, whereas M3S3 situated farther from origin thus indicating higher discriminating ability. *R. dentatus* was more favored under M1S1, M1S2, M1S3, M2S1, M2S2, M2S3, and M3S2 treatment combinations. The population of *C. didymus* and *M. alba* was favored by M1S4, M2S4, and M3S4 combinations. The weeds were not favored by environments M1S5, M2S5, and M3S5 being situated at the origin.

3.2.2 Mean vs. stability

Figure 2b represents the mean performance of weed population across different treatments and stability among the weeds. It was observed that higher than the average population of weeds was recorded for *R. dentatus*, *C. album*, and *P. minor* with *R. dentatus* being situated at right side, whereas *A. ludoviciana*, *A. arvensis*, *M. alba*, and *C. didymus* were recorded lower population than average. Furthermore, *P. minor* recorded higher stability in terms of population across all the treatments indicated by lowest projection from AEC, indicating its more frequent presence in all the treatment combinations. *A. ludoviciana* and *A. arvensis* recorded lower population than the average population and also similar in stability in population under all treatments.

3.2.3 Ranking genotypes

No genotypes (here species) were observed within the concentric circle indicating the treatments significantly reduced the population of all weed species. *P. minor* being situated farthest from the concentric circle indicating lowest population (Figure 2c). The genotypes can be ranked in descending order as *R. dentatus* >*C. didymus*> *M. alba* > *C. album* > *A. ludoviciana* > *A. arvensis* > *P. minor*.

3.2.4 Ranking environments

M3S1 treatment combination (Figure 2d) was closest to the concentric circles signifying highest population of weeds followed by M1S1 and M2S1. The environments, namely, M1S5, M2S5, and M3S5, were clustered together and farthest from concentric circle implying similar reduction in weed population and lowest weed population was recorded. The environments can be ranked in descending order as M3S1> M1S1 > M2S1 > M1S3 > M2S2> M2S3= M3S2 > M1S2 > M1S4 > M2S4 > M3S3 >M3S4 > M1S5= M2S5 = M3S5.

TABLE 5 Weed control efficiency and weed control index as influenced by crop establishment methods and weed management options (pooled data of 2 years) at 40 DAS.

Treatments	Weed control efficiency (WCE, %)	Weed control index (WCI, %)
Year		
2021–22	66.28[a]	67.02[a]
2022–23	60.62[b]	60.31[b]
Crop establishment methods (C)*		
EBRC	63.32[a]	63.44[a]
DZRC	62.38[a]	62.95[a]
ITRI	64.65[a]	64.60[a]
Weed management options (W)		
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	72.66[c]	71.98[c]
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	80.34[b]	79.37[b]
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	64.25[d]	66.95[d]
Unweeded check	0.00[d]	0.00[e]
Weed-free check (WFC)	100.00[a]	100.00[a]

*EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation. Footnote indicate that means within a column followed by the same lowercase letter(s) are not significantly different at < 0.05 according to the Tukey's HSD test.

3.3 Wheat growth and yield

Across the 2-year data, non-significant differences were observed in leaf area index (LAI), dry matter accumulation (DMA) (Table 6), tiller count per meter row length (Table 7), crop growth rate (CGR) (Figure 3), relative growth rate (RGR) (mg g^{-1} m^{-2}) (Figure 4), net assimilation rate (NAR) (Figure 5), ear length (cm), and the number of seeds per ear (Table 8) across crop establishment methods and weed management options as well during the experimentation period. There were no significant variations in LAI at 40 DAS, DMA at 40, 80, and 120 DAS (Table 6), tiller count per meter row length at 40, 80, and 120 DAS (Table 7), CGR (Figure 3), RGR (mg g^{-1} m^{-2}) (Figure 4), and NAR (Figure 5) among the crop establishment systems. However, LAI values at 80 DAS (4.47) and 120 DAS (3.01) were significantly higher under the EBRC compared to DZRC. These LAI values for EBRC were statistically on par with those observed under ITRI. This indicates that the EBRC provided a favorable environment for enhanced crop growth during later growth stages.

