frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 19 June 2026
DOI 10.3389/fsufs.2026.1793203

Check for updates

OPEN ACCESS

EDITED BY
Vijay Singh Meena,
ICAR - Mahatma Gandhi Integrated Farming Research Institute, India

REVIEWED BY
Pratonu Bandyopadhyay,
Midnapore City College, India
Kangujam Bokado,
Lovely Professional University, India

*CORRESPONDENCE
Shanmugam Vijayakumar
vijitnau@gmail.com
Buta Singh Dhillon
bsdhillon@pau.edu

RECEIVED 21 January 2026
REVISED 06 May 2026
ACCEPTED 11 May 2026
PUBLISHED 19 June 2026

CITATION
Dhillon BS, Vijayakumar S, Vij L, Gopalakrishnan S, Mahender Kumar R and Sundaram RM (2026) Yield performance of imidazolinone-tolerant basmati rice genotypes under dry direct-seeded conditions and its impact on succeeding crops.
Front. Sustain. Food Syst. 10:1793203.
doi: 10.3389/fsufs.2026.1793203

COPYRIGHT
© 2026 Dhillon, Vijayakumar, Vij, Gopalakrishnan, Mahender Kumar and Sundaram. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Yield performance of imidazolinone-tolerant basmati rice genotypes under dry direct-seeded conditions and its impact on succeeding crops

Buta Singh Dhillon[1]*, Shanmugam Vijayakumar[2]*, Lavanya Vij[1], Subbaiyan Gopalakrishnan[3], Rapolu Mahender Kumar[2] and Raman Meenakshi Sundaram[2]

[1]Punjab Agricultural University, Ludhiana, India, [2]ICAR-Indian Institute of Rice Research, Hyderabad, India, [3]ICAR-Indian Agricultural Research Institute, New Delhi, India

Introduction: Weed management is a major challenge in dry direct-seeded rice (DDSR) systems due to severe weed infestation and limited selectivity of post-emergence herbicides in basmati rice. The development of imidazolinone (IMI)-tolerant rice genotypes offers an opportunity for effective herbicide-based weed management in DDSR systems. This study evaluated the performance of IMI-tolerant basmati rice genotypes under different herbicide regimes and assessed their effects on weed dynamics, productivity and residual toxicity to succeeding crops.

Methods: A two-year field experiment was conducted at Punjab Agricultural University, Ludhiana using a randomized complete block design. The study included IMI-tolerant genotypes, *viz*., Pusa Basmati (PB) 1979 and PB 1985 along with their recurrent parents, PB 1121 and PB 1509 under different weed management treatments involving pendimethalin, imazethapyr, bispyribac-Na and hand weeding. Weed flora composition, weed control efficiency, yield attributes, grain yield and residual effects on succeeding crops were evaluated.

Results: Weed flora assessments revealed grasses as the dominant group (*Eleusine indica* > *Echinochloa colona* > *Eragrostis tanella*), followed by broadleaves (*Sphenoclea zeylanica* > *Ammania baccifera*) and sedge (*Cyperus rotundus*). IMI-tolerant genotypes performed significantly better under imazethapyr-based treatments and recorded grain yields ranging from 4.43 to 5.63 t ha^{-1}, whereas recurrent parents exhibited complete mortality under imazethapyr application. Sequential herbicide applications proved superior to single herbicide applications. Pendimethalin @ 0.75 kg a.i. ha^{-1} followed by imazethapyr @ 100 g a.i. ha^{-1} or bispyribac-Na @ 25 g a.i. ha^{-1} achieved weed control efficiency (~80%) comparable to hand weeding. Multivariate analyses revealed strong negative associations of weed density and weed biomass with crop productivity. Bioassay studies indicated no adverse residual effects on succeeding crops.

Discussion: The study demonstrated that integration of IMI-tolerant basmati rice genotypes with sequential imazethapyr-based herbicide regimes provides effective weed control, improved crop productivity and environmental safety under DDSR systems. These findings highlight the potential of IMI-tolerant technology as a sustainable weed management approach for direct-seeded basmati rice cultivation.

KEYWORDS
carryover effect, direct-seeded Rice, herbicide efficiency, imazethapyr, IMI-rice genotypes, weed flora dynamics, yield performance

1 Introduction

Basmati rice (*Oryza sativa* L.) commands a premium price in the international specialty food market for its unique aroma, extra-long slender grain, and superior cooking quality (Siddiq et al., 2012). This distinguished rice variety plays a significant role in the agricultural economies of India and Pakistan, which are the exclusive geographical regions and producers of authentic Basmati. India is the foremost global producer and exporter of Basmati rice (Mahajan et al., 2018). The country's Basmati production is concentrated within the specific Geographical Indication (GI) region of the Western Indo–Gangetic Plains, primarily in Northwest India. This region is critical to national food security and international trade, with Basmati rice being one of India's most valuable agricultural export commodities (Villalba et al., 2024; Vijayakumar et al., 2024). Annual production contributes substantially to global trade, making the Basmati rice–wheat cropping system not only central to the livelihoods of millions of farmers but also a major driver of national export earnings (Mahajan et al., 2018). The sustainability of this high-value system is therefore of strategic importance (Bhatt et al., 2016; Dhanda et al., 2022).

The dominant rice cultivation practice in this region, i.e., Puddled Transplanted Rice (PTR), is increasingly recognized as environmentally and economically unsustainable (Bhatt et al., 2016). PTR is characterized by intensive requirements for water, labor, and energy, and critically, it contributes to elevated methane (CH_4) emissions, a potent greenhouse gas (GHG) exacerbating global warming and climate change (Vijayakumar and Padma, 2023). In contrast, Direct Seeded Rice (DSR) offers a compelling resource-conserving alternative. DSR eliminates costly field operations such as nursery raising and transplanting, leading to substantial reductions (18–50%) in irrigation water use and a decrease of up to 70% in methane emissions (Kumar and Ladha, 2011; Dhillon et al., 2021a; Ahmed et al., 2025). This translates to significant economic benefits, including lower production costs and reduced irrigation expenses (USD 74–91 ha^{-1}). Consequently, DSR adoption is rapidly expanding in Northwest India, incentivized by supportive central and state policies (Kaur et al., 2024).

Despite its clear advantages, the widespread adoption of DSR is severely constrained by several agronomic challenges, including nutrient deficiencies (N: nitrogen, P: phosphorus, S: sulphur, Fe: iron), soil crusting, and, most critically, intense weed infestation (Devi, 2023; Dhillon et al., 2021b; Jat et al., 2019). The absence of standing water during crop establishment allows weeds to emerge simultaneously with rice seedlings, creating severe competition for light, moisture, and nutrients (Singh et al., 2016; Ramesh et al., 2021). Weed flora in DSR is diverse, encompassing difficult-to-manage grasses (*Echinochloa* spp., *Eleusine* spp.), sedges (*Cyperus* spp.), and broadleaf weeds (*Ammania* spp., *Ludwigia* spp.). Unchecked weed competition can result in devastating yield losses, reaching 50–100% in DSR, significantly higher than losses typically observed in PTR (Matloob et al., 2015; Rathod et al., 2025). Current reliance on conventional herbicides (e.g., butachlor, pretilachlor, pendimethalin, bispyribac-Na) provides only partial control, and the documented shift in weed flora and the emergence of herbicide resistance necessitate the urgent development of new, effective weed management strategies (Choudhary et al., 2022; Merotto Jr et al., 2016; Rodenburg and Demont, 2009).

A significant technological advancement for addressing this challenge is the development and deployment of imidazolinone-tolerant (IMI) rice varieties. These herbicide-tolerant (HT) genotypes carry a mutation in the acetolactate synthase (ALS) enzyme (Shoba et al., 2017), which confers resistance to imidazolinone-group herbicides. This resistance enables the safe application of imazethapyr, a broad-spectrum herbicide effective against a wide range of grasses, sedges, and broadleaf weeds (Heap, 2023; Kumar et al., 2025). International experience in countries like the USA, Brazil, and Malaysia confirms the efficacy of IMI-rice technology in controlling problematic weeds, including weedy rice and enhancing productivity (Burgos et al., 2014; Kumar et al., 2025). Recently, the Indian Council of Agricultural Research (ICAR) released two non-genetically modified (non-GM) imazethapyr-tolerant Basmati rice cultivars, also known as RobiNOweed genotypes: Pusa Basmati 1979 (PB 1979) and Pusa Basmati 1985 (PB 1985). The RobiNOweed genotypes are near-isogenic lines of PB 1121 and PB 1509 (recurrent parents) that are tolerant to the broad-spectrum herbicide, imazethapyr 10% SL. These lines were created at the ICAR-Indian Agricultural Research Institute (ICAR-IARI), New Delhi, through marker-assisted backcross breeding using Robin (earlier named HTM-N22, identified under the N22 Functional Genomics Project) as the donor parent (Kar et al., 2024).

This development opens a crucial, sustainable pathway for effective weed management in the Basmati-growing tracts of North India, a region that contributes over 80% to India's Basmati production and export (Dhillon and Gill, 2024). However, a critical knowledge gap remains. There is a pronounced lack of data on optimizing imazethapyr herbicide for these new IMI Basmati cultivars under the dry direct-seeded conditions of the Western Indo–Gangetic Plains. Specifically, systematic information is needed regarding (i) dose refinement for single and sequential applications of imazethapyr, (ii) integration strategies with widely used pre-emergence herbicides, such as pendimethalin, to provide season-long control of multiple weed flushes and (iii) the potential impact of different herbicide regimes on crop phytotoxicity and the succeeding crops in the Basmati rice-based system.

Optimizing herbicide regimes is essential for effective weed control, reducing crop phytotoxicity and minimizing dependence on labor-intensive hand weeding in dry DSR (Kumar et al., 2025). Sequential applications or tank-mixes with pre-emergence herbicides may prolong weed suppression during the critical crop-weed competition period. Therefore, the study was undertaken to evaluate the effectiveness of imazethapyr-based herbicide programmes in dry direct-seeded IMI-tolerant basmati rice under Northwestern Indian conditions. The study aimed to (i) compare single and sequential applications of imazethapyr at different doses, applied alone and in combination with pendimethalin, against conventional weed management practices, (ii) assess the response of herbicide-tolerant basmati genotypes (PB 1979 and PB 1985) and their recurrent parent (PB 1121 and PB 1509) to these optimized herbicide regimes and (iii) evaluate the residual effects of herbicide treatments on the establishment and growth of succeeding crops in the basmati rice based systems.

Abbreviations: A.I., Active ingredient; CAGR, Compound annual growth rate; DAHA, Days after herbicide application; DBHA, Days before herbicide application; DAS, Days after sowing; DSR, Direct seeded rice; IMI rice, Imidazolinone tolerant rice; PE, Pre-Emergence; PoE, Post-Emergence; PTR, Puddled transplanted rice.

2 Materials and methods

2.1 Site of the study

The experiment was conducted during two consecutive wet (*kharif*) seasons in 2020 and 2021 at the Research Farm, Department of Plant Breeding and Genetics, Punjab Agricultural University (PAU), Ludhiana, India, as part of the All India Coordinated Research Project on Rice (AICRPR). The site is located in the Western Indo–Gangetic Plains Region (30°56' N; 75°52' E; 247 m A.S.L.) and is characterized by a subtropical and semi-arid climate. The average annual rainfall is 733 mm, with ~80% occurring during July–September. Daily weather data on effective rainfall, sunshine hours, and maximum and minimum air temperatures during the study period for both wet seasons were gathered at the agro–meteorological observatory situated 200 m from the experimental site, PAU, Ludhiana, and are presented in the Supplementary Figures 1A,B.

The experimental field had a sandy loam soil texture, classified as *Typic Ustipsamment* under USDA Soil Taxonomy. The soil analysis (0–15 cm depth) indicated that the field was low in available nitrogen (264 kg/ha), medium in available phosphorus (23.4 kg/ha), and high in available potassium (248 kg/ha), with an organic matter of 0.71%. The soil was adequate in available zinc (1.1 mg/kg) and exhibited a pH of 7.5 and an electrical conductivity of 0.24 dS/m (recorded at 25 °C). These values fell within normal ranges, indicating non-saline conditions that were suitable for rice cultivation. Available nitrogen, phosphorus, and potassium were determined using standard methods described by Subbiah and Asija (1956), Olsen et al. (1954), and Jackson (1973), respectively, while soil pH and electrical conductivity were measured following standard procedures (Jackson, 1973). The available zinc was determined using the DTPA extraction method (Lindsay and Norvell, 1978).

2.2 Plant material and experimental design

The experiment tested four Basmati rice genotypes which included two RobiNOweed Basmati rice genotypes Pusa Basmati 1979 (IET 28812) and Pusa Basmati 1985 (IET 28814) and their recurrent parental Basmati genotypes Pusa Basmati 1121 and Pusa Basmati 1509, respectively. For brevity, Pusa Basmati is hereafter referred to as 'PB' throughout the manuscript. These parental lines are the two most popular cultivars in Basmati GI region. The experiment was laid out in Randomised Complete Block Design (RCBD) with three replications. The study comprised two factors: Factor A consisted of four Basmati rice genotypes, including IMI-tolerant genotypes (PB 1979 and PB 1985) and their recurrent parents (PB 1121 and PB 1509), while Factor B consisted of ten weed management treatments (T_1-T_{10}) (Table 1). Thus, a total of 40 treatment combinations (4 genotypes × 10 weed management practices) were evaluated in the study.

These treatments included seven imazethapyr-based weed management regimes, one PAU recommended treatment (pendimethalin *followed by* bispyribac-Na), hand weeding, and weedy check. All treatments were randomly allocated within each replication. These treatments are hereafter referred to by their codes (T_1-T_{10}) in tables, figures and text. The net plot area for each treatment was 7.95 m^2, from which all observations and data were recorded.

2.3 Field preparation and crop raising

The field was made into a fine tilth using a plough, harrows, and rotavators for sowing dry DSR. Sowing was performed on June 23, 2020, and on June 11, 2021, for the first and second year of the experiment, respectively. Seed sowing was carried out using the *kera* method, where seeds were placed in an open furrow and then covered by light planking to ensure proper seed-soil contact. Seeds were sown at a row spacing of 20 cm with a seed rate of 20 kg/ha in plots measuring a net area of 7.95 m^2. The crop was fertilized by applying N at 60 kg/ha and $ZnSO_4$ (21%) at 25 kg/ha. Nitrogen was applied in three equal splits at 21, 42 and 63 DAS and zinc was applied as a basal dose as per the PAU recommendation (Anonymous, 2020a). As soil P and K levels were adequate, these nutrients were not applied. One light irrigation was given immediately after sowing, followed by irrigations at 5 and 19 DAS, and thereafter soil moisture was maintained at -15 kPa until 10 days before harvest.

2.4 Recording of crop growth and yield parameters

Plant height was measured using a meter scale on five randomly selected plants per plot at the panicle initiation stage, while, days to 50% flowering was recorded as the period from sowing until 50% of plants in a plot exhibited fully emerged panicles. Panicle density (productive tillers per m^2) was recorded at physiological maturity by counting tillers in two 1-meter row lengths per plot. Panicle weight was determined by harvesting, threshing, and weighing the grain and chaff from five randomly selected panicles per plot, which were also used to calculate panicle sterility (%) as the ratio of unfilled to total grains per panicle. 1000-grain weight was measured from 1000 grain sample taken from each plot. Finally, grain yield (t/ha) was obtained after harvesting and processing, with grain moisture standardized to 14% using a digital grain moisture meter (Kett's RICETER J). Straw yield (t/ha) was measured after three days of sun-drying and harvest index (%) was subsequently calculated based on the methodology described by Donald and Hamblin (1976).

