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Transplanted rice response to non-chemical weed management in a degraded wetland ecosystem

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Rice (*Oryza sativa* L.) is a staple crop feeding over half of the global population, especially in Asia where it contributes 90% of global production. Weed infestation remains a critical constraint in rice ecosystems, significantly reducing yield. To evaluate the efficacy of non-chemical weed management practices in transplanted rice, a field experiment was conducted at the Wetland Farm of Tamil Nadu Agricultural University, Coimbatore, during *rabi* 2022 and *kharif* 2024 seasons. The study assessed growth, physiological traits and yield of rice under 12 weed management strategies arranged in a randomized block design (RBD) with three replications. The treatments included traditional chemical control as a standard treatment for comparison, hand weeding and a range of non-chemical treatments including ITK-based foliar spray (cow urine, lime solution, khadi soap and common salt), dual cropping and incorporation of *Azolla*, intercropping with *dhaincha*, rice bran application, rice hull extract, double green manuring, cono-weeding and mycoherbicide applications. The standard chemical control treatment (Butachlor @ 1 kg ha⁻¹ at 3 DAT + Bispyribac sodium @ 25 g ha⁻¹ at 25 DAT – T₉) produced the highest grain and straw yield (5427 and 7238 kg ha⁻¹ in *rabi* 2022 and 5385 and 7189 kg ha⁻¹ in *kharif* 2024), followed by hand weeding twice (T₁₁). Among the non-chemical treatments, the foliar spray of ITK-based farmers' practice combined with hand weeding (T₁) recorded the highest value in growth, physiology and yield followed by dual cropping with *Azolla* (T₅) and cono-weeding (T₈). The findings highlights that non-chemical weed management strategies can effectively suppress weeds and sustain rice productivity, offering viable alternatives to herbicide-based approaches.

KEYWORDS

growth and physiology, *Mycoherbicide*, non-chemical weed management, rice, yield

1 Introduction

Rice (*Oryza sativa* L.) is a staple crop feeding over half of the global population. Its cultivation is vital for food security, particularly in Asia, sub-Saharan Africa and South America, where it forms a major part of daily caloric intake. In 2024, India ranked as the second-largest rice producer and the largest exporter with a production of 137.83 million metric tons and 47.6 million hectares under cultivation [USDA Foreign Agricultural Service (USDA), 2024]. Globally, rice is grown on approximately 168 million hectares (Walkley and Black, 1934). Weeds pose a major threat

to rice production by competing for resources and reduces yield when left untreated by 15–60% in transplanted rice (Nivetha et al., 2017; Korav et al., 2018). Weeds compete with crops for resources and space which affects plant height, dry matter accumulation, leaf area index and physiological processes such as photosynthesis (Korav et al., 2018). Increased weed density has been shown to reduce net photosynthetic rate, grain filling, and yield (Xu et al., 2018). Weeds also negatively impact chlorophyll content, dry matter accumulation and tillering, leading to fewer panicles and lower grain yield (Gogoi et al., 2002; Li et al., 2021). Allelopathic effect of weeds extracts further delay flowering and reduce grain characteristics (Gogoi et al., 2002). These effects are comparable to abiotic stresses like drought, which reduce photosynthesis and chlorophyll content (Packirisamy et al., 2023).

In India, weeds are commonly controlled using herbicides. With use or over-use of herbicides in due time, a need for sustainable approach of weed control has become crucial for sustainability. Usually, three growing seasons are followed in India, namely, *kharif*, *rabi* and *zaid* where, *kharif* is monsoon or rainy season, *rabi* is winter season and *zaid* is summer or spring season. The rice was transplanted using SRI (System of Rice Intensification) method.