Among the weed management options, the weed-free check (WFC) consistently recorded the highest values for LAI (1.63,

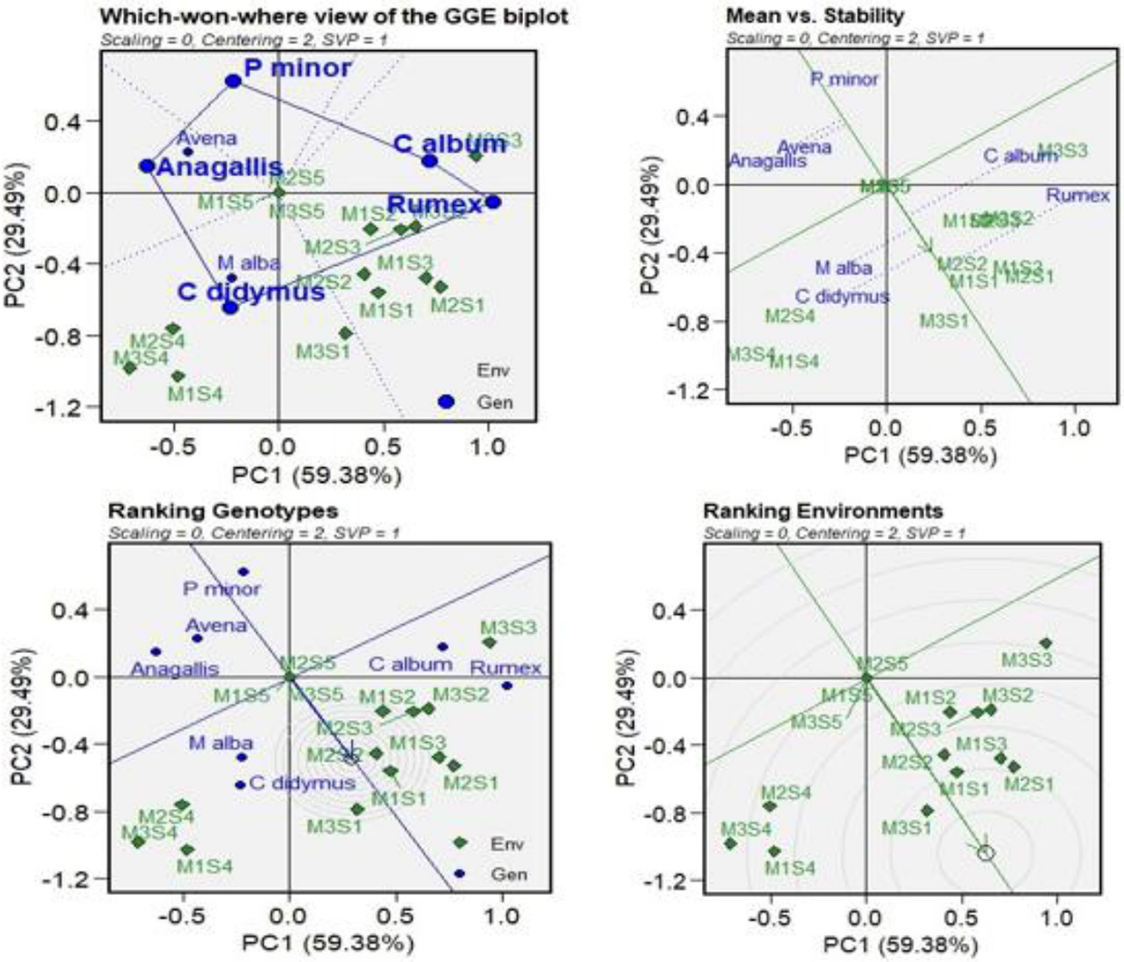

FIGURE 2
Species-wise GGE biplot analysis of weed population in wheat: **(a)** Which-won-where view of the GGE biplot; **(b)** Mean vs. Stability; **(c)** Ranking genotypes; **(d)** Ranking environments. Species-wise GGE biplot analysis of weed population in wheat.

5.07, and 3.27), DMA (72.5, 807.0, and 1253.2 g m^{-2}), and tiller count (83.4, 119.0, and 125.3 per meter row length) at 40, 80, and 120 DAS, respectively, compared to all herbicidal treatments studied. The treatment where co-application of herbicides has been done (Pyro–MetCarf) demonstrated significantly higher LAI (1.60, 4.92, and 3.19), DMA (68.2, 775.1, and 1213.3 g m^{-2}), and tiller counts (82.0, 115.9, and 112.4 m^{-1} row length) at 40, 80, and 120 DAS, respectively. Furthermore, this treatment recorded 53.8% higher LAI, 29.4 5% higher dry matter, and 19.9% more number of tillers compared to UWC after 80 DAS. During the early growth stage (0–40 DAS), the highest crop growth rate (CGR), relative growth rate (RGR), and net assimilation rate (NAR) were observed under the WFC (2.41 g m^{-2} day^{-1}, 4.28 mg g^{-1} day^{-1}, and 0.72 g m^{-2} day^{-1}, respectively), followed closely by Pyro–MetCarf application (2.27 g m^{-2} day^{-1}, 4.18 mg g^{-1} day^{-1}, and 0.66 g m^{-2} day^{-1}, respectively). Non-significant differences were seen at later stages of crop growth (40–80 DAS and 80–120 DAS) in RGR and NAR. At later growth stages (80 and 120 DAS), wheat plants approach maturity with reduced vegetative growth and biomass accumulation, leading to stabilization of RGR and NAR values. Moreover, canopy closure and uniform environmental conditions minimize treatment effects, resulting in non-significant differences among herbicide treatments.