2.5 Recording of weed parameters

Weed population and biomass were recorded using 0.25 m^2 quadrat at two key stages: 1 day before (DBHA) and 60 days after post-emergence herbicide (imazethapyr) application (DAHA), enabling evaluation of the impact of herbicide treatments on weed dynamics and crop competition. Weeds were categorized into three groups: grassy (*Eleusine indica*; *Eragrostis tanella*; *Echinochloa colona*), broadleaf (*Ammania baccifera*; *Sphenoclea zeylanica*) and sedge (*Cyperus rotundus*). Weed biomass was measured by harvesting the weeds from each quadrat, oven-drying them at 65 ± 5 °C until a constant weight, and expressing the data in g/m^2. Weed control efficiency (WCE) was calculated as the percentage reduction in weed density relative to the weedy check (Equation 1), and the weed index (WI) was determined to quantify yield losses due to weed competition (Equation 2) (Mani et al., 1973).

$$\text{Weed control efficiency}\left(\text{WCE},\%\right)=\frac{W_c-W_t}{W_c}\times 100 \quad (1)$$

$$\text{Weed index}\left(\text{WI},\%\right)=\frac{Y_{wf}-Y_t}{Y_{wf}}\times 100 \quad (2)$$

Where, W_c is the weed density in control plot, W_t is the weed density in the treated plot, Y_{wf} is the crop yield in the weed-free plot, Y_t is the crop yield in the treatment plot for which WI is to be calculated.

2.6 Crop bioassay for herbicide carryover

Bioassay studies were conducted to assess the potential carryover effects of imazethapyr and other herbicide regimes on succeeding winter (*rabi*) crops. The experiment utilized a RCBD with three replications. The succeeding crops namely wheat (*var*. Unnat PBW 343), potato (*var*. Kufri Sindhuri), mustard (*var*. GSC 7), gram (*var*. PBG 7), and pea (*var*. Matar Ageta–7), were sown following the completion of the basmati rice experiments, using the recommended seed rates and maintaining standard row-to-row spacing as per PAU package of practices for *Rabi* crops and vegetables (Anonymous, 2020b, 2020c). All crops were grown during both years (2020 and 2021), except pea, which was included only in *rabi* (winter) 2021. To evaluate herbicide carryover effects, plant height, plant population per m^2 and fresh biomass (g/m^2) were recorded at 45 DAS following standard germination and growth assessment protocols. All plots were maintained under optimal agronomic management, with manual weed removal to eliminate potential confounding effects.

TABLE 1 Details of weed management treatments.

Treatment	Description
T^1	Imazethapyr @ 100 g a.i. ha^{-1} at 16–18 DAS
T^2	Imazethapyr @ 125 g a.i. ha^{-1} at 16–18 DAS
T_3	Imazethapyr @ 200 g a.i. ha^{-1} at 16–18 DAS
T_4	Imazethapyr @ 100 g a.i. ha^{-1} at 16–18 DAS + 100 g a.i. ha^{-1} at 35–37 DAS
T_5	Imazethapyr @ 125 g a.i. ha^{-1} at 16–18 DAS + 125 g a.i. ha^{-1} at 35–37 DAS
T_6	Imazethapyr @ 200 g a.i. ha^{-1} at 16–18 DAS + 200 g a.i. ha^{-1} at 35–37 DAS
T_7	Pendimethalin @ 0.75 kg a.i. ha^{-1} (pre-emergence, within 2 DAS) *f.b.* Imazethapyr @ 100 g a.i. ha^{-1} at 16–18 DAS
T_8	Pendimethalin @ 0.75 kg a.i. ha^{-1} (pre-emergence, within 2 DAS) *f.b.* Bispyribac-Na @ 25 g a.i. ha^{-1}
T_9	Hand weeding at 20 and 35 DAS
T_{10}	Weedy check (Unweeded)

DAS – Days after sowing, a.i. – active ingredient, @ - at the rate.

2.7 Statistical analysis

Data were subjected to analysis of variance (ANOVA) following a factorial randomized complete block design (FRCBD) using genotype and weed management treatment as fixed factors and replication as a random factor. Due to complete mortality of recurrent parent genotypes under imazethapyr-based treatments (T_1-T_7), data corresponding to these genotype–treatment combinations were structurally absent. Therefore, statistical analysis was performed in two parts: (i) Analysis for IMI-tolerant genotypes across all treatments (T_1-T_{10}) and (ii) analysis of recurrent parents restricted to non-imazethapyr treatments (T_8-T_{10}). Mixed-model approaches for incomplete datasets were not employed as the absence of the data for the recurrent parents under imazethapyr treatments was due to uniform biological response (complete mortality) rather than random observations. This approach ensured biologically meaningful comparisons while avoiding distortion of treatment effects due to non-survival under specific herbicide regimes.

Treatment means were compared using the least significant difference (LSD) test and Tukey's Honestly Significant Difference (HSD) test at 5% probability level. Correlation analysis between weed density at 1 DBHA and final crop growth and yield attributes was performed using RStudio (version 4.3.1). Data visualization included correlation matrix heatmaps, hierarchically clustered Z-score heatmaps and principal component analysis (PCA) biplots to explore trait and treatment associations at 60 DAHA.

3 Results

3.1 Crop growth and yield performance

The HT genotypes PB 1979 and PB 1985, demonstrated consistently superior growth and yield attributes under herbicide treatments in both years of the study. Crucially, their non-HT recurrent counterparts (PB 1121 and PB 1509) exhibited complete growth failure under all imazethapyr based weed management regimes in both years (Tables 2–4).

3.1.1 Comparison of HT genotypes

Across both the years of study, PB 1979 recorded significantly greater plant height and days to 50% flowering, while grain yield remained statistically comparable between the two genotypes (Tables 2–4). Although, panicle density ($384.8/m^2$) and straw yield (10.49 t/ha) of PB 1979 was significantly higher than PB 1985 during 2020 but the effect could not translate into grain yield in any of the years. Despite the non-significant difference in grain yield, PB 1979 documented significant variations in other yield attributes and a higher straw yield (10.49 t/ha), whereas PB 1985 consistently exhibited a significantly higher harvest index (Table 4).

3.1.2 Performance of the recurrent parent

The recurrent parents (PB 1121 and PB 1509) were severely injured (nil growth) by imazethapyr-based treatments. Consequently, their performance was only evaluated under the three non-imazethapyr based weed management treatments (T_8–T_{10}). Across these treatments, both genotypes exhibited broadly comparable grain yield, with no significant differences; however, PB 1121 tended to produce higher straw yield, whereas PB 1509 exhibited a relatively higher harvest index. PB 1121 also recorded greater plant height and longer duration to 50% flowering compared to PB 1509 (Table 2).

3.2 Efficacy of weed management regimes

Large contrasts in crop performance were observed across the weed management treatments compared to the weedy check (T_{10}). Across both years, all herbicide treatments (T_1–T_8) significantly improved growth, panicle density, and grain yield over the weedy check (Tables 3, 4). Grain yield under herbicide treatments ranged

TABLE 2 Effect of imazethapyr-based weed management regimes on the growth attributes of the IMI-rice and their recurrent parent genotypes in the *kharif* (wet) seasons of 2020 and 2021.

Parameter	Plant height (cm) at panicle emergence stage		Days to 50% flowering	
Year	2020	2021	2020	2021
HT genotypes (A)				
PB 1979	108.3a	112.4a	90.9a	99.8a
PB 1985	102.0b	91.3b	76.2b	77.7b
L.S.D. ($p \leq 0.05$)	1.86	1.73	0.50	0.72
Weed control treatments (B)				
T_1	109.5a	106.5ab	83.2a	88.3ab
T_2	108.5a	103.7ab	84.3a	88.5ab
T_3	109.9a	97.9b	84.0a	89.7ab
T_4	109.4a	105.3ab	84.2a	88.8ab
T_5	109.9a	103.8ab	84.8a	88.5ab
T_6	107.5a	98.0b	84.7a	90.3a
T_7	109.9a	107.3a	84.0a	88.7ab
T_8	110.5a	107.7a	83.7a	88.8ab
T_9	105.0a	105.7ab	84.0a	89.5ab
T_{10}	71.7b	82.5c	78.7b	86.2b
L.S.D. ($p \leq 0.05$)	4.15	3.87	1.11	1.61
Interaction (A × B)				
L.S.D. ($p \leq 0.05$)	NS	NS	NS	NS
Non-HT genotypes (A)				
PB 1121	97.5a	108.4a	98.3a	108.8a
PB 1509	89.2a	82.0b	76.1b	76.3b
L.S.D. ($p \leq 0.05$)	5.79	5.19	0.60	1.06
Weed control treatments (B)				
T_8	106.6a	105.1a	89.3a	92.7ab
T_9	99.6a	104.2a	89.2a	93.7a
T_{10}	73.9b	76.3b	83.2b	91.3b
L.S.D. ($p \leq 0.05$)	7.09	6.35	0.74	1.30
Interaction (A × B)				
L.S.D. ($p \leq 0.05$)	NS	NS	NS	NS

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods.

from 4.43 to 5.63 t/ha and remained statistically comparable to the hand weeded treatment (T_9). These yields represented an impressive 16 to 17 folds increase over the weedy check. Among treatments, sequential herbicidal regime of pendimethalin (0.75 kg a.i. ha^{-1}) with either imazethapyr (T_7: 100 g a.i. ha^{-1}) or bispyribac-Na (T_8: 25 g a.i. ha^{-1}) consistently delivered the higher yields, remaining statistically at par with the twice hand weeding treatment (T_9). Conversely, high-dose imazethapyr sprays, both singular (T_3) and sequential (T_6), failed to confer any additional yield benefits (Table 4).

3.2.1 Weed flora dynamics before PoE herbicide application

Weed density and biomass prior to PoE herbicide application (15 DAS) were statistically comparable across different treatments (T_1 to T_6 and T_9-T_{10}) in both years (Table 5), confirming a uniform initial weed infestation in the field. However, T_7 and T_8, allocated for pendimethalin followed by PoE herbicidal application, showed reduced initial weed densities due to the immediate PE impact of pendimethalin on emerging weed seedlings (Figures 1A,B). All other treatments (T_1–T_6), the hand-weeded treatment, and the weedy check, recorded comparable initial weed establishment, ensuring an unbiased baseline for evaluating post-treatment efficacy. Across all plots, mean total weed densities ranged from 30 to 40 plants/m^2 in both years. The grasses constituted the dominant component of the weed flora, comprising approximately 40–45% of the total weed population, followed by sedges (~ 30–32%) and broadleaf species (~ 25–28%).

3.2.2 Weed flora dynamics 60 DAHA

Significant differences in weed populations were observed 60 DAHA across treatments (Table 6; Figure 2; Supplementary Figures 4–9). Weed flora was dominated by grasses (~65–70%), followed by broadleaf weeds (~17–24%), with sedges contributing only marginally (~9–13%), with similar composition across

TABLE 3 Effect of imazethapyr-based weed management regimes on the growth and yield attributes of the IMI-rice and their recurrent parent genotypes in the *kharif* (wet) seasons of 2020 and 2021.

Parameter	Panicle density/m²		Panicle weight (g)		Test weight (g)		Sterility (%)	
Year	2020	2021	2020	2021	2020	2021	2020	2021
HT genotypes (A)								
PB 1979	384.8a	369.3a	1.77a	1.64a	27.0a	27.5a	20.0a	24.1a
PB 1985	368.3a	330.7a	1.80a	1.77a	27.0a	27.2a	20.7a	24.4a
L.S.D. ($p \leq 0.05$)	NS	15.59	NS	0.05	NS	NS	NS	NS
Weed control treatments (B)								
T_1	434.2a	379.6a	1.91a	1.84a	27.5a	27.4a	11.4b	21.1b
T_2	428.3a	380.4a	1.91a	1.83a	27.6a	27.2a	17.4b	24.9ab
T_3	425.0a	360.8a	1.92a	1.72a	27.6a	27.1a	14.0b	22.3b
T_4	396.7a	379.6a	1.93a	1.83a	27.5a	27.4a	20.0b	23.4b
T_5	385.0a	378.3a	1.94a	1.84a	27.5a	27.3a	16.0b	22.1b
T_6	392.5a	362.5a	1.88a	1.70a	27.3a	27.4a	13.2b	25.4ab
T_7	396.3a	380.3a	1.97a	1.85a	27.3a	27.4a	13.9b	23.7b
T_8	402.5a	378.8a	1.97a	1.83a	27.5a	27.5a	14.2b	23.8b
T_9	407.5a	364.6a	1.96a	1.85a	27.6a	27.5a	15.8b	18.4b
T_{10}	97.5b	135.0b	0.50b	0.75b	22.2b	27.5a	67.7a	37.0a
L.S.D. ($p \leq 0.05$)	45.00	34.86	0.17	0.11	0.76	NS	4.48	5.43
Interaction (A × B)								
L.S.D. ($p \leq 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS
Non-HT genotypes (A)								
PB 1121	266.7a	354.7a	1.40b	1.32b	26.2a	27.9a	41.2a	34.3a
PB 1509	251.1a	270.8b	1.61a	1.49a	26.0a	27.8a	32.8b	36.0a
L.S.D. ($p \leq 0.05$)	14.23	36.59	0.13	0.07	NS	NS	3.65	NS
Weed control treatments (B)								
T_8	346.7a	399.2a	1.96a	1.76a	27.7a	27.8a	18.8b	30.3b
T_9	361.7a	404.2a	1.97a	1.76a	27.7a	27.9a	19.6b	26.5b
T_{10}	68.3b	135.0b	0.58b	0.69b	23.0b	27.8a	72.6a	48.6a
L.S.D. ($p \leq 0.05$)	17.43	44.81	0.16	0.08	1.43	NS	4.47	8.76
Interaction (A × B)								
L.S.D. ($p \leq 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods.

both years. The weedy check (T_{10}) recorded the highest mean weed density and biomass, indicating severe weed pressure. The single and sequential application of imazethapyr (T_1–T_6) and PE herbicide integrated treatments (T_7 and T_8) suppressed the weed populations by ~50 to 80%.

Pendimethalin–integrated with either imazethapyr @ 100 g a.i. ha^{-1} (T_7) or bispyribac-Na @ 25 g a.i. ha^{-1} (T_8), effectively reduced the weed density of grasses and broadleaf weeds by 5 to 8 folds and two-fold, respectively over control. All weed management treatments achieved 100% successful elimination or near complete elimination of sedges in both the years, recording a density range of 0–1.3 sedges/m^2 (statistically similar across treatments) and significantly lower than the weedy check (9.6–10.7 sedges/m^2) (Table 6). The twice hand-weeded plots (T_9) consistently maintained the lowest weed density, serving as the effective weed-free baseline. In 2020, sequential imazethapyr-based treatments (T_3 and T_6) and the pendimethalin-integrated combination treatments (T_7 and T_8) exhibited the lowest total weed density, recording substantial reductions of 84–88% relative to the weedy check. Furthermore, PAU recommendation of pendimethalin *followed by* bispyribac-Na (T_8) consistently performed better with a weed control efficiency exceeding 80%.

Total weed population and total weed biomass recorded at 60 DAHA clearly reflected the effectiveness of different weed management treatments, singular, sequential and integrated, across both years. The weedy check (T_{10}) consistently recorded the highest weed population and biomass, indicating severe weed pressure under untreated conditions (Figures 2A,B). Among the herbicide treatments, integrated approaches involving pre-emergence followed by

TABLE 4 Effect of imazethapyr-based weed management regimes on the yield performance of the IMI-rice and their recurrent parent genotypes in the *kharif* (wet) seasons of 2020 and 2021.