Indigenous technical knowledge (ITK) offers eco-friendly, cost-effective weed management through manual weeding, plant-based extracts and cultural practices like water management and organic amendments (Barman et al., 2024; Shakrawar et al., 2018). Despite ITK's sustainability benefits, rising labor cost and shortages have driven greater herbicide use, especially in direct-seeded rice (Pervaiz et al., 2024). ITK-based foliar spray (cow urine, lime solution, khadi soap and common salt) was given as a treatment to control weeds. Rice by-products were used as a treatment to control weeds. Rice bran was applied at transplanting as a treatment and rice hull was soaked in water and the solution was applied as a treatment. Cultural practices provide viable alternatives to chemical herbicides. Intercropping *Sesbania* in rice suppresses weeds via ground cover and adds organic matter, enhancing yield (Parthipan et al., 2013). Azolla is a free-floating aquatic fern found in tropical and subtropical regions. It is widely known for its symbiotic relationship with the nitrogen-fixing cyanobacterium *Anabaena azollae*, which resides in its leaf cavities. This association allows Azolla to fix atmospheric nitrogen, making it an excellent biofertilizer, especially in rice cultivation. Azolla dual cropping acts as a living mulch and fixes nitrogen, promoting crop growth and weed suppression. Regular cono-weeding disrupts weed seedlings and enhances soil aeration, aiding root development (Subramanian et al., 2006). Off-season land preparation with green manuring using *Sesbania aculeata* (Poir.) reduces the weed seed bank, improving subsequent crop growth (Gnanavel and Kathiresan, 2002). Hand weeding remains highly effective in transplanted rice yielding maximum weed control and grain yield (Parthipan and Ravi, 2016; Ashraf et al., 2006; Baloch et al., 2005).

Mycoherbicides derived from fungi present a sustainable alternative to chemical herbicides (Saitheja et al., 2024). *Bipolaris eleusines* (Alcorn) and *Curvularia lunata* (Wakker) Boedijn are effective against barnyard grass (*Echinochloa crusgalli* (L.) P. Beauv.) control, a major rice weed. *B. eleusines* is highly specific and effective with minimal impact on rice and its efficacy is enhanced

when combined with herbicides like penoxsulam and bensulfuron-methyl (Zhang et al., 2014). *C. lunata* strain LD2 is similarly potent, especially at early weed growth stages, with limited non-target effects (Nandhini et al., 2019; Zhang et al., 2014). Preliminary and field trials have validated the potential of these fungi in integrated weed management (Jyothi et al., 2010; Zhang et al., 2022). The comparative efficacy of non-chemical alternatives, particularly keeping their yield high while reducing herbicide dependency is still not well studied in transplanted rice systems. To address this gap, we evaluated non-chemical weed management strategies under field conditions at Tamil Nadu Agricultural University, Coimbatore. We hypothesized that non-chemical approaches would (1) provide weed suppression comparable to conventional herbicides; (2) maintain rice growth and physiological efficiency and (3) reduce long-term reliance on chemical inputs without compromising yield. This study, thus aims to identify sustainable alternatives to current herbicide-dominated practices, offering insights for resilient rice cultivation.

2.1 Study location and weather condition

Field trials were conducted at the Wetland Farm of Tamil Nadu Agricultural University, Coimbatore, during two cropping seasons—*rabi* 2022 and *kharif* 2024. The experimental location lies in the Western Agro-climatic Zone of Tamil Nadu, situated at 11°8'13"N latitude and 77°7'43"E longitude, with an altitude of 426.7 meters above mean sea level. The experimental site experiences a tropical climate with an average annual rainfall of approximately 846 mm. The weather parameters recorded during the crop growth periods are presented below. The average wind velocity was 8.0 km h⁻¹, with daily sunshine of 5.6 h, mean evaporation of 5.6 mm day⁻¹ and mean solar radiation of 324.7 cal cm⁻² day⁻¹ (Figure 1).

2.2 Treatment details

The experiment consisted of 12 treatments comprising different weed management strategies. The treatments details are T₁: Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT, T₂: Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT, T₃: Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT, T₄: Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT, T₅: Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT, T₆: Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT, T₇: Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT, T₈: Cono-weeding 4 times on 10, 20, 30 and 40 DAT, T₉: Butachlor @ 1 kg/ha at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE, T₁₀: Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT, T₁₁: Hand weeding twice at 20 and 40 DAT, T₁₂: Unweeded check. The selected mycoherbicides, *Bipolaris eleusines* and *Curvularia lunata*, were isolated from infected *Echinochloa crusgalli* leaves, then sub-cultured and prepared for inoculation. The detailed experimental treatments are presented in Table 1.