However, CGR was significantly higher under Pyro–MetCarf and the weed-free check (WFC) during these periods, highlighting the superior weed suppression and crop growth benefits of these treatments.

The number of effective tillers, ear length, and the number of grains per ear of wheat were not affected significantly due to temporal variations (year effects) or crop establishment systems as well. However, imposed weed management practices had a significant impact on all yield attributes (number of effective tillers, ear length, and number of grains per ear, Table 7). The weed-free check (WFC) recorded the highest values for yield parameters, including number of effective tillers (110.38), ear length (12.49 cm), and number of grains per ear (61.44). In contrast, the lowest values for these attributes were observed in the UWC, which were 22.1, 18.2, and 7.6% lower than WFC in number of effective tillers, ear length, and number of grains per ear, respectively. Dual-stage application of Pyro-MetCarf

TABLE 6 Leaf area index and dry matter accumulation of wheat as influenced by crop establishment methods and weed management options (pooled data of 2 years).

Treatments	Leaf area index			Dry matter accumulation (g m^{-2})		
	40 DAS	80 DAS	120 DAS	40 DAS	80 DAS	120 DAS
Year						
2021–22	1.42[a]	4.42[a]	2.94[a]	64.33[a]	728.22[a]	1090.82[a]
2022–23	1.40[a]	4.27[a]	2.91[a]	63.33[a]	727.25[a]	1086.51[a]
Crop establishment methods (C)*						
EBRC	1.44[a]	4.47[a]	3.01[a]	65.36[a]	740.67[a]	1111.03[a]
DZRC	1.38[a]	4.17[b]	2.84[b]	62.10[a]	711.97[a]	1062.63[a]
ITRI	1.41[a]	4.41[ab]	2.92[ab]	64.04[a]	730.57[a]	1092.33[a]
Weed management options (W)						
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	1.20[c]	3.98[c]	2.79[c]	60.66[c]	715.39[c]	1003.00[c]
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	1.60[ab]	4.92[a]	3.19[ab]	68.22[b]	775.06[ab]	1213.28[a]
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	1.54[b]	4.56[b]	3.04[b]	65.51[a]	742.06[bc]	1073.33[b]
Unweeded check	1.09[d]	3.20[d]	2.33[d]	52.22[d]	599.04[d]	900.56[d]
Weed-free check	1.63[a]	5.07[a]	3.27[a]	72.55[a]	807.13[a]	1253.17[a]

*EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation. Footnote indicate that means within a column followed by the same lowercase letter(s) are not significantly different at < 0.05 according to the Tukey's HSD test.

TABLE 7 Number of tillers per meter row length as influenced by crop establishment methods and weed management options (pooled data of 2 years).

Treatments	Tillers (number per m row length)		
	40 DAS	80 DAS	120 DAS
Year			
2021–22	79.02[a]	110.40[a]	115.17[a]
2022–23	76.75[a]	108.84[a]	115.08[a]
Crop establishment methods (C)*			
EBRC	78.36[a]	111.93[a]	117.83[a]
DZRC	75.96[a]	106.06[a]	112.86[a]
ITRI	79.33[a]	110.86[a]	116.20[a]
Weed management options (W)			
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	74.22[c]	105.27[c]	113.55[b]
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	82.00[ab]	115.94[ab]	122.44[a]
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	79.38[b]	111.16[b]	115.33[b]
Unweeded check	70.38[d]	96.66[d]	101.50[c]
Weed-free check	83.44[a]	119.05[a]	125.33[a]

*EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation. Footnote indicate that means within a column followed by the same lowercase letter(s) are not significantly different at < 0.05 according to the Tukey's HSD test.

significantly enhanced yield attributes, recording 105.6 effective tillers per meter row length, 12.0 cm ear length, and 60.2 number of grains per ear. These values were statistically comparable to those achieved under the WFC, indicating the efficacy of Pyro-MetCarf in optimizing wheat yield attributes through effective weed control.