Parameter	Grain yield (t/ha)		Straw yield (t/ha)		Harvest index (%)	
Year	2020	2021	2020	2021	2020	2021
HT genotypes (A)						
PB 1979	4.93a	4.36a	10.49a	9.09a	31.6b	31.0a
PB 1985	4.79a	4.31a	7.57b	8.57a	37.8a	31.6a
L. S. D. ($p \leq 0.05$)	NS	NS	0.85	0.26	2.17	NS
Weed control treatments (B)						
T_1	5.63a	4.90a	9.78a	9.69a	36.9a	33.6a
T_2	5.54a	4.81a	9.97a	9.68a	36.3a	33.3a
T_3	5.57a	4.48a	11.43a	9.24a	33.1ab	32.7a
T_4	5.09a	4.90a	9.50a	9.67a	35.8ab	33.6a
T_5	5.15a	4.80a	9.94a	9.66a	34.5ab	33.2a
T_6	5.23a	4.43a	9.24a	9.18a	37.0a	32.6a
T_7	5.32a	4.90a	9.90a	9.67a	35.7ab	33.6a
T_8	5.44a	4.95a	9.84a	9.81a	36.4a	33.6a
T_9	5.31a	4.90a	9.78a	9.89a	36.4a	33.1a
T_{10}	0.32b	0.29b	0.92b	1.82b	24.8b	13.3b
L.S.D. ($p \leq 0.05$)	0.41	0.29	1.89	0.57	4.85	2.04
Interaction (A × B)						
L.S.D. ($p \leq 0.05$)	NS	NS	NS	NS	NS	NS
Non-HT genotypes (A)						
PB 1121	3.04a	3.40a	7.48a	7.52a	28.2b	28.0a
PB 1509	3.33a	3.15a	5.68b	6.58b	33.5a	27.0a
L.S.D. ($p \leq 0.05$)	0.26	NS	1.56	0.40	2.94	NS
Weed control treatments (B)						
T_8	4.66a	4.76a	9.62a	9.95a	33.3a	32.4a
T_9	4.65a	4.79a	9.40a	9.87a	33.8a	32.7a
T_{10}	0.24b	0.28b	0.71b	1.34b	25.4b	17.4b
L.S.D. ($p \leq 0.05$)	0.32	0.31	1.91	0.49	3.60	3.25
Interaction (A × B)						
L.S.D. ($p \leq 0.05$)	NS	NS	NS	NS	NS	NS

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods.

post-emergence herbicides (T_7 and T_8) significantly reduced both weed population and biomass, performing comparably to hand weeding (T_9). Overall, lower weed population was associated with reduced biomass accumulation, demonstrating effective control of weed emergence as well as subsequent growth under integrated and sequential herbicide regimes.

Species-wise assessment at 60 DAHA is critical because this stage represents the peak period of crop–weed competition and strongly influences final yield. The weed flora was dominated by *Echinochloa colona* and *Eleusine indica*, followed by *Eragrostis tanella*, *Cyperus rotundus*, *Ammania baccifera,* and *Sphenoclea zeylanica*. In both years, the weedy check (T_{10}) recorded the highest densities across all species, with *Echinochloa colona* exceeding 20–25 plants/m^2 and *Eleusine indica* reaching ~33–37 plants/m^2 in 2020. while *Eragrostis tanella* ranged from 13 to 15 plants/m^2. *Cyperus rotundus* also persisted strongly (9–12 plants/m^2). This multi-species dominance led to the drastic yield suppression in T_{10} (Supplementary Figures 4–9). The weed density observed at 60 DAHA largely represents late-emerging weed cohorts and partially suppressed individuals rather than early-season weed growth, as aerobic conditions under DSR favour staggered emergence. Significant genotypic differences were documented, with lower broadleaved weed density observed in HT genotypes, particularly in conjunction with higher imazethapyr doses. Additionally, the complete mortality of the non-HT recurrent parents created open niches, facilitating the proliferation and rapid accumulation of biomass by certain broadleaf species, notably *Ammania baccifera* and *Sphenoclea zeylanica*.

3.3 Persistent weeds and yield implication

Imazethapyr-based treatments (T_1-T_3) effectively suppressed sedges (*Cyperus rotundus*) and broadleaf weeds (*Ammania baccifera*), across both the years. However, grassy weeds, particularly *Eleusine indica* and

TABLE 5 Effect of imazethapyr-based weed management regimes on category-wise weed density dynamics (no./m^2) 1 day before post-emergence herbicide application (DBHA) in the IMI-rice and their recurrent parent genotypes in the *kharif* (wet) seasons of 2020 and 2021.

Years	Weed control treatments	Grasses					Broadleaf Weeds					Sedges				
		PB 1979	PB 1121	PB 1985	PB 1509	Mean	PB 1979	PB 1121	PB 1985	PB 1509	Mean	PB 1979	PB 1121	PB 1985	PB 1509	Mean
2020	T_1	17.6a	17.6a	18.2a	18.1a	17.9A	9.5ab	10.4a	9.5ab	8.6ab	9.5AB	11.5ab	10.9a-e	12.1a	11.1a-e	11.4A
	T_2	18.5a	18.7a	18.7a	17.3a	18.3A	9.6ab	9.9ab	9.5ab	9.5ab	9.6AB	12.1a	11.6ab	11.2a-e	11.4abc	11.6A
	T_3	17.6a	18.5a	17.9a	17.8a	18.0A	9.5ab	9.2ab	9.8ab	9.2ab	9.4AB	11.1a-e	11.2a-e	11.5ab	10.5a-h	11.1A
	T_4	18.5a	17.2a	18.0a	18.4a	18.0A	9.8ab	9.7ab	9.8ab	9.5ab	9.7AB	11.2a-e	10.3a-h	11.8a	10.6a-g	11.0A
	T_5	17.6a	16.7a	19.0a	18.7a	18.0A	9.1ab	9.5ab	9.2ab	9.7ab	9.4AB	11.4abc	11.4abc	10.9a-e	10.6a-g	11.1A
	T_6	17.9a	18.7a	18.4a	18.1a	18.3A	9.7ab	9.2ab	9.2ab	9.2ab	9.4AB	10.8a-f	11.2a-e	11.2a-e	10.6a-g	11.0A
	T_7	2.0b	1.8b	2.2b	2.2b	2.4B	4.0ab	3.4ab	4.0ab	3.5ab	3.7 BC	2.9gh	2.7 h	3.0fgh	3.4e-h	3.0B
	T_8	2.0b	2.0b	2.2b	1.9b	2.0B	3.0ab	3.6ab	3.6ab	2.8b	3.3C	3.5d-h	3.6c-h	3.8b-h	3.8b-h	3.7B
	T_9	16.3a	17.5a	17.5a	19.0a	17.6A	9.1ab	9.4ab	8.6ab	9.2ab	9.1ABC	11.1a-e	10.8a-f	11.4abc	10.9a-e	11.1A
	T_{10}	17.6a	18.7a	16.6a	18.4a	17.8A	9.8ab	9.6ab	10.5a	10.3ab	10.0A	11.5ab	11.3a-d	11a-e	10.8a-f	11.2A
	Mean	14.6A	14.8A	14.9A	15.0A		8.3A	8.4A	8.4A	8.2A		9.7A	9.5A	9.8A	9.4A	
	L.S.D. ($p \leq 0.05$)	A = NS, B = 2.91, A × B = NS					A = NS, B = 1.85, A × B = NS					A = NS, B = 1.94, A × B = NS				
2021	T_1	19.0abc	16.7abc	18.0abc	18.7abc	18.1A	11.7a	12.3a	9.7a	11.0a	11.2A	17.0a	10.7abc	14.7abc	13.3abc	13.9A
	T_2	18.7abc	18.3abc	20.7a	17.3abc	18.8A	11.7a	11.3a	10.0a	11.0a	11.0A	12.0abc	11.0abc	11.7abc	11.0abc	11.4AB
	T_3	22.3a	18.3abc	21.0a	17.7abc	19.8A	12.0a	12.0a	10.7a	11.3a	11.5A	11.0abc	10.7abc	9.3abc	11.7abc	10.7AB
	T_4	15.7abc	18.3abc	19.7ab	23.3a	19.3A	11.7a	11.0a	11.7a	12.7a	11.8A	11.3abc	14.0abc	14.3abc	15.3abc	13.8AB
	T_5	21.7a	20.0a	19.7ab	22.0a	20.8A	11.3a	9.7a	13.0a	11.3a	11.3A	11.0abc	11.3abc	15.3abc	12.3abc	12.5AB
	T_6	20.0a	22.7a	22.3a	18.0abc	20.8A	12.7a	12.7a	11.7a	11.0a	12.0A	13.0abc	12.0abc	13.0abc	12.7abc	12.7AB
	T_7	2.3c	3.0bc	2.3c	2.7c	2.6B	5.7a	5.0a	5.7a	4.3a	5.2B	4.3bc	4.7bc	5.3abc	3.7c	4.5B
	T_8	2.7c	3.0bc	2.7c	2.7c	2.8B	5.3a	4.7a	5.3a	4.0a	4.8B	10.0abc	10.7abc	8.7abc	12.3abc	10.4AB
	T_9	17.3abc	20.7a	19.7ab	18.3abc	19.0A	11.0a	16.0a	10.7a	14.3a	13.0A	14.3abc	12.3abc	13.0abc	13.7abc	13.3AB
	T_{10}	20.7a	20.3a	17.7abc	19.7ab	19.6A	16.3a	12.3a	13.0a	9.3a	12.8A	16.0ab	12.3abc	10.7abc	14.7abc	13.4AB
	Mean	16.0A	16.1A	16.4A	16.0A		10.9A	10.7A	10.1A	10.0A		12.0A	11.0A	11.6A	12.1A	
	L. S. D. ($p \leq 0.05$)	A = NS, B = 4.12, A × B = NS					A = NS, B = 3.21, A × B = NS					A = NS, B = 3.02, A × B = NS				

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods; A refers to the genotypes; B refers to the weed control treatments and A × B refers to their interaction.

10.3389/fsufs.2026.1793203

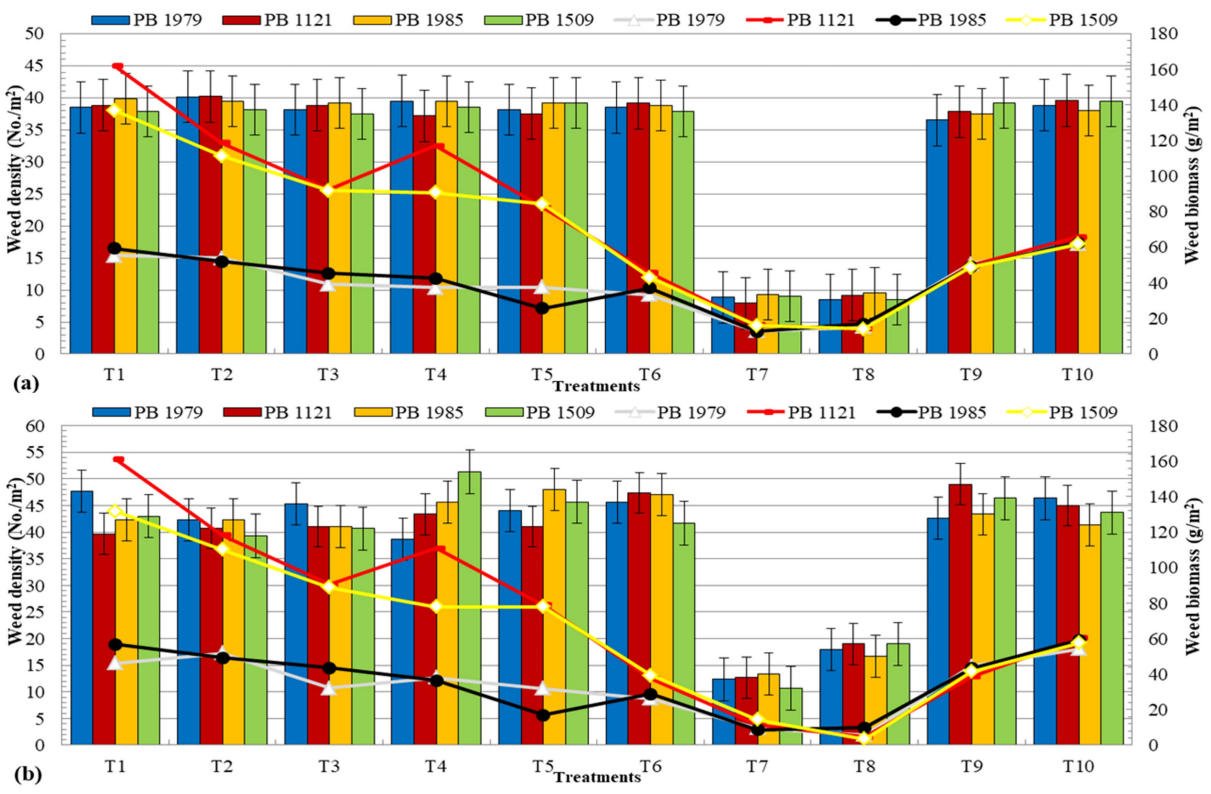


FIGURE 1
Total weed density (no./m²) and biomass (g/m²) in IMI-rice and their recurrent parent genotypes at 15 DAS (1 DBHA) during the *kharif* (wet) seasons of **(A)** 2020 and **(B)** 2021. Bars represents mean values ± standard error (SE) indicating total weed density and lines indicate biomass. T_1–T_{10} refers to the weed management treatments specified in materials and methods.

Eragrostis tanella, still persisted at moderate densities (8–16 plants/m²) (Supplementary Figures 4, 5). Between 2020 and 2021, overall weed density in the weedy check declined by ~25–30%, reflecting lower natural weed pressure in the second year. *Echinochloa colona* and *Eleusine indica* consistently dominated the weed spectrum, collectively contributing >60% of the total flora. *Cyperus rotundus* showed slight persistence in untreated plots but was almost fully suppressed in treated ones.

The pendimethalin-integrated herbicide treatments (T_7 and T_8) achieved 6 to 8 fold reductions in total weed density, relative to the weedy check across both years (Supplementary Figures 4, 5, 8). This result confirms their broad-spectrum, and sustained efficacy, which was comparable to the labor-intensive hand weeding treatment (T_9). Species-wise patterns further clarify treatment outcomes, where *Eleusine indica* remained partially unchecked (T_1–T_3). In contrast, T_7 and T_8 effectively minimized the density of *Eleusine indica* and other weeds.

3.4 Yield penalty and competitive dynamics across treatments

The WI provided quantitative metrics to assess the relationship between weed interference and crop performance across the treatments (Figure 3). WI which quantifies yield penalties due to weed interference, was minimal (< 5%) under the integrated herbicide regimes (T_7 and T_8), placing yields statistically at par with the manual weeding standard (T_9). Conversely, the unchecked weed pressure in weedy check (T_{10}) resulted in devastating yield penalties (>90%), reflecting the severe suppression of crop growth and a complete shift in the crop-weed balance in favor of weeds uncontrolled conditions.

3.5 Weed control efficiency (WCE)

The pendimethalin (PE) integrated with PoE treatments (T_7 and T_8) consistently recorded high WCE (~73–83%) among all herbicidal regimes, comparable to the hand weeding treatment (T_9) which consistently exhibited the highest WCE (~80–82%) across genotypes (Figure 4). This highlights the critical role of PE herbicide component in conjunction with PoE application, providing season-long suppression and effectively curbing weed pressure throughout the critical competition period. Sequential imazethapyr regimes (T_6) also achieved a moderate to high WCE (~59–67%), but were slightly less effective against later-emerging weed flushes.