The differences in wheat biological yield were not reached to significant levels because of temporal variations and different crop establishment methods studied as demonstrated by a pooled analysis of 2-year data (Table 8). Among the crop establishment systems, EBRC produced the highest grain yield (5.55 t ha^{-1}), followed by ITRI at 5.45 t ha^{-1}, and DZRC at 5.29 t ha^{-1} (Figure 6). The treatment WFC recorded the highest grain yield (6.27 t ha^{-1}), while the UWC obtained the lowest crop yield (4.37 t ha^{-1}). Among the sequential herbicide treatments, Pyro-MetCarf recorded the highest grain yield (5.77 t ha^{-1}). Over the 2 years, Pyro-MetCarf resulted in a mean grain yield increase of 24.3% compared to the UWC, highlighting its effectiveness in improving yield through better weed control efficacy.

The weed index (WI), which reflects the percentage reduction in crop yield due to crop-weed competition, showed that the highest yield loss (30.3%) occurred in the UWC, underscoring the substantial negative impact of uncontrolled weed growth on crop productivity. The WFC served as the standard control in which no weed growth was permitted, thereby representing an ideal weed-free environment where crop yield was not affected by weed interference (Figure 7). Among the sequential herbicide treatments, the lowest weed index (8.02%) was recorded with Pyro-MetCarf, closely followed by SulfoMet at 12.7%. The highest weed index among herbicide treatments was observed with Pyro alone (15.9%), suggesting that while it provided some degree of weed suppression, it was less effective than the sequential applications. These findings highlight the critical role of integrated weed management, particularly the use of sequential herbicides such as Pyro-MetCarf in minimizing yield losses caused by weed competition.

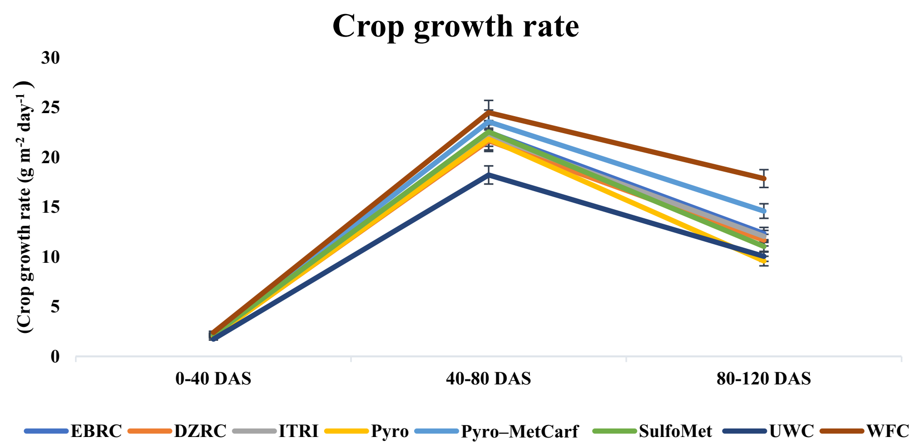

FIGURE 3
Effect of crop establishment methods and weed management options on crop growth rate of wheat (pooled mean). EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

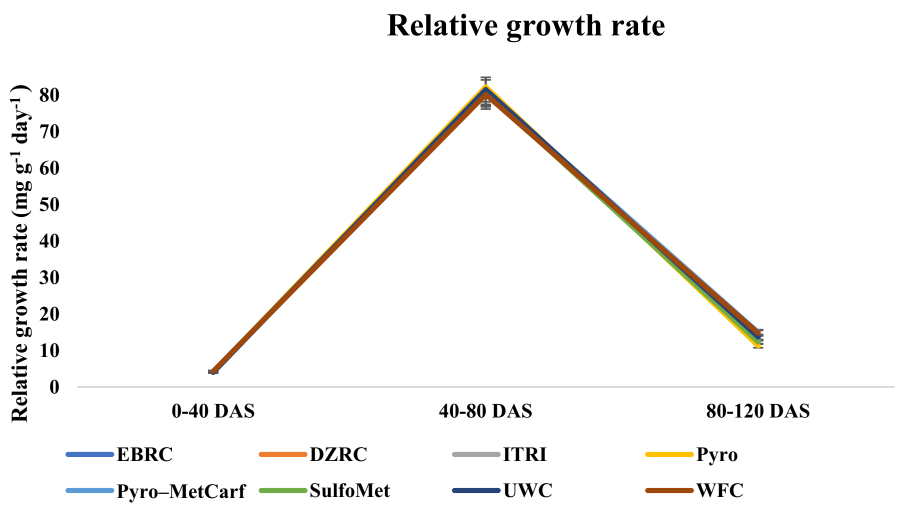

FIGURE 4
Effect of crop establishment methods and weed management options on relative growth rate of wheat (pooled mean). EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

4 Discussion

4.1 Weed dynamics

Crop establishment methods had a pronounced impact, resulting in significantly higher density and dry weight of narrow-leaved weeds (NLWs), broad-leaved weeds (BLWs), sedges, and total weed populations in the first year of experimentation compared to the second year. This trend can be attributed to favorable environmental conditions in the first year, particularly optimal precipitation, promoting multiple flushes of weed seed germination during the wheat-growing period (Figure 1). In contrast, the retention of crop residues as mulch proved highly effective in reducing weed density and dry matter accumulation. Maize residues applied on the soil surface functioned as a physical barrier, restrictin g light penetration to the soil, thereby suppressing weed germination and growth of numerous weed species infesting the wheat crop (Sharma et al., 2023). In addition, the residue covers likely induced physico-chemical and biological changes in the soil environment, further suppressing weed seed germination and emergence (Teasdale, 2000; Jabran and Chauhan, 2015).

The EBRC remained significantly more effective in reducing the densities of NLWs, BLWs, sedges, and total weeds compared to DZRC and ITRI systems (Sharma et al., 2023; Kumar and Kaur, 2024). The EBRC enhanced wheat growth by improving root density, increasing dry matter accumulation, and promoting a greater number of tillers (Kumar et al., 2023). These improvements facilitated better nutrient acquisition throughout the growing season. The higher tiller count in wheat strengthened its competitive ability, effectively suppressing weed growth on raised

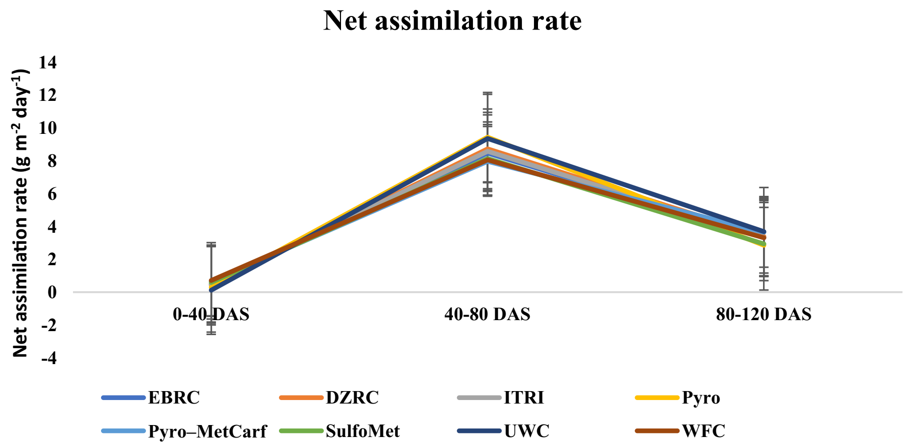

FIGURE 5
Effect of crop establishment methods and weed management options on net assimilation rate of wheat (pooled mean). EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

TABLE 8 Yield parameter of wheat influenced by crop establishment methods and weed management options (pooled data of 2 years).

Treatments	Effective tillers	Ear length	Grains per ear	Biological yield
Year				
2021–22	100.79[a]	11.43[a]	59.64[a]	11.66[a]
2022–23	97.42[a]	11.58[a]	59.08[a]	11.65[a]
Crop establishment methods (C)*				
EBRC	100.26[a]	11.65[a]	60.00[a]	11.98[a]
DZRC	79.86[a]	11.45[a]	58.90[a]	11.37[a]
ITRI	99.06[a]	11.42[a]	59.20[a]	11.61[a]
Weed management options (W)				
Pyroxasulfone 85WG at 0.15 kg/ha (PE)	95.83[c]	11.16[c]	58.72[bc]	11.21[b]
Pyroxasulfone at 0.15 kg/ha (PE) fb (metsulfuron + carfentrazone) at 0.05 kg/ha (PoE)	105.61[b]	12.02[ab]	60.22[ba]	12.85[a]
Sulfosulfuron +metsulfuron at 0.04 kg/ha (PoE)	98.00[c]	11.63[bc]	59.66[ba]	11.75[b]
Unweeded check	85.50[d]	10.22[d]	56.77[c]	9.06[c]
Weed-free check	110.38[a]	12.49[a]	61.44[a]	13.40[a]

*EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation. Footnote indicate that means within a column followed by the same lowercase letter(s) are not significantly different at < 0.05 according to the Tukey's HSD test.

beds compared to flatbed systems, irrespective of the tillage method employed (Kumar and Kaur, 2024).