3.6 Comparison of yield gains

The percent variation in grain yield relative to the weedy check vividly demonstrated the superiority of effective interventions. Grain yield losses under T_{10} exceeded 90% compared with the best-performing treatments. In contrast, twice hand weeding treatment (T_9) improved yields by over 1,500% relative to T_{10}, while pendimethalin-based integrated strategies (T_7 and T_8) provided the highest gains, ranging from 1,600–1700%. Sequential imazethapyr at moderate doses (T_4 and T_5) performed well, but high-dose regimes (T_3 and T_6) did not yield proportionately higher gains, and in fact, were associated with elevated sterility (Tables 2, 3). The WI (Figure 3) was lowest under T_7 and T_8, indicating minimal yield loss due to weeds, whereas the WCE was high under these treatments, reflecting superior crop competitiveness. (Figure 4).

TABLE 6 Effect of imazethapyr-based weed management regimes on category-wise weed density dynamics (no./m^2) 60 days after post-emergence herbicide application (DAHA) in the IMI-rice and their recurrent parent genotypes in the *kharif* (wet) seasons of 2020 and 2021.

Years	Weed control treatments	Grasses					Broadleaf Weeds					Sedges				
		PB 1979	PB 1121	PB 1985	PB 1509	Mean	PB 1979	PB 1121	PB 1985	PB 1509	Mean	PB 1979	PB 1121	PB 1985	PB 1,509	Mean
2020	T_1	28.3b	29.7b	29.0b	29.3b	29.1B	20.0b-i	26.3a	21.0a-h	26.7a	23.5A	0.7b	1.0b	0.7b	0.7b	0.8B
	T_2	27.0b	29.0b	28.0b	26.7b	27.7B	18.7e-j	26.3a	19.7c-i	26.0ab	22.7A	0.3b	0.3b	0.3b	0.3b	0.3B
	T_3	25.0b	28.0b	27.0b	27.0b	26.8B	18.0 g-k	25.0a-d	19.3c-j	25.0a-d	21.3AB	0.0b	0.0b	0.0b	0.0b	0.0B
	T_4	26.0b	27.3b	26.7b	26.7b	26.7B	18.3f-j	26.3a	20.0b-i	26.7a	22.8A	0.0b	0.0b	0.0b	0.0b	0.0B
	T_5	25.7b	25.0b	25.0b	25.7b	25.3B	18.7e-j	24.7a-e	19.0d-j	25.0a-d	21.8AB	0.0b	0.0b	0.0b	0.0b	0.0B
	T_6	22.7bc	22.0bcd	21.7b-e	21.0b-f	21.8B	14.3i-m	20.0b-i	15.0 h-l	21.0a-h	17.6B	0.0b	0.0b	0.0b	0.0b	0.0B
	T_7	8.7 fg	11.3c-g	7.3 g	11.0c-g	9.6C	7.7no	12.0 k-o	8.7mno	13.3 L-o	10.4C	0.7b	1.0b	0.0b	1.3b	0.8B
	T_8	9.0efg	9.0efg	9.3d-g	8.7 fg	9.0C	8.3mno	9.7 L-o	8.7mno	10.3 l-o	9.3C	0.3b	0.3b	0.7b	0.3b	0.4B
	T_9	10.0c-g	9.3d-g	11.7c-g	12.0c-g	10.8C	8.0no	7.3no	6.7o	7.0no	7.3C	1.3b	1.7b	1.0b	1.3b	1.3B
	T_{10}	69.7a	71.0a	67.7a	73.3a	70.4A	23.3a-g	25.3abc	24.7a-e	24.3a-f	24.4A	9.0a	9.7a	11.0a	8.7a	9.6A
	Mean	25.2A	26.2A	25.3A	26.1A		15.5C	20.3AB	16.3 BC	20.5A		1.2A	1.4A	1.4A	1.3A	
	L.S.D. ($p \leq 0.05$)	A = NS, B = 3.16, A × B = NS					A = 0.97, B = 1.53, A × B = 3.06					A = NS, B = 0.582, A × B = NS				
2021	T_1	26.0bcd	27.3bcd	25.3b-e	26.3bcd	26.3B	11.0c-j	16.0abc	10.7d-j	16.0abc	13.4A	0.0c	0.0c	0.0c	0.0c	0.0B
	T_2	23.3b-g	30.3b	23.7b-f	28.3bc	26.4B	10.0f-j	15.0a-f	9.3 g-k	16.7ab	12.8A	0.0c	0.0c	0.0c	0.0c	0.0B
	T_3	20.0c-i	25.7bcd	21.3b-h	24.3b-f	22.8 BC	8.0j-n	14.3a-g	7.7j-n	16.3ab	11.6A	0.0c	0.0c	0.0c	0.0c	0.0B
	T_4	18.0d-j	21.3b-h	18.0d-j	21.3b-h	19.7 BCD	9.7 g-j	15.7a-d	10.3e-j	17.0a	13.2A	0.0c	0.0c	0.0c	0.0c	0.0B
	T_5	15.7f-j	20.0c-i	16.0e-j	21.3b-h	18.3CDE	9.7 g-j	15.3a-e	9.0 h-l	15.7a-d	12.4A	0.0c	0.0c	0.0c	0.0c	0.0B
	T_6	16.0e-j	19.3c-j	16.3e-j	18.7d-j	17.6CDE	8.3i-m	15.7a-d	7.7j-n	15.0a-f	11.7A	0.0c	0.0c	0.0c	0.0c	0.0B
	T_7	11.0ij	13.0hij	10.0j	12.3hij	11.6E	4.3 k-o	9.7 g-j	4.2 L-o	11.7b-j	7.5B	0.3c	0.0c	0.0c	0.0c	0.1B
	T_8	13.3hij	15.0f-j	12.3hij	14.0 g-j	13.7DE	3.0no	3.3mno	3.7mno	3.3mno	3.3C	0.0c	0.0c	0.0c	0.0c	0.0B
	T_9	11.0ij	11.3ij	10.7ij	10.0j	10.8E	2.3o	2.3o	2.3o	2.3o	2.3C	1.3c	1.7c	1.0c	1.3c	1.3B
	T_{10}	53.7a	57.3a	53.3a	57.0a	55.3A	13.3a-i	13.3a-i	14.0a-h	15.0a-f	13.9A	9.0b	12.0a	9.8b	12.0a	10.7A
	Mean	20.8A	24.1A	20.7A	23.4A		8.0B	12.1A	7.9B	12.9A		1.1A	1.4A	1.1A	1.3A	
	L.S.D. ($p \leq 0.05$)	A = 1.46, B = 2.31, A × B = NS					A = 0.78, B = 1.24, A × B = 2.47					A = NS, B = 0.52, A × B = 1.04				

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods; A refers to the genotypes; B refers to the weed control treatments and A × B refers to their interaction.

10.3389/fsufs.2026.1793203

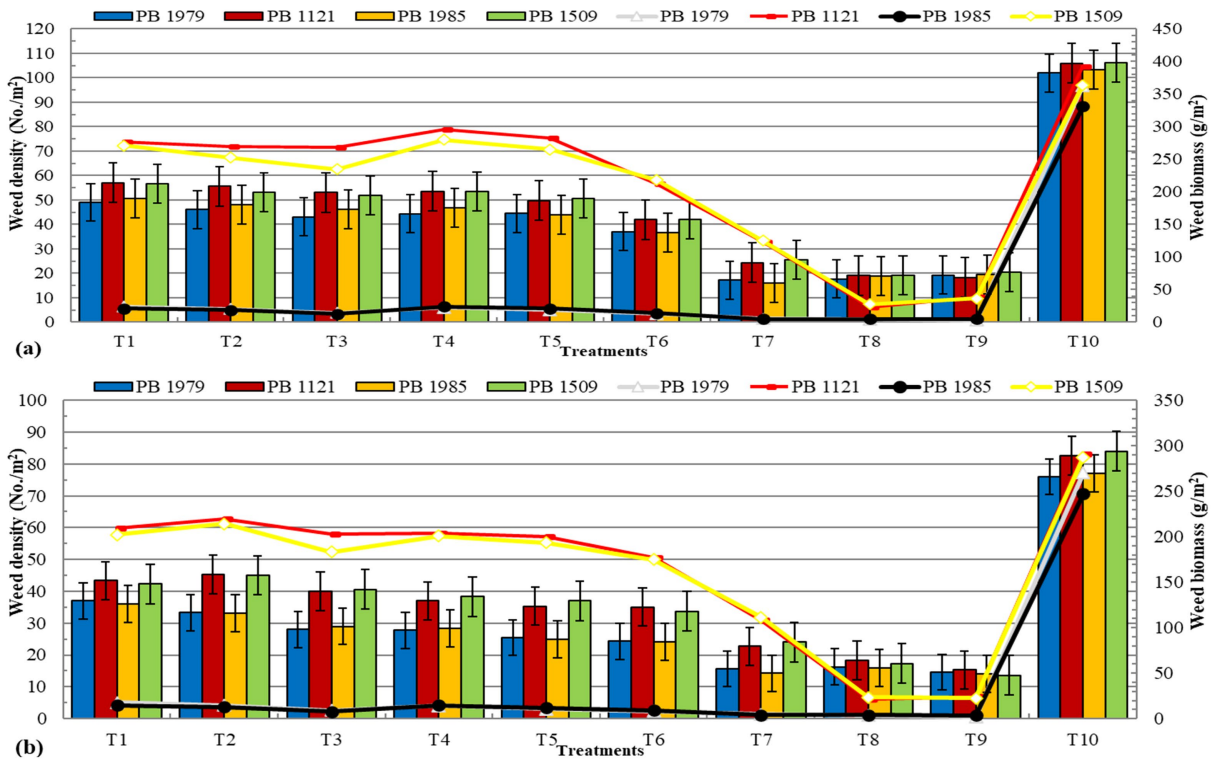


FIGURE 2
Total weed density (no./m^2) and biomass (g/m^2) in IMI-rice and their recurrent parent genotypes at 60 DAHA during the *kharif* (wet) seasons of **(A)** 2020 and **(B)** 2021. Bars represents mean values ± standard error (SE) indicating total weed density and lines indicate biomass. T_1T_{10} refers to the weed management treatments specified in materials and methods.

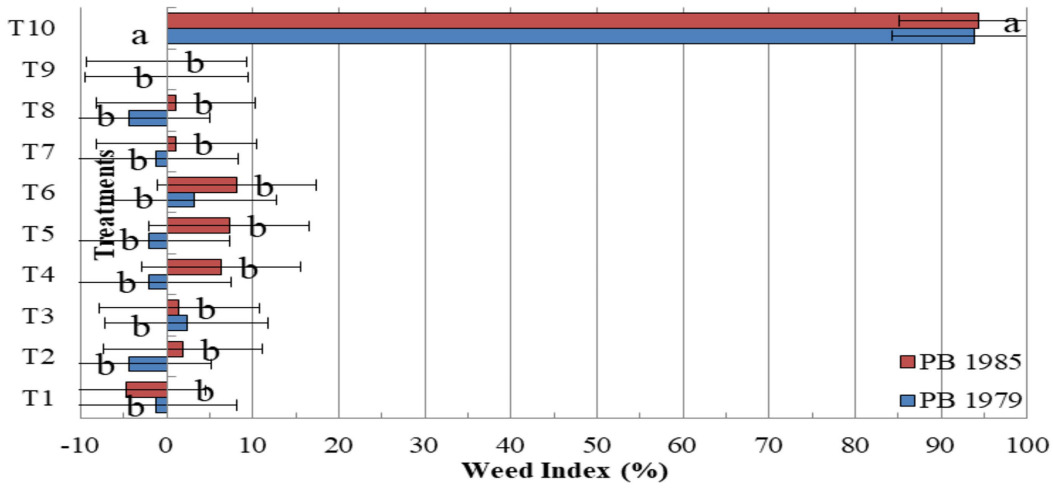


FIGURE 3
Weed index (%) of IMI-rice genotypes pooled over the *kharif* (wet) seasons of 2020 and 2021 under different herbicide treatments. Bars represent mean values ± standard error (SE). Different letters indicate significant differences among treatments at $p \leq 0.05$.

3.6.1 Performance in recurrent parents

The WI was significantly lower, whereas, WCE was the highest for both pendimethalin *fb* bispyribac-Na (T_8) and hand-weeded control (T_9), demonstrating comparable efficacy (Supplementary Figures 2, 3). These results highlight the imperative role of PE herbicide in establishing an efficient, multi-tactic weed management regime across all tested genotypes.

3.7 Correlation with weed density and biomass at 1 DBHA

Correlation analysis provided further insights into the strong interdependence of weed pressure, crop growth, and yield formation (Figure 5). Weed biomass exhibited strong and statistically significant negative associations with key productivity traits, notably panicle density ($r = -0.78$), grain yield ($r = -0.82$), and harvest index ($r = -0.75$),

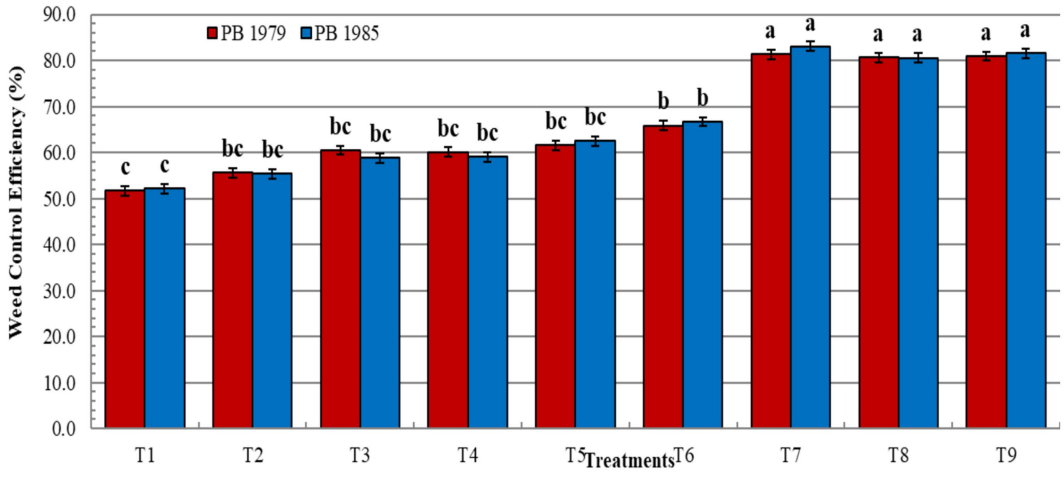


FIGURE 4
Weed control efficiency (%) of IMI-rice genotypes pooled over the *kharif* (wet) seasons of 2020 and 2021 under different herbicide treatments. Bars represent mean values ± standard error (SE). Different letters indicate significant differences among treatments at $p \leq 0.05$.