The influence of tillage on the weed seed bank remains a topic of ongoing debate. Some studies have reported negligible effects of tillage on increasing (Barberi et al., 2001) or decreasing (Murphy et al., 2006) weed seed bank density. Tillage practices affect the redistribution of weed seeds across the soil profile (0–30 cm) in varying ways. For instance, conventional tillage (CT) evenly distributes weed seeds within the plow zone, while zero tillage (ZT) results in accumulation of 60–90% of weed seeds in the top 0–5 cm of the soil (Hoffman et al., 1998). During the initial period from conventional to CA and no-tillage systems, the germinable weed seed bank tended to increase temporarily. However, later, no-tillage practices led to a significant reduction in weed seed bank density, by ∼45–75%, compared to CT (Sergeja et al., 2024).

In addition, the dual-stage application of Pyro-MetCarf demonstrated remarkable efficacy in reducing weed densities. Over 2 years, this treatment achieved significant reductions in the densities of NLWs (64.1%), BLWs (58.9%), and sedges (41.2%) compared to the unweeded check.

Pyroxasulfone proved highly effective in controlling early-emerging NLWs, BLWs, and sedges by targeting them at the germination stage. This pre-emergence herbicide, characterized by its pyridine and oxazole rings, inhibits the biosynthesis of very-long-chain fatty acids, thereby arresting weed growth. On the other hand, the post-emergence combination of Met+Carf effectively controlled later-emerging NLWs and BLWs. A similar pattern

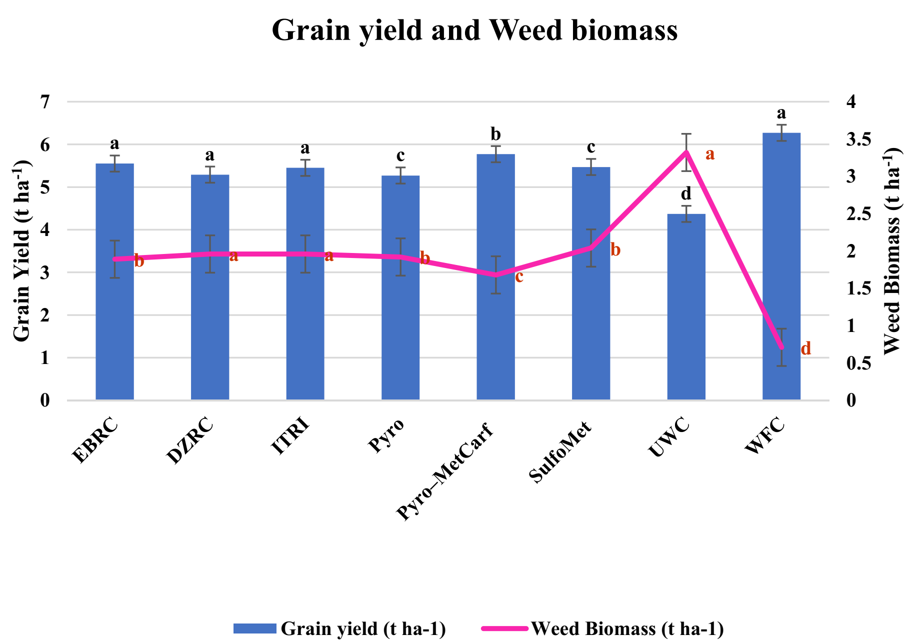

FIGURE 6
Effect of crop establishment methods and weed management options on wheat grain yield (t ha^{-1}) and dry weed biomass (t ha^{-1}) at 40 DAS (pooled mean). EBRC, elevated bed with residue cover; DZRC, double zero-tillage with residue cover; ITRI, intensive tillage with residue incorporation.