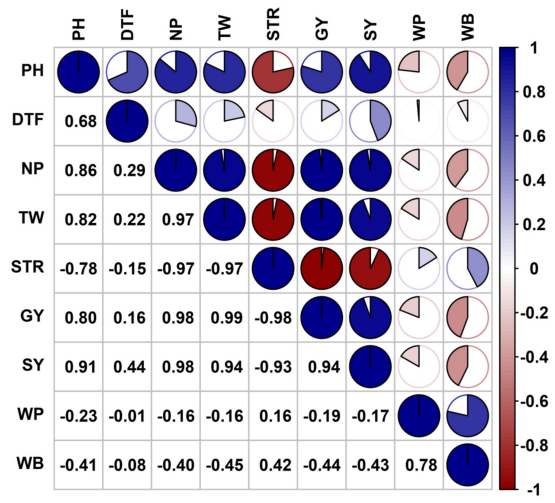


FIGURE 5
Correlation analysis of weed dynamics in IMI-rice genotypes along with growth and yield attributes 1 DBHA. PH – Plant height at panicle emergence; DTF – Days to 50% flowering; NP – Panicle density; TW – Test weight; STR – Sterility; GY – Grain yield; SY – Straw yield; WP – Total weed density (no./m^2) at 1 DBHA; and WB – Total weed biomass (g/m^2) at 1 DBHA.

confirming that unchecked weed competition severely restricts both tiller survival and reproductive efficiency, consistent with the minimal panicle density and reduced yields observed in the weedy check (T_{10}). The significant negative correlation with harvest index is particularly crucial, as it indicates that resource competition under weedy conditions disproportionately restricts the partitioning of assimilates into grain rather than straw.

Conversely, grain yield showed strong positive associations with panicle density ($r = 0.84$) and straw yield ($r = 0.71$), suggesting that tiller survival into fertile panicles is the most reliable predictor of yield in DSR, while higher total biomass under effective weed control indirectly contributes to greater grain output. Thousand-grain weight did not differ significantly among treatments and, along with panicle weight, showed weak and inconsistent associations with grain yield, indicating that yield variation under different weed pressures was primarily governed by differences in panicle density rather than grain size. Overall, the patterns underline that effective early and sustained weed control is the single most important factor safeguarding yield potential in DSR, primarily through enhancing tiller survival, reducing sterility, and improving assimilate partitioning to grain.

3.8 Correlation with weed density at 60 DAHA

A second correlation analysis performed on a pooled dataset (across both years) of IMI-rice genotypes PB 1979 and PB 1985 across ten weed management regimes, revealed distinct and powerful inter-trait associations between the weed densities at 60 DAHA and crop performance (Figure 6A). Weed densities of grasses, broadleaf weeds, and sedges all exhibited strong and consistent negative correlations ($r = -0.84$ to -0.99) with all major growth and yield parameters. Conversely, plant height (PH), panicle density (NP), 1000-grain weight (TW), straw yield (SY) and grain yield (GY) were highly and positively correlated, ranging from $r = 0.91$ to 0.99, reflecting their direct and synchronized contribution to crop productivity and further indicating the inverse relationship between the reductions in weed pressure and improved overall crop performance (Figure 6A). When all four genotypes (two IMI-rice genotypes and their recurrent parental lines) were analyzed together for treatments T_8–T_{10}, a similar, yet more pronounced correlation pattern emerged (Figure 6B).

3.9 Principal component analysis of weed density at 60 DAHA and crop performance

Biplot analysis using PCA effectively visualized the complex interdependence of traits and treatment performance. A highly consistent PCA structure was observed across both years, demonstrating stable trait–treatment interactions. For PB 1979, the first two principal components (PC1 and PC2) explained 97.3% of the total variability, indicating that most of the variation in the dataset could be effectively captured in the biplot. PC1 was strongly and positively associated with weed densities (grasses, broadleaf weeds, and sedges) but negatively correlated with major yield-related traits, such as grain

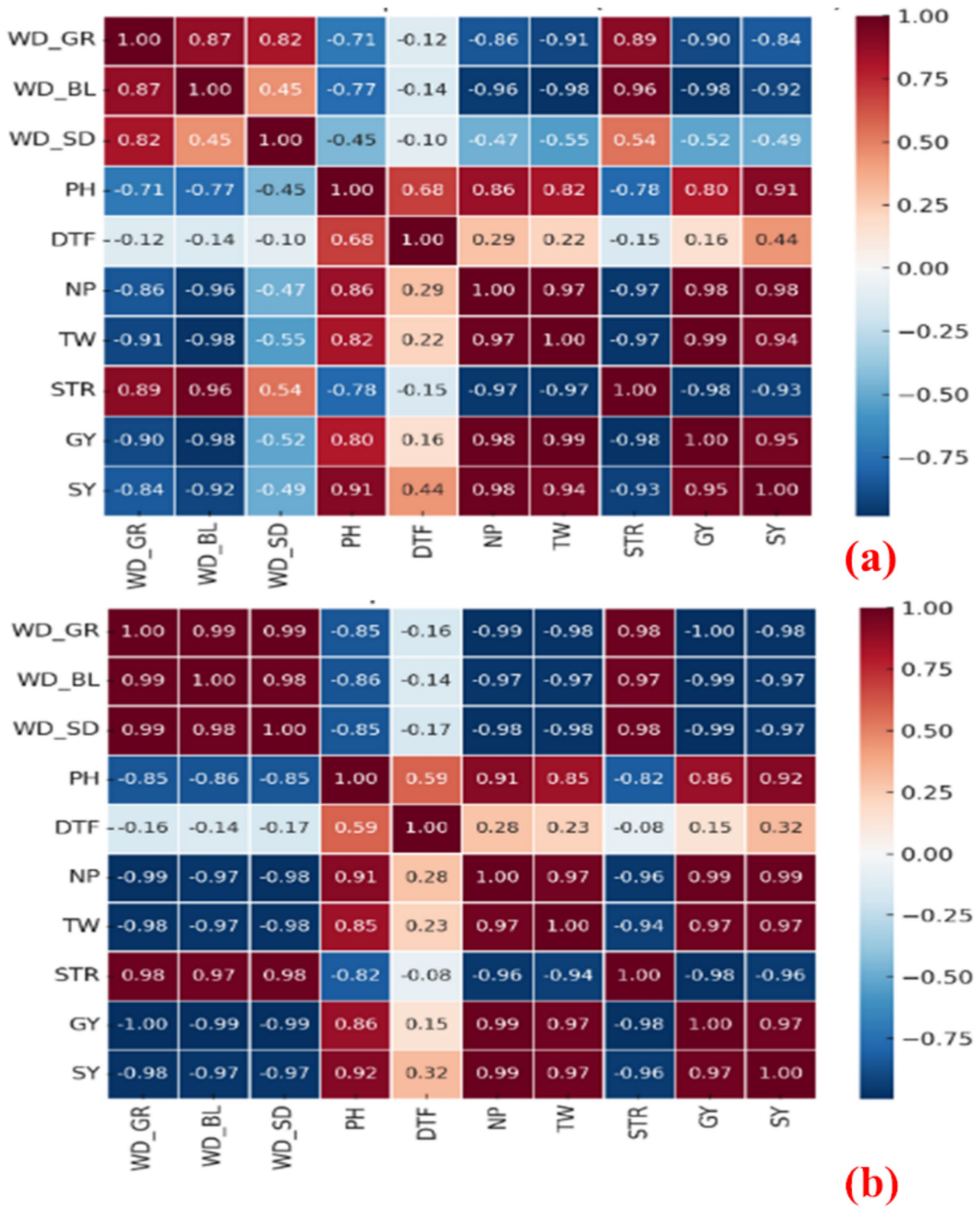


FIGURE 6
Correlation heatmap showing associations among weed density categories at 60 days after herbicide application (60 DAHA) and various growth and yield characteristics of **(A)** IMI-rice genotypes – PB 1979 and PB 1985 and **(B)** all IMI-rice and their recurrent parent genotypes for treatments T_8–T_{10}. PH – Plant height at panicle emergence; DTF – Days to 50% flowering; NP – Panicle density; TW – Test weight; STR – Spikelet sterility; GY – Grain yield; SY – Straw yield; WP_GR – Weed density of grasses at 60 DAHA; WP_BL – Weed density of broadleaf weeds at 60 DAHA; and WP_SD – Weed density of sedges at 60 DAHA.

yield (GY), straw yield (SY), and panicle density (NP), clearly indicated that increased weed pressure severely reduced yield attributes and overall productivity. The highly effective PE integrated herbicide treatments (T_7 and T_8) and two-times hand weeded treatment (T_9), clustered closely with high-yield parameters, and were located opposite to the high weed-density vectors, confirming their strong suppressive effect on weed flora and their positive influence on yield. Conversely, T_{10} (weedy check) plotted distinctly along the weed density vectors, reflecting poor crop performance under unchecked weed competition.

The separation of treatments along PC1 clearly represented a weed-pressure gradient, with lower-dose imazethapyr treatments (T_1–T_3) and sequential applications (T_4–T_6) occupying intermediate positions between the effective integrated treatments and the weedy check, indicating moderate weed suppression relative to T_{10}, but inferior performance compared with pendimethalin 0.75 kg a.i. ha^{-1} *f.b.* imazethapyr 100 g a.i. ha^{-1} (T_7) and the twice hand-weeded treatment (T_9) (Figure 7A). For PB 1985, PC1 and PC2 accounted for 96.8% of the total variation, with patterns largely consistent with PB 1979, where T_7, T_8 and T_9 were closely associated with positive yield parameters

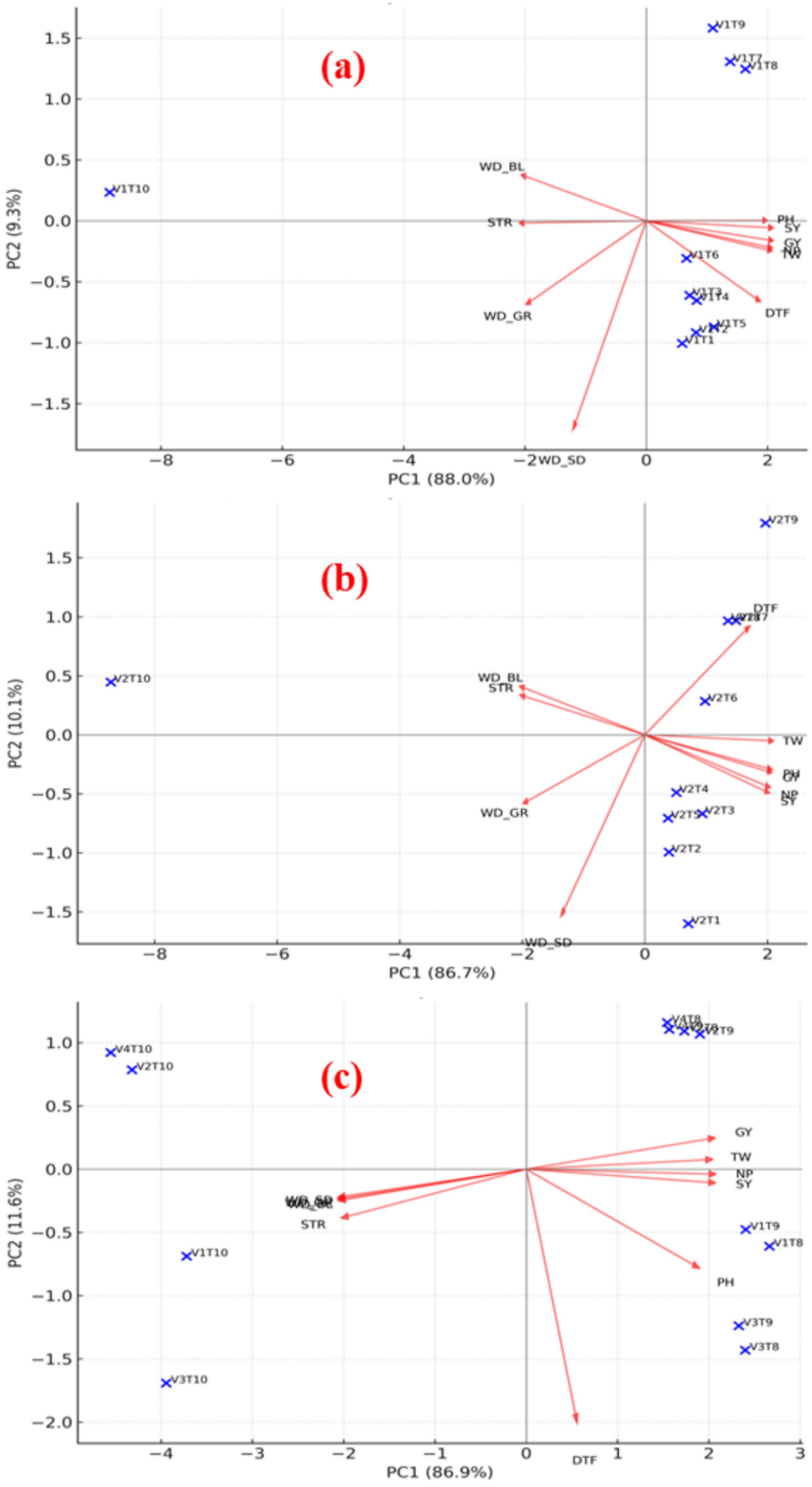


FIGURE 7
Principal component analysis (PCA) biplot showing associations among weed density categories at 60 DAHA and various growth and yield characteristics of **(A)** IMI-rice genotype PB 1979, **(B)** IMI-rice genotype PB 1985, and **(C)** all IMI-rice and their recurrent parents' genotypes for treatments T_8–T_{10}. V_1 – PB 1979, V_2 – PB 1985; V_3 – PB 1121; V_4 – PB 1509 and T_1 to T_{10} represent all the various weed management regimes stated in materials and methods section. PH – Plant height at panicle emergence; DTF – Days to 50% flowering; NP – Panicle density; TW – Test weight; STR – Spikelet sterility; GY – Grain yield; SY – Straw yield; WP_GR – Weed density of grasses at 60 DAHA; WP_BL – Weed density of broadleaf weeds at 60 DAHA; and WP_SD – Weed density of sedges at 60 DAHA. Trait vectors indicate the contribution of each variable to total variance, and treatment scores represent their relative positions along the principal components.

(GY, SY, NP) and positioned opposite to the weed density vectors, while the weedy check (T_{10}) again occupied a distinct quadrant defined by high weed densities, sterility (STR) and extremely low grain and straw yields (Figure 7B).

Finally, when PCA was performed using data from four genotypes (PB 1979, PB 1985, PB 1121, and PB 1509) across the three common treatments (T_8, T_9, and T_{10}), the first two components (PC1 and PC2) together explained 98.5% of the total variation, starkly revealing genotypic and treatment variations. The two-hand weeding treatment (T_9) and pendimethalin @ 0.75 kg a.i. ha^{-1} *f.b.* bispyribac-Na @ 25 g a.i. ha^{-1} (T_8) treatments for both tolerant lines and recurrent parents clustered in quadrants associated with higher yield (GY, SY), panicle density (NP), and optimal plant height, clearly segregating them from the weedy check (T_{10}) across all genotypes. The T_{10} points grouped near the vectors for weed densities and sterility, reflecting the strong negative association between weed load and productivity, while the tolerant lines (PB 1979 and PB 1985) maintained a superior growth and yield advantage compared to their recurrent parents, which clustered close to moderate-yield and higher-weed-load regions, effectively distinguishing varietal tolerance and herbicide efficacy (Figure 7C).

3.10 Z-score clustering heatmap analysis

The z-score heatmap visualized relative treatment performance across all traits, confirming the efficacy hierarchies observed in the previous analyses. Treatments T_7, T_8, and T_9 formed a close cluster, demonstrating low weed density and high yield and associated attributes, achieving efficacy comparable to manual weeding. Within this cluster, Positive z-scores (red cells) were strongly concentrated for high-value traits like grain yield (GY), straw yields (SY), plant height, panicle density (NP), and test weight (TW), confirming their above-average performance. Conversely, T_{10} exhibited strong negative z-scores for all yield attributes and pronounced positive z-scores for weed densities, consistent with severe weed competition and poor growth, and its distinctly separate positioning confirmed its poor agronomic performance (Figure 8). A second group of close clusters was formed by the singular or sequential application of imazethapyr regimes (T_1–T_6), indicating higher weed densities, where, low-dose imazethapyr applications (T_1–T_3) proved insufficient, and while sequential sprays (T_4–T_6) improved weed control, they still considerably lagged behind pendimethalin-integrated regimes (Figure 8).

This robust pattern was further validated when a similar z-score clustering heatmap was arranged for four genotypes across treatments T_8, T_9, and T_{10}, showing consistent patterns (Figure 9). T_8 and T_9 across all four varietal sets maintained positive z-score for yield traits and negative z-scores for weed density, verifying their stable, superior performance, while T_{10} consistently displayed high weed density and extremely low yield regardless of variety. Hierarchical clustering grouped T_8 and T_9 closely across genotypes, while T_{10} formed a distinct outlier branch, indicating consistent treatment-wise divergence in weed suppression and yield response across the tested genotypes.

The combined multivariate evidence thus emphasizes that integrated and sequential herbicide strategies are superior to single-application imazethapyr, with T_7 and T_8 achieving weed control and yield responses statistically equivalent to the hand weeded treatment (T_9), thereby offering a practical robust, and high-yielding alternative under labor-limited conditions. The strong inverse correlation between weed density and yield attributes further confirms that lower weed pressure is closely associated with improved crop performance under the present experimental conditions.

3.11 Assessment of soil residue and crop bioassay for herbicide carryover

The assessment of soil residue through crop bioassay indicated that the residual effect of imazethapyr-based weed management treatments on succeeding *rabi* (winter) crops at 45 DAS was minimal. The growth of succeeding crops (potato, gram, mustard, pea and wheat) did not vary significantly across plots previously treated with different imazethapyr regimes, suggesting no residual phytotoxicity or adverse effect on crop establishment. This absence of carryover effect may be attributed to the degradation and dissipation of imazethapyr in soil before the establishment of succeeding crops, resulting in residue levels below phytotoxic thresholds. Growth parameters, including plant population (m^{-2}), plant height, and plant dry biomass (g m^{-2}) of IMI treatments (T_1-T_7)remained statistically comparable with hand-weeded treatment (T_9), weedy check (T_{10}) and the recommended treatment (T_8) (Tables 7–9). However, during the 2020 *rabi* (winter) season, potato dry biomass was significantly reduced under the highest sequential dose of imazethapyr (200 + 200 g a.i. ha^{-1}), indicating a possible dose-dependent and weather related effects. This effect was not observed in the subsequent 2021 season (Table 9). The treatment comprising pendimethalin (0.75 kg a.i. ha^{-1}) followed by imazethapyr (100 g a.i. ha^{-1}) showed no adverse effects on any succeeding crop, indicating its safety and compatibility. Considering its effective weed control, yield performance and lack of residual toxicity, T_7 appears to be a suitable alternative to the existing recommendation.

4 Discussion

Effective weed management is critical for maximizing productivity in dry DSR, where simultaneous crop–weed emergence under aerobic conditions intensifies competition during early growth stages, severely limiting tiller survival, panicle formation, and grain yield (Chauhan, 2012; Rao et al., 2007). The study demonstrated strong evidence that the deployment of IMI-tolerant basmati rice genotypes, Pusa Basmati 1979 and Pusa Basmati 1985, is essential for enabling effective chemical weed control. These HT genotypes consistently outperformed their recurrent parents (PB 1121 and PB 1509) across all imazethapyr-based regimes. The recurrent parents, lacking the necessary tolerance, were severely penalized under imazethapyr application. This confirms that the successful deployment of ALS-inhibiting herbicides intrinsically depends on the availability of the corresponding HT genetic backgrounds that prevent herbicide binding, allowing selective weed control without crop injury (Kar et al., 2024; Tan et al., 2005; Chiapinotto et al., 2024).

Understandably, weed infestation in the weedy check plots resulted in severe yield reductions, emphasizing the magnitude of losses that can occur in the absence of effective control measures. This is primarily due to intense competition for light, nutrients, and moisture during early crop establishment, which restricts tiller development and panicle formation, ultimately reducing yield potential. These findings are consistent with earlier reports that weeds can cause yield losses up to 60% in rice when left uncontrolled (Chauhan, 2012; Rao

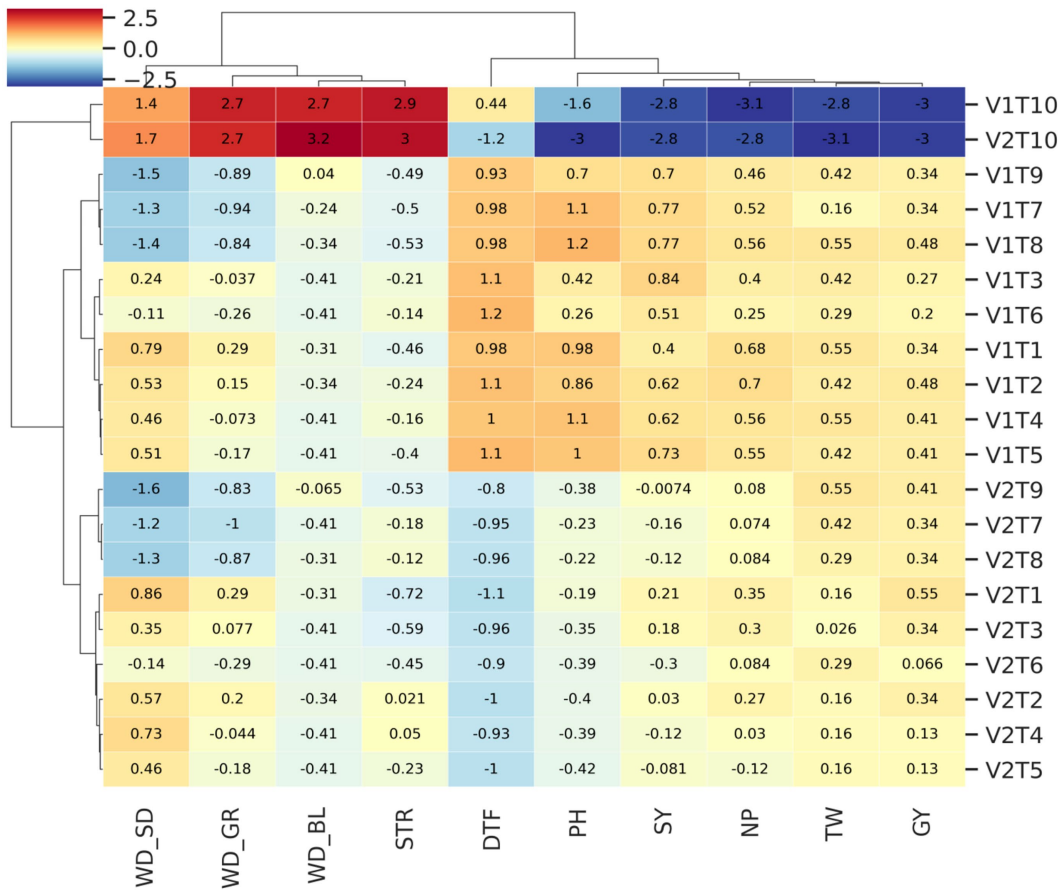


FIGURE 8
Hierarchically clustered *z*-score heatmap showing similarity patterns among weed density categories at 60 DAHA and growth and yield characteristics of IMI-rice genotypes – PB 1979 and PB 1985. T_1 to T_{10} represent all the various weed management regimes stated in materials and methods section. PH – Plant height at panicle emergence; DTF – Days to 50% flowering; NP – Panicle density; TW – Test weight; STR – Spikelet sterility; GY – Grain yield; SY – Straw yield; WP_GR – Weed density of grasses at 60 DAHA; WP_BL – Weed density of broadleaf weeds at 60 DAHA; and WP_SD – Weed density of sedges at 60 DAHA.

et al., 2007). Sequential application of imazethapyr provided better weed suppression than single sprays in reducing weed biomass at 60 DAHA, as it enables the control of both early- and late-emerging weed flushes, which are common under aerobic conditions. Similar observations have been reported in soybean and maize systems where sequential imidazolinone applications extended weed control into the later crop growth stages (Shaner, 2014). Importantly, the pendimethalin (0.75 kg a.i. ha^{-1}) *followed by* imazethapyr (100 g a.i. ha^{-1}) offered the optimal weed suppression as PE pendimethalin helped by controlling non-target weeds of imazethapyr and maximized crop performance. This may be attributed to the complementary action of pre-emergence and post-emergence herbicides, where pendimethalin suppresses initial weed flushes while imazethapyr controls later-emerging weeds. Conversely, higher spray doses, particularly the sequential post-application of imazethapyr at 125 + 125 g a.i. ha^{-1} and 200 + 200 g a.i. ha^{-1} did not result in proportional yield benefits, likely due to diminishing returns beyond optimal dose thresholds. This supports the concept of herbicide dose optimization to avoid unnecessary chemical load, mitigate environmental risk and minimize production costs.

Weed flora assessments revealed grasses as the predominant weed group (~40–45% of total density at 1 DBHA escalating to ~70% of total density at 60 DAHA), followed by broadleaves and sedges. Both early-season and later weed flushes strongly influenced yield formation. Single-dose imazethapyr applications provided effective suppression of sedges and broadleaves but were insufficient against later-emerging and more competitive grasses, such as *Eleusine indica*, This is due to the relatively lower sensitivity of certain grassy weeds to ALS-inhibiting herbicides, coupled with their rapid growth rate and competitive ability under aerobic soil conditions.

While sequential imazethapyr applications improved the control of these late-emerging grasses, the highest efficacy and most sustained suppression were achieved with the pre-emergence pendimethalin followed by a post-emergence imazethapyr or bispyribac-Na. These regimes reduced total weed densities by ~80% and successfully achieved grain yields comparable to the hand weeded plots (Chauhan et al., 2015). These findings emphasize that integration of pre- and post-emergence herbicides is a superior management strategy to relying solely on single post-emergence applications in DSR systems because pre-emergence herbicides suppress initial weed cohorts, while post-emergence applications target later-emerging individuals, ensuring season-long control (Choudhary and Dixit, 2021).

The present study, in accordance with recent literature (Sharma et al., 2024; Kumar et al., 2015), demonstrated that imazethapyr-based

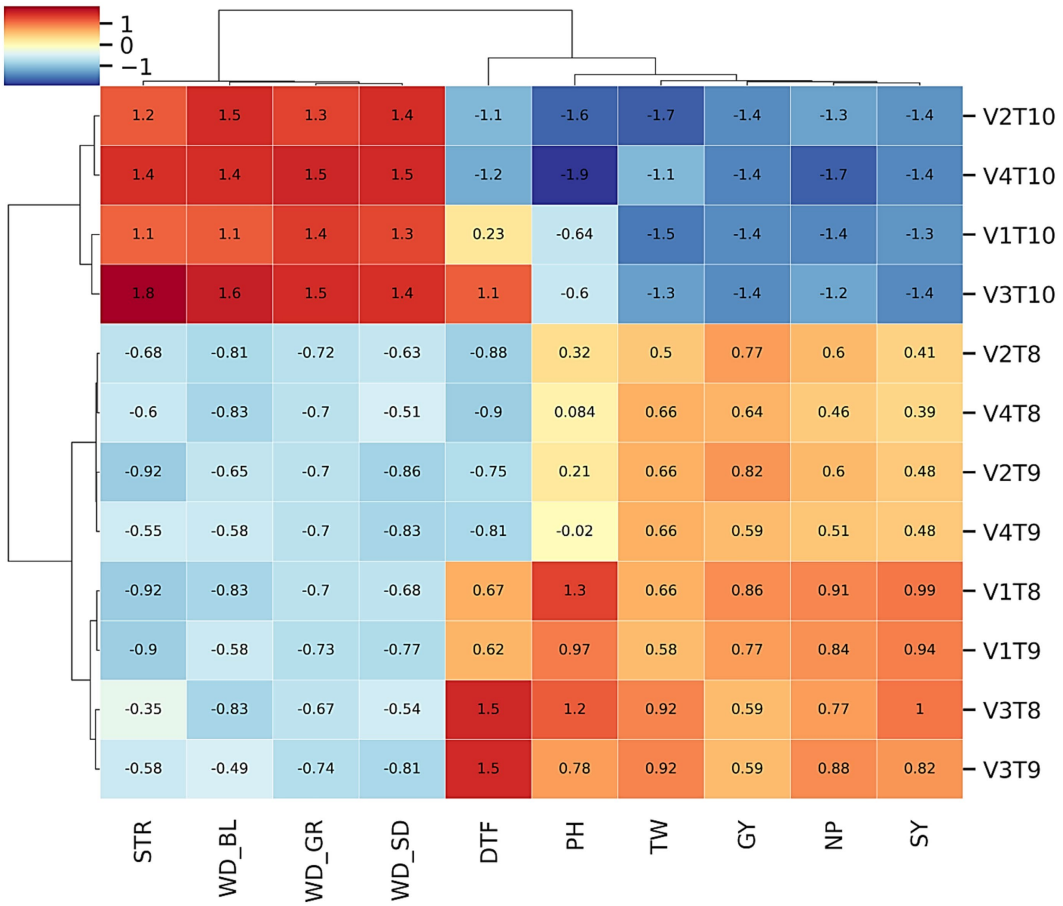


FIGURE 9
Hierarchically clustered *z*-score heatmap showing similarity patterns among weed density categories at 60 DAHA and growth and yield characteristics of all IMI-rice and their recurrent parent genotypes. T_8 to T_{10} represent all the various weed management regimes stated in materials and methods section. PH – Plant height at panicle emergence; DTF – Days to 50% flowering; NP – Panicle density; TW – Test weight; STR – Spikelet sterility; GY – Grain yield; SY – Straw yield; WP_GR – Weed density of grasses at 60 DAHA; WP_BL – Weed density of broadleaf weeds at 60 DAHA; and WP_SD – Weed density of sedges at 60 DAHA.

TABLE 7 Plant height (cm) at 45 DAS recorded during bioassay studies assessing the residual effect of imazethapyr herbicidal treatments on the following crop in 2020 and 2021 at PAU, Ludhiana (sandy loam soil).

Weed control treatments	Plant height (cm) at 45 DAS															
	2020								2021							
	Potato		Gram		Mustard		Wheat		Potato		Gram		Peas		Mustard		Wheat	
T_1	16.3	a	13.8	a	8.9	a	16.6	a	14.3	a	11.6	a	20.6	a	10.6	a	26.3	a
T_2	16.3	a	13.7	a	8.8	a	16.8	a	14.2	a	11.7	a	20.9	a	11.1	a	25.9	a
T_3	16.5	a	13.7	a	8.8	a	16.5	a	14.3	a	11.5	a	20.5	a	10.6	a	26.3	a
T_4	16.2	a	13.8	a	8.9	a	16.8	a	14.4	a	11.6	a	20.6	a	10.5	a	26.2	a
T_5	16.3	a	13.9	a	8.8	a	16.9	a	14.2	a	11.8	a	20.4	a	11.1	a	26.1	a
T_6	15.7	a	13.7	a	8.5	a	16.7	a	13.9	a	11.4	a	20.7	a	10.1	a	26.3	a
T_7	16.4	a	13.8	a	9.0	a	16.6	a	14.4	a	11.6	a	20.9	a	10.3	a	26.3	a
T_8	16.3	a	13.9	a	9.1	a	16.5	a	14.3	a	11.6	a	20.8	a	10.4	a	26.3	a
T_9	16.4	a	13.7	a	8.9	a	16.6	a	14.5	a	11.5	a	20.6	a	10.4	a	26.3	a
T_{10}	16.5	a	13.6	a	8.9	a	16.8	a	14.4	a	11.6	a	20.9	a	10.5	a	26.4	a
L.S.D. ($p \leq 0.05$)	NS		NS		NS		NS		NS		NS		NS		NS		NS	

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods.