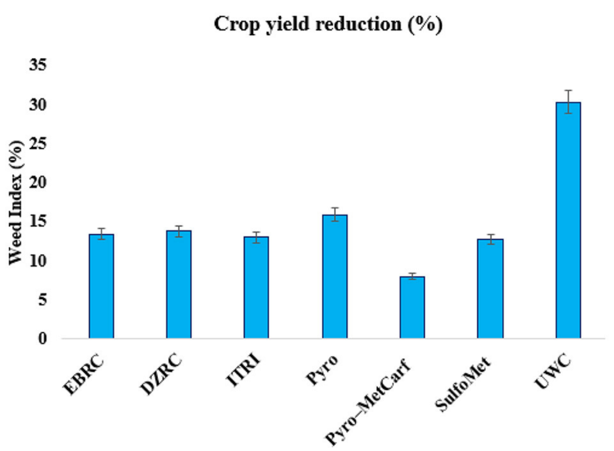

FIGURE 7
Effect of crop establishment methods and weed management options on weed index (% reduction of wheat yield due to weeds) (pooled of 2 years).

was observed in the reduction of weed dry matter across NLWs, BLWs, and sedges. Higher WCE was recorded in elevated beds and intensive tillage with residue retention due to a lower weed density (Kaur et al., 2019; Kumar et al., 2022). Conversely, DZRC exhibited lower WCE and WCI, primarily due to the accumulation of a larger weed seed bank in the upper soil layer and the absence of soil disturbance in ZT practices.

The sequential application of Pyro-MetCarf demonstrated the highest WCE and WCI. This superior performance can be attributed to its ability to significantly reduce both the density and dry matter accumulation by weeds, ensuring balanced and sustained weed control throughout the crop growth period.

The GGE biplot analysis of weed population under different main plot and subplot combination revealed that *R. dentatus* was not controlled effectively by the combination of EBRC and DZRC along with varied herbicide application, whereas *C. didymus* and *M. alba* were controlled by these treatments when compared to UWC. This might have been due to shifting of weed flora from grassy weeds to more resistant *R. dentatus* along resistance to tolerate even higher dose of some herbicides (Chhokar et al., 2022). Furthermore, the population of *P. minor* was lowest implying effective control by different treatment combinations. The lowest population of *P. minor* might be owing to the inhibition of light penetration for germination and growth of weeds with residue retention combined with effectiveness of various herbicides (Ghosh et al., 2022a,b; Kaur and Singh, 2019). Herbicide resistance in *R. dentatus* and other broad-leaved weeds has been linked with increased metabolic resistance and altered translocation, as in case of *P. minor* for isoproturon resistance (Chhokar et al., 2022). Moreover, repeated use of single-site herbicides such as pyroxasulfone may select for cross-resistance in multiple weed species, necessitating integrated weed management strategies involving herbicide rotation and mixtures (Kaur and Singh, 2019). *A. ludoviciana* and *A. arvensis* were recorded similar mean population along with stability indicating the identical effectiveness of treatment combinations in controlling the population of these two weeds. Ranking of the environments analysis revealed ITRI in combination with sulfoMet was most effective treatment in controlling weed population significantly followed by DZRC and EBRC. The combination of ITRI and pyroxasulfone was inferior in controlling weed population indicating higher population of weeds. Relatively higher population of weeds might be attributed to lower control of some broad-leaved weeds by application of pyroxasulfone alone which otherwise could be effectively controlled by a combination of both pre- and post-emergence herbicides (Kaur and Singh, 2019; Samota et al., 2024).

4.2 Growth parameters, yield attributes, and yield

During the second year of experimentation, a significant decline in yield was noticed. The unexpected rainfall at the grain-filling stage of wheat resulted in significant crop lodging and subsequent yield reductions. However, wheat cultivated on elevated beds demonstrated resilience to lodging and achieved higher yields. This advantage was attributed to better root proliferation, reduced weed density, and a more favorable microclimate that supported better crop growth under EBRC. Furthermore, the EBRC system significantly minimized the competition for critical resources, including space, light, nutrients, and moisture, and also benefitted from the weed-suppressive effects of maize residue retention (Raj et al., 2022; Kaur et al., 2024a). The maize residue cover acted as a physical barrier, which effectively suppressed weed germination and growth by limiting light penetration and altering soil microclimatic conditions (Bana et al., 2020). In addition, the retained residue improved soil health by enhancing moisture retention, moderating temperature fluctuations, and fostering beneficial microbial activity (Bana et al., 2023b).