TABLE 8 Plant population/ m² at 45 DAS recorded during bioassay studies assessing the residual effect of imazethapyr herbicidal treatments on the following crop in 2020 and 2021 at PAU, Ludhiana (sandy loam soil).

Weed control treatments	Plant population/m² at 45 das															
	2020								2021							
	Potato		Gram		Mustard		Wheat		Potato		Gram		Peas		Mustard		Wheat	
T_1	7.2	a	17.2	a	52.5	a	40.4	a	8.6	a	18.6	a	11.7	a	36.4	a	57.5	a
T_2	7.2	a	17.4	a	52.1	a	42.1	a	8.7	a	19.1	a	11.8	a	35.8	a	55.9	a
T_3	7.5	a	17.5	a	51.6	a	40.8	a	8.3	a	18.9	a	11.9	a	32.2	a	57.5	a
T_4	7.1	a	17.3	a	52.6	a	41.2	a	8.5	a	18.6	a	12.0	a	33.9	a	57.5	a
T_5	7.3	a	17.5	a	51.2	a	41.5	a	8.7	a	18.5	a	12.1	a	35.7	a	56.9	a
T_6	7.2	a	17.6	a	52.1	a	40.8	a	8.5	a	18.7	a	11.8	a	33.2	a	55.8	a
T_7	7.6	a	17.5	a	52.2	a	40.9	a	8.6	a	18.6	a	11.9	a	36.7	a	57.1	a
T_8	7.6	a	17.7	a	52.1	a	41.0	a	8.5	a	18.5	a	12.0	a	36.6	a	56.9	a
T_9	7.5	a	17.5	a	52.3	a	40.9	a	8.6	a	18.7	a	11.9	a	36.4	a	57.2	a
T_{10}	7.4	a	17.4	a	52.1	a	40.5	a	8.7	a	18.5	a	11.9	a	36.1	a	57.1	a
L.S.D. ($p \leq 0.05$)	NS		NS		NS		NS		NS		NS		NS		NS		NS	

Different letters indicate significant differences among treatments at $p \leq 0.05$. *T_1-T_{10} refers to the weed management treatments specified in materials and methods.

TABLE 9 Fresh weight (g/m²) at 45 DAS recorded during bioassay studies assessing the residual effect of imazethapyr herbicidal treatments on the following crop in 2020 and 2021 at PAU, Ludhiana (sandy loam soil).

Weed control treatments	Fresh weight (g/m²) at 45 DAS															
	2020								2021							
	Potato		Gram		Mustard		Wheat		Potato		Gram		Peas		Mustard		Wheat	
T_1	1100.0	a	160.0	a	101.0	a	767.0	a	1332.0	a	193.0	a	288.0	a	87.0	a	973.0	a
T_2	1105.0	a	165.0	a	100.0	a	779.0	a	1375.0	a	205.0	a	278.0	a	87.0	a	969.0	a
T_3	1074.0	ab	171.0	a	99.0	a	775.0	a	1333.0	a	201.0	a	288.0	a	86.0	a	972.0	a
T_4	1089.0	a	172.0	a	101.0	a	785.0	a	1359.0	a	209.0	a	290.0	a	86.0	a	975.0	a
T_5	1079.0	ab	168.0	a	98.5	a	769.0	a	1328.0	a	204.0	a	275.0	a	83.0	a	964.0	a
T_6	985.0	b	169.0	a	97.9	a	772.0	a	1299.0	a	214.0	a	289.0	a	79.0	a	960.0	a
T_7	1096.0	a	170.0	a	102.0	a	770.0	a	1346.0	a	204.0	a	286.0	a	87.0	a	972.0	a
T_8	1099.0	a	169.0	a	100.0	a	773.0	a	1340.0	a	203.0	a	281.0	a	88.0	a	981.0	a
T_9	1101.0	a	168.0	a	99.0	a	771.0	a	1339.0	a	202.0	a	287.0	a	87.0	a	976.0	a
T_{10}	1105.0	a	170.0	a	101.0	a	771.0	a	1365.0	a	205.0	a	279.0	a	87.0	a	979.0	a
L.S.D. ($p \leq 0.05$)	57		NS		NS		NS		NS		NS		NS		NS		NS	

Different letters indicate significant differences among treatments at $p \leq 0.05$.*T_1-T_{10} refers to the weed management treatments specified in materials and methods.

weed management, particularly when integrated with pre-emergence herbicides such as pendimethalin, provided highly effective control of complex weed flora in direct-seeded basmati rice, while also ensuring safety for succeeding crops. The relative suppression effect of imazethapyr, showed the greatest suppression of grasses and sedges followed by broadleaf weeds (Kumar et al., 2015), is consistent with global findings. However, the partial survival of grassy weeds under single-dose applications underscores the selectivity and efficacy limitations of this herbicide when used alone, a challenge repeatedly observed in the Indo-Gangetic plains (Kumar and Ladha, 2011; Chauhan, 2012). This corroborates the global call for optimized herbicidal regimes and integrated weed management systems in conjunction with the utilization of the imidazolinone-herbicide tolerant rice genotypes, owing to the moderate effectiveness of IMI herbicide on an array of grassy weeds (Ulguim et al., 2021).

Furthermore, correlation and multivariate analysis (PCA and clustering analyses) also provided clear evidence that integrated and sequential herbicide applications significantly improved the growth and yield performance compared to single PoE applications of imazethapyr. The PE herbicide integrative regimes pendimethalin 0.75 kg a.i. ha^{-1} *f.b.* imazethapyr @ 100 g a.i. ha^{-1} (T_7) or bispyribac-Na @ 25 g a.i. ha^{-1} (T_8) achieved superior weed suppression, reflected by minimal weed densities and maximized grain and straw yields. Their proximity to the hand weeded

treatment (T_9) in the multivariate space explicitly demonstrates that these combinations mimic the efficacy of manual weeding (Figures 5–8). These multivariate patterns confirm that weed suppression is the primary determinant of yield variability across treatments. The superiority reflects the necessary complementarity of pre- and post-emergence herbicides, which target both early-emerging and later weed flushes. Several authors have stressed that season-long weed control in DSR requires such integration, as PE herbicides provide the first line of suppression while PoE products manage later flushes resulting in improved WCE and yield advantages compared to single-application strategies (Mahajan and Chauhan, 2011; Mahajan and Chauhan, 2013). These integrated programs not only matched but often equaled hand-weeding in efficiency, highlighting their potential to reduce labor reliance in regions facing escalating rural wages.

The comprehensive multivariate analyses (PCA and Z-score heatmaps) strongly supported the field evaluation data, with the weedy check (T_{10}) consistently positioned opposite to yield vectors in PCA space and displayed deep-blue (negative) z-scores for productivity traits, representing the lowest agronomic performance. Conversely, the moderate-performing treatments (T_1–T_6) reflect the partial control achieved by varying imazethapyr regimes, with T_5 (imazethapyr @ 125 + 125 g a.i. ha^{-1}) performing optimally within this group and clustering near the highly effective integrated treatments (T_7 and T_8). This suggests that sequential applications enhance weed control duration and reduce regrowth between spray intervals, though they remain inferior to integrated pre-emergence approaches. The molecular basis of imidazolinone herbicide tolerance in these lines (mutations in the acetohydroxy acid synthase (AHAS) gene) allows them to withstand otherwise injurious doses, providing a necessary genetic platform for chemical weed control (Kar et al., 2024; Tan et al., 2005).

Performance differences between the HT and recurrent parent genotypes were stark, as the recurrent parents (PB 1121 and PB 1509) showed negligible survival under imazethapyr treatments, reaffirming that the deployment of imazethapyr is only feasible in tolerant genotypes. In contrast, HT lines not only resisted imazethapyr but also demonstrated improved growth and yield attributes under reduced weed pressure, validating the genetic advantage conferred by altered ALS alleles in HT backgrounds, as reported in Clearfield® rice and wheat systems globally (Kar et al., 2024; Sudianto et al., 2013; Tan et al., 2005).

However, the drastic penalties observed in the weedy check, which confirmed that unchecked weed pressure can reduce DSR yields by >80%, concurs with global estimates ranging from 40–90% depending on species composition and crop establishment (Rao et al., 2007; Chauhan and Johnson, 2011). The correlation analysis further emphasizes that weed biomass exerts its greatest impact on tiller survival and harvest index. The strong negative associations between weed biomass and yield components mirror reports from IRRI indicating that weed competition reduces assimilate availability for reproductive development, thereby lowering harvest index and grain yield (Chauhan and Johnson, 2011; Chauhan and Opena, 2013). These insights highlight that effective weed suppression not only prevents direct resource competition but also safeguards reproductive efficiency.

The bioassay studies confirm that imazethapyr residues in sandy loam soils of Punjab did not show carryover risks to succeeding *rabi* (winter) crops such as wheat, gram, mustard, peas or potato under present conditions. A similar non-significant effect was observed in succeeding pearl millet and sorghum and black gram treated with various doses of imazethapyr (Sharma et al., 2024). This can be attributed to rapid microbial degradation of imazethapyr under aerobic soil conditions, resulting in residue levels below phytotoxic thresholds before establishment of succeeding crops. Although several studies report no significant residual impact of imazethapyr on succeeding crops, others have documented its potential leaching to greater soil depths and adverse effects on soil microbial health and successive crop growth under prolonged or high-dose usage (Kundu et al., 2011; Lyon and Wilson, 2005; Sondhia, 2013; Zhang et al., 2010). The significant reduction in potato biomass observed in 2020 under the highest sequential imazethapyr dose, but not in 2021, may be attributed to year-to-year variation in environmental conditions influencing herbicide persistence and degradation (Table 9).

Differences in rainfall and temperature between seasons may have accelerated herbicide degradation in 2021, thereby reducing residual effects. Higher soil moisture under increased rainfall conditions (+358.6 mm; ~89% higher rainfall in *kharif* 2021) and more humid conditions is known to accelerate herbicide leaching to lower soil layers (Sondhia, 2013) and dissipation through microbial activity. Imazethapyr exhibits weak and reversible sorption in soils, with degradation occurring primarily through microbial metabolism under aerobic conditions with a half-life of ~60–90 days, indicating moderate persistence with minimal leaching or volatilization (Shaner, 2014). Hence, the lower dose of imazethapyr in combination with a PE herbicide such as pendimethalin (T_7 – pendimethalin @ 0.75 kg a.i. ha^{-1} + imazethapyr @100 g a.i. ha^{-1}) proved most effective, achieving the best balance between strong weed suppression while minimizing chemical residue in soil, preserving soil microbial health and still significantly obtaining higher grain and straw yields. These findings are crucial for crop rotations in the Indo-Gangetic plains, where *rabi* (winter) crops follow rice without significant fallow, and residual toxicity could otherwise threaten system sustainability.

Despite the apparent benefits, we must not disregard the potential challenges associated with the complete adoption of HT rice on soil and crop health. Indeed, evidence of imazethapyr-tolerant populations has already emerged in Asia (Chander et al., 2023; Hu et al., 2025) and Latin America (Bonow et al., 2018; Matzenbacher et al., 2015). Strategic diversification of herbicide modes of action, i.e., integration of PE pendimethalin, along with cultural measures such as stale seedbed techniques and competitive cultivars, is therefore essential to prolong the useful life of this chemistry (Abraham and Jose, 2015; Kaur and Singh, 2017; Singh et al., 2018). Long-term cultivation of HT rice can lead to evolutionary consequences, as population genetic studies have shown that herbicide-tolerant weedy rice often arises through gene flow from tolerant cultivars and subsequent seed dispersal (Merotto Jr et al., 2016).

From a systems perspective, the present results highlight both opportunity and caution. HT rice combined with imazethapyr-based regimes can deliver reliable, labor-saving weed control, making DSR more attractive under water and labor scarcity (Kumar et al., 2025; Mahajan and Chauhan, 2013; Singh et al., 2011). On the other hand, the ecological risks of herbicide overuse (weed flora shifts, resistance evolution and soil microbial perturbations) are real and documented (Chiapinotto et al., 2024; Norsworthy et al., 2012; Ulguim et al., 2021). The most sustainable path forward is therefore an integrated approach: rotation of herbicides with different sites of action, combination of pre- and post-emergence herbicides, and incorporation of cultural practices that reduce weed seedbank pressure.

The combination of HT rice with pendimethalin followed by imazethapyr at lower dose 100 g a.i. ha^{-1}, as in the present study (T_7), offers combines efficacy with notable advantages and multiple merits. It reduces reliance on labor-intensive manual weeding, ensures broad-spectrum weed suppression and potentially delays the onset of herbicide resistance by integrating two modes of action. However, continuous and indiscriminate use of imazethapyr alone could still exert selection pressure on weed populations, necessitating careful stewardship and rotation with other herbicides and cultural practices.

5 Conclusion

The superior field performance of the integrated weed management strategy is directly attributable to the complementary temporal and biochemical activities of pendimethalin followed by imazethapyr. Pendimethalin forms a critical pre-emergence barrier that effectively inhibits the germination of the early flush of grasses and broadleaf weeds, whereas the subsequent application of imazethapyr, which is systemic and selective through ALS enzyme inhibition characterized by shoot and root activity, efficiently targets later-emerging and residual weeds. This temporal sequencing and biochemical complementarity significantly mitigate interspecific competition during the critical early growth phase of DSR, thereby stabilizing tiller survival, improving canopy development, and enhancing grain formation. Consequently, the combination of HT rice genotypes with the pendimethalin (0.75 kg a.i. ha^{-1} at 1–2 DAS) *followed by* post-emergence imazethapyr (100 g a.i. ha^{-1} at 16–18 DAS) provides sustained, broad-spectrum weed suppression, resulting in improved crop growth and enhanced yield potential. The adoption of this integrated herbicide strategy serves as an effective alternative to manual weeding under labor-scarce conditions, capable of improving crop productivity.

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 author/s.

Author contributions

BD: Supervision, Investigation, Conceptualization, Writing – review & editing, Writing – original draft, Formal analysis, Visualization, Data curation. SV: Supervision, Writing – original draft, Visualization, Writing – review & editing, Conceptualization. LV: Data curation, Visualization, Writing – review & editing, Formal analysis, Writing – original draft. SG: Methodology, Supervision, Writing – original draft, Conceptualization, Writing – review & editing. RM: Conceptualization, Supervision, Writing – review & editing, Writing – original draft, Methodology, Visualization. RS: Writing – original draft, Project administration, Validation, Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the ICAR-IIRR through All India Coordinated Project on Rice and Punjab Agricultural University, Ludhiana.

Acknowledgments

The authors extend their gratitude to Punjab Agricultural University, Ludhiana and ICAR-IIRR through All India Coordinated Project on Rice.

Conflict of interest

The author(s) declared that this work 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) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1793203/full#supplementary-material

References

Abraham, C. T., and Jose, N. (2015). Weedy rice invasion and its management. *Ind. J. Weed Sci.* 47, 216–223.

Ahmed, S., Kumar, V., Zaman, A. U., Dewan, M. R., Khatun, A., Hossain, K., et al. (2025). Dry direct-seeded and broadcast rice: a profitable and climate-smart alternative to puddled transplanted aus rice in Bangladesh. *Field Crop Res.* 322:109739. doi: 10.1016/j.fcr.2025.109739

Anonymous (2020a). *Package of Practices for Crops of Punjab-Kharif 2020*. Ludhiana, Punjab: Punjab Agricultural University.

Anonymous (2020b). *Package of Practices for Crops of Punjab-Rabi 2020–21*. Ludhiana, Punjab: Punjab Agricultural University.

Anonymous (2020c). *Package of Practices for Cultivation of Vegetables*. Ludhiana, Punjab: Punjab Agricultural University.

Bhatt, R., Kukal, S. S., Busari, M. A., Arora, S., and Yadav, M. (2016). Sustainability issues on rice–wheat cropping system. *Int. Soil Water Conserv. Res.* 4, 64–74. doi: 10.1016/j.iswcr.2015.12.001

Bonow, J., Lamego, F., Andres, A., Avila, L., Teló, G., and Egewarth, K. (2018). Resistance of *Echinochloa crusgalli var. mitis* to imazapyr+imazapic herbicide and alternative control in irrigated rice. *Planta Daninha* 36:e018168627. doi: 10.1590/s0100-83582018360100028

Burgos, N. R., Singh, V., Tseng, T. M., Black, H., Young, N. D., Huang, Z., et al. (2014). The impact of herbicide-resistant rice technology on phenotypic diversity and population structure of United States weedy rice. *Plant Physiol.* 166, 1208–1220. doi: 10.1104/pp.114.242719

Chander, S., Ghosh, D., Tyagi, V. C., Chethan, C. R., Pawar, D., Gharde, Y., et al. (2023). Imazethapyr-resistant jungle rice (*Echinochloa colona*) in soybean growing belt of Central India: a case study. *Agric. Res.* 12, 298–307. doi: 10.1007/s40003-023-00651-0

Chauhan, B. S. (2012). Weed ecology and weed management strategies for dry-seeded rice in Asia. *Weed Technol.* 26, 1–13. doi: 10.1614/WT-D-11-00105.1

Chauhan, B. S., Ahmed, S., and Awan, T. H. (2015). Performance of sequential herbicides in dry-seeded rice in the Philippines. *Crop Prot.* 74, 124–130. doi: 10.1016/j.cropro.2015.04.013

Chauhan, B. S., and Johnson, D. E. (2011). Row spacing and weed control timing affect yield of aerobic rice. *Field Crop Res.* 121, 226–231. doi: 10.1016/j.fcr.2010.12.008

Chauhan, B. S., and Opena, S. (2013). Weed management and grain yield of rice sown at low seeding rates in mechanized dry-seeded systems. *Field Crop Res.* 141, 9–15. doi: 10.1016/j.fcr.2012.11.002

Chiapinotto, D. M., Avila, L. A., Aranha, B. C., Viana, V. E., Benedetti, L., Araújo, B. O. N., et al. (2024). Potential reduction of non-imidazolinone rice grain yield by imidazolinone soil residual activity. *Adv. Weed Sci.* 42:e020240044. doi: 10.51694/AdvWeedSci/2024;42:00029

Choudhary, V. K., and Dixit, A. (2021). Bio-efficacy of sequential herbicide application for weed management in dry direct seeded rice. *Indian J. Agric. Sci.* 91, 79–83. doi: 10.56093/ijas.v91i1.110930

Choudhary, V. K., Naidu, D., and Dixit, A. (2022). Weed prevalence and productivity of transplanted rice influences by varieties, weed management regimes and row spacing. *Arch. Agron. Soil Sci.* 68, 1872–1889. doi: 10.1080/03650340.2021.1937606

Devi, B. R. (2023). Direct seeded rice as resource efficient technology. *Int. J. Environ. Climate Chang.* 13, 1169–1174. doi: 10.9734/ijecc/2023/v13i82056

Dhanda, S., Yadav, A., Yadav, D. B., and Chauhan, B. S. (2022). Emerging issues and potential opportunities in the rice–wheat cropping system of North-Western India. *Front. Plant Sci.* 13:832683. doi: 10.3389/fpls.2022.832683

Dhillon, B. S., Bansal, T., and Kumar, R. M. (2021a). Managing weed menace in direct seeded rice (*Oryzasativa*): a review. *Ind. J. Agron.* 66, 214–225.

Dhillon, B. S., Bansal, T., Sagwal, P., Kumar, V., Bhullar, M. S., and Singh, S. (2021b). Weed competitive cultivars as a component of integrated weed management in direct-seeded rice: a review. *Ind. J. Weed Sci.* 53, 230–237. doi: 10.5958/0974-8164.2021.00043.5

Dhillon, B. S., and Gill, R. S. (2024). *Basmati: The Nature's Pride to India*. Ludhiana, Punjab: Punjab Agricultural University.

Donald, C. M., and Hamblin, J. (1976). The biological yield and harvest index of cereals as agronomic and plant breeding criteria. *Adv. Agron.* 28, 361–405. doi: 10.1016/S0065-2113(08)60559-3

Heap, I.. (2023). The international herbicide resistant weed database. Available online at: https://www.weedscience.org/Pages/RecentCases.aspx (Accessed October 5, 2025).

Hu, X., Xu, Y., Li, C., Mao, H., Liu, Z., Xiao, Y., et al. (2025). A five-year examination into the occurrence of herbicide-resistant barnyardgrass populations in paddy from Jiangsu Province, China. *Sci. Rep.* 15:14781. doi: 10.1038/s41598-025-99846-4

Jackson, M. L. (1973). *Soil Chemical Analysis*. New Delhi: Prentice Hall of India.

Jat, R. K., Singh, R. G., Gupta, R. K., Gill, G., Chauhan, B. S., and Pooniya, V. (2019). Tillage, crop establishment, residue management and herbicide applications for effective weed control in direct seeded rice of eastern indo–Gangetic Plains of South Asia. *Crop Prot.* 123, 12–20. doi: 10.1016/j.cropro.2019.05.007

Kar, M.K., Chakraborti, M., Munda, S., Saha, S., Swain, P., Mukherjee, A.K., et al. (2024). Herbicide tolerant rice research in India. NRRI Research Bulletin No. 51. ICAR-National Rice Research Institute, Cuttack, Odisha, India, 753006. Available online at: https://icar-nrri.in/wp-content/uploads/2024/08/NRRI_Research-Bulletin-No-51.pdf (Accessed October 17, 2025).

Kaur, S., Ahmed, S., Awan, T. H., Ali, H. H., Singh, R., Mahajan, G., et al. (2024). Adoption pattern of direct-seeded rice systems in three south Asian countries during COVID-19 and thereafter. *Crops* 4, 324–332. doi: 10.3390/crops4030023

Kaur, J., and Singh, A. (2017). Direct-seeded rice: prospects, problems/constraints and researchable issues in India. *Curr. Agric. Res. J.* 5, 3. doi: 10.12944/CARJ.5.1.03

Kumar, V., Choudhary, V. K., Krishnan, S. G., Mishra, J. S., Singh, A. K., and Singh, S. (2025). *Stewardship Guidelines for Non-GM Imazethapyr Tolerant Rice in India*. Jabalpur, Madhya Pradesh: ICAR-Directorate of Weed Research.

Kumar, N., Hazra, K. K., and Nadarajan, N. (2015). Efficacy of post- emergence application of Imazethapyr in summer mungbean (*Vigna radiata* L.). *Legum. Res.* 39, 96–100. doi: 10.18805/lr.v0iOF.6793

Kumar, V., and Ladha, J. K. (2011). Direct-seeding of rice: recent developments and future research needs. In: Sparks, D.L. (ed) *Advances in Agronomy*. Vol. 111, pp. 297–413. (Radarweg, Amsterdam: Academic press, Elsevier Inc). doi: 10.1016/B978-0-12-387689-8.00001-1

Kundu, R., Brahmachari, K., Bera, P. S., Kundu, C. K., and Roychoudhary, S. (2011). Bioefficacy of imazethapyr on the prominent weeds in soybean. *J. Crop Weed.* 7, 173–178.

Lindsay, W. L., and Norvell, W. A. (1978). Development of a DTPA soil test for zinc iron manganese and copper. *Soil Sci. Soc. Am. J.* 42, 421–428. doi: 10.2136/sssaj1978.03615995004200030009x

Lyon, D. J., and Wilson, R. G. (2005). Chemical weed control in dryland and irrigated chickpea. *Weed Technol.* 19, 959–965. doi: 10.1614/WT-05-013R.1

Mahajan, G., and Chauhan, B. S. (2011). Effects of planting pattern and cultivar on weed and crop growth in aerobic rice system. *Weed Technol.* 25, 521–525. doi: 10.1614/WT-D-11-00025.1

Mahajan, G., and Chauhan, B. S. (2013). Herbicide options for weed control in dry-seeded aromatic rice in India. *Weed Technol.* 27, 682–689. doi: 10.1614/WT-D-13-00016.1

Mahajan, G., Matloob, A., Singh, R., Singh, V. P., and Chauhan, B. S. (2018). Basmati rice in the Indian subcontinent: strategies to boost production and quality traits. *Adv. Agron.* 151, 159–213. doi: 10.1016/bs.agron.2018.04.002

Mani, V. S., Malla, M. C., Gautam, K. C., and Bhagwant, S. (1973). Weed killing chemicals in potato cultivars. *Indian Farming* 32, 17–18.

Matloob, A., Khaliq, A., Tanveer, A., Hussain, S., Aslam, F., and Chauhan, B. S. (2015). Weed dynamics as influenced by tillage system, sowing time and weed competition duration in dry-seeded rice. *Crop Prot.* 71, 25–38. doi: 10.1016/j.cropro.2015.01.009

Matzenbacher, F. O., Bortoly, E. D., Kalsing, A., and Merotto, A. Jr. (2015). Distribution and analysis of the mechanisms of resistance of barnyardgrass (*Echinochloa crus-galli*) to imidazolinone and quinclorac herbicides. *J. Agric. Sci.* 153, 1044–1058. doi: 10.1017/s0021859614000768

Merotto, A. Jr., Goulart, I. C. G. R., Nunes, A. L., Kalsing, A., Markus, C., Menezes, V. G., et al. (2016). Evolutionary and social consequences of introgression of nontransgenic herbicide resistance from rice to weedy rice in Brazil. *Evol. Appl.* 9, 837–846. doi: 10.1111/eva.12387

Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webser, T. M., et al. (2012). Reducing the risks of herbicide resistance: best management practices. *Weed Sci.* 60, 31–62. doi: 10.1614/WS-D-11-00155.1

Olsen, S. R., Cole, C. V., Watanabe, F. S., and Dean, L. A. (1954). *Estimation of Available Phosphorus in Soils by Extraction with sodium Bicarbonate USDA Circular 939*. Washington DC: United States Department of Agriculture.

Ramesh, K., Vijayakumar S, Upadhyay, P. K., and Chauhan, B. S. (2021). Revisiting the concept of the critical period of weed control. *J. Agric. Sci.* 159, 636–642. doi: 10.1017/S0021859621000939

Rao, A. N., Johnson, D. E., Sivaprasad, B., Ladha, J. K., and Mortimer, A. M. (2007). Weed management in direct-seeded rice. *Adv. Agron.* 142, 171–221. doi: 10.1016/S0065-2113(06)93004-1

Rathod, A. M., Patel, T. U., Diwan, S., and Vaja, R. P. (2025). Predominate weed flora in summer rice as influenced by methods of establishment and weed management practices. *Bioscan* 20, 756–763. doi: 10.63001/tbs.2025.v20.i01.pp756-763

Rodenburg, J., and Demont, M. (2009). Potential of herbicide-resistant rice technologies for sub-Saharan Africa. *AgBioforum* 12, 313–325.

Shaner, D. L. (2014) in *Herbicide Handbook*, ed. Herbicide Handbook Committee. 10th ed (Lawrence, Kansas: Weed Science Society of America).

Sharma, K., Punia, S. S., Mehta, A. K., and Leharwan, M. (2024). Bioefficacy of imazethapyr applied alone and in combination with other herbicides in black gram and their residual effect on succeeding pearl-millet and sorghum crops. *Legum. Res.* 47, 106–112. doi: 10.18805/LR-4494

Shoba, D., Raveendran, M., Manonmani, S., Utharasu, S., Dhivyapriya, D., Subhasini, G., et al. (2017). Development and genetic characterization of a novel herbicide (Imazethapyr) tolerant mutant in rice (*Oryza sativa* L.). *Rice* 10:10. doi: 10.1186/s12284-017-0151-8

Siddiq, E. A., Vemireddy, L. R., and Nagaraju, J. (2012). Basmati Rices: genetics, breeding and trade. *Agric. Res.* 1, 25–36. doi: 10.1007/s40003-011-0011-5

Singh, M., Bhullar, M. S., and Gill, G. (2018). Integrated weed management in dry-seeded rice using stale seedbeds and post sowing herbicides. *Field Crop Res.* 224, 182–191. doi: 10.1016/j.fcr.2018.03.002

Singh, V. P., Singh, S. P., Dhyani, V. C., Banga, A., Kumar, A., Satyawali, K., et al. (2016). Weed management in direct-seeded rice. *Ind. J. Weed Sci.* 48, 233–246. doi: 10.5958/0974-8164.2016.00059.9

Singh, Y., Singh, V. P., Singh, G., Yadav, D. S., Sinha, R. K., Johnson, D. E., et al. (2011). The implications of land preparation, crop establishment method and weed management on rice yield variation in the rice–wheat system in the indo-Gangetic plains. *Field Crop Res.* 121, 64–74. doi: 10.1016/j.fcr.2010.11.012

Sondhia, S. (2013). Evaluation of imazethapyr leaching in soil under natural rainfall conditions. *Ind. J. Weed Sci.* 45, 58–61.

Subbiah, B. V., and Asija, G. L. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.* 25, 259–260.

Sudianto, E., Song, B. K., Neik, T. X., Saldain, N. E., Scott, R. C., and Burgos, N. R. (2013). Clearfield® rice: its development, success, and key challenges on a global perspective. *Crop Prot.* 49, 40–51. doi: 10.1016/j.cropro.2013.02.013

Tan, S., Evans, R. R., Dahmer, M. L., Singh, B. K., and Shaner, D. L. (2005). Imidazolinone-tolerant crops: history, current status and future. *Pest Manag. Sci.* 61, 246–257. doi: 10.1002/ps.993

Ulguim, A. R., Fruet, B. L., Merotto, A. Jr., and Silva, A. L. (2021). Status of weed control in imidazolinone-herbicide resistant rice in Rio Grande do Sul. *Advances in Weed Science* 39:e237355. doi: 10.51694/AdvWeedSci/2021;39:00007

Vijayakumar, S., Gobinath, R., Kannan, P., and Murugaiyan, V. (2024). Optimizing potassium mining in rice-wheat system: strategies for promoting sustainable soil health-a review. *Farming System* 2:100099. doi: 10.1016/j.farsys.2024.100099

Vijayakumar, S., and Padma, S. (2023). Unlocking the energy-water-carbon nexus in rice cultivation: a comprehensive review. *J. Rice Res.* 16, 1–21. doi: 10.58297/PSJA9488

Villalba, R., Joshi, G., Daum, T., and Venus, T. E. (2024). Financing climate-smart agriculture: a case study from the indo-Gangetic Plains. *Mitig. Adapt. Strateg. Glob. Chang.* 29:33. doi: 10.1007/s11027-024-10127-3

Zhang, C., Xu, J., Liu, X., Dong, F., Kong, Z., Sheng, Y., et al. (2010). Impact of imazethapyr on the microbial community structure in agricultural soils. *Chemosphere* 81, 800–806. doi: 10.1016/j.chemosphere.2010.06.079