These improvements allowed the wheat crop to establish better anchorage and deeper root systems, which facilitated enhanced nutrient and moisture acquisition. This, in turn, supported efficient photosynthesis, leading to increased leaf area, greater dry matter accumulation, and vigorous vegetative growth across the crop canopy (Duan et al., 2024). Moreover, the reduction in weed density and dry matter minimized competition for critical resources, such as water, nutrients, and space, while improving soil aeration in the EBRC system (Mondal et al., 2020). This favorable environment created ideal atmosphere for robust crop development, resulting in higher number of tillers, longer ear length, and an increased number of grains per ear (Table 8). These findings are in the line with the studies from Ghosh et al. (2022a), Sharma et al. (2023), and Kaur et al. (2024b), which emphasize the advantages of raised bed planting systems in enhancing wheat growth and productivity. Collectively, these factors underscore the superiority of the EBRC method in mitigating yield losses under adverse weather scenarios, such as rainfall-induced lodging, and in promoting higher and more sustainable wheat yields through improved weed suppression, resource use efficiency, and crop growth performance (Ghosh et al., 2022b).

Among the weed management strategies tested, the dual-stage application of Pyro-MetCarf emerged as the most effective option for controlling a wide spectrum of weed flora. This treatment provided a weed-free environment during the critical period of crop-weed interference, a key factor in minimizing yield losses and optimizing crop growth (Ghosh et al., 2022b; Kumar et al., 2022). The comprehensive weed suppression achieved through the sequential herbicide application not only minimized competition for vital resources but also created season-long idealistic environment for wheat growth, ultimately resulting in higher grain yields.

Despite these advancements in weed control, no significant differences in grain yield were observed across the various crop establishment systems within the short duration of the experiment. This lack of variation could be attributed to the limited time frame of the study as changes in soil health and productivity often require a longer period to manifest. The physical and biological properties of soil, including soil structure, microbial activity, and nutrient availability, evolve gradually over time (Kumar et al., 2023). Moreover, the accumulation of soil organic carbon, which is vital for sustaining long-term soil fertility and crop productivity, may take several years of consistent management practices to reach levels that significantly influence yields (Bana et al., 2023a). It is plausible that sustained experimentation over 4–5 years or more would reveal significant differences in grain yield among the crop establishment systems (Bana et al., 2020, 2023b). Continuous implementation of practices such as residue retention, elevated bed planting, or no-tillage could progressively enhance soil properties, improve water-use efficiency, and build resilience against biotic and abiotic stresses, ultimately contributing to sustainable and higher crop yields (Govaerts et al., 2007).

5 Conclusion

In the maize–wheat cropping system of the Indo-Gangetic Plains, integrating elevated-bed planting with residue retention and sequential herbicide applications, pyroxasulfone as pre-emergence followed by tank mix application of metsulfuron methyl + carfentrazone as post-emergence application (Pyro–MetCarf) have proven highly effective in managing narrow-leaved weeds (NLWs), broad-leaved weeds (BLWs), and sedges. This combined approach not only enhances weed control efficiency and the weed control index but also improves wheat growth and yield attributes. The dual-stage herbicide application effectively targets both early and late-emerging weed species, ensuring comprehensive weed management throughout the cropping season. In addition, the retention of maize residues as mulch suppresses weed germination and growth, further contributing to a healthier wheat crop, in addition to its moisture saving effects. Therefore, it can be concluded that bed planting + residue along with sequential application of herbicides, Pyro–MetCarf, provides better control of weeds and leads to higher yield of wheat crop in Indo-Gangetic Plains of India. Further research is warranted to refine the broad-spectrum sequential herbicide-based integrated weed management strategy by assessing their long-term effects on weed seed-bank dynamics, herbicide resistance development, soil health, and system productivity under diverse agro-climatic conditions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

SK: Writing – original draft, Data curation, Conceptualization, Supervision, Validation, Investigation. RK: Resources, Writing – original draft, Investigation, Project administration, Validation, Funding acquisition, Conceptualization, Supervision, Writing – review & editing. RB: Visualization, Formal analysis, Validation, Writing – review & editing, Writing – original draft, Conceptualization. TJ: Data curation, Software, Writing – original draft. SM: Writing – review & editing, Funding acquisition, Resources, Project administration, Investigation. TS: Writing – review & editing, Visualization, Resources. SSa: Writing – original draft, Data curation, Methodology. SSe: Writing – review & editing, Conceptualization. SA: Formal analysis, Writing – original draft, Software, Resources. AD: Writing – review & editing, Supervision. TD: Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1624283/full#supplementary-material

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