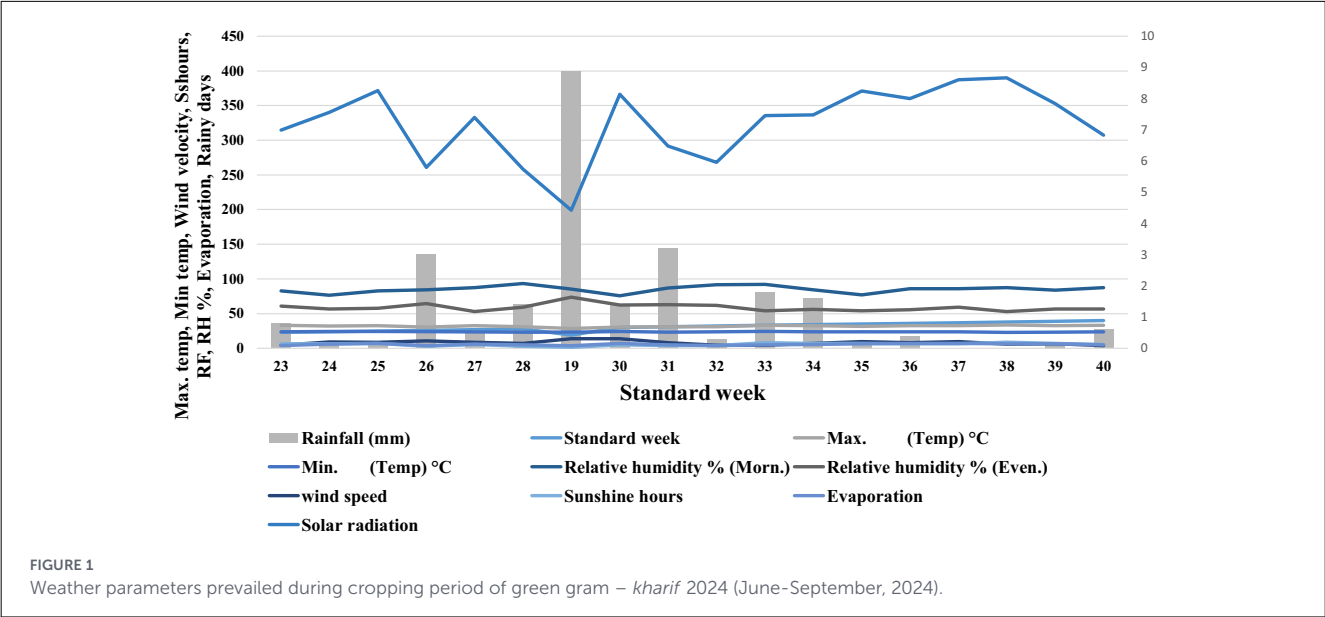


TABLE 1 Experimental treatment details.

Treatment No.	Treatment details
T ₁	Foliar spray (FS) of ITK-based farmers’ practices (cow urine + lime solution + khadi soap + common salt) at 25 days after transplanting (DAT) followed by hand weeding at 40 DAT
T ₂	Mycoherbicide-1 application at 25 DAT + hand weeding at 40 DAT
T ₃	Application of rice bran @ 5 t ha ⁻¹ as basal at transplanting + hand weeding at 40 DAT
T ₄	Intercropping Dhaincha with rice in a 3:1 ratio and incorporation at 40 DAT
T ₅	Dual cropping of Azolla @ 1 t ha ⁻¹ and incorporation at 40 DAT
T ₆	Rice hull solution (50% spray) at 15 DAT + hand weeding at 40 DAT
T ₇	Double green manuring @ 6.25 t ha ⁻¹ at transplanting and again at 25 DAT
T ₈	Cono-weeding at 10-day intervals for four cycles (10, 20, 30, and 40 DAT)
T ₉	Recommended herbicide practice comprising Butachlor @ 1 kg ha ⁻¹ at 3 DAT (pre-emergence) and Bispyribac sodium @ 25 g ha ⁻¹ at 25 DAT (post-emergence)
T ₁₀	Mycoherbicide-2 at 25 DAT + hand weeding at 40 DAT
T ₁₁	Hand weeding twice at 15 and 40 DAT
T ₁₂	No weeding (control).

2.3 Soil analysis

Prior to the initiation of the experiment, composite soil samples were randomly collected from the research field. These pre-sowing samples were air-dried, finely ground, passed through a 2 mm sieve and subsequently analyzed to determine key physico-chemical characteristics (Table 2). Standard analytical procedures were employed for these assessments: soil texture was determined using Robinson’s International Pipette method (Piper, 1966); pH was measured using an “ELICO” pH meter, and EC using an “ELICO” conductivity bridge (Jackson, 1973). Available nitrogen was estimated using the alkaline permanganate method (Subbiah and Asija, 1956), while available phosphorus was determined by Olsen’s colorimetric method (Olsen et al., 1954). Available potassium was assessed using the neutral normal ammonium acetate extraction method (Stanford and English, 1949). Organic carbon content was analyzed via chromic acid

wet digestion (Walkley and Black, 1934) and organic matter was subsequently calculated by multiplying the organic carbon value by a factor of 1.724 (Walkley and Black, 1934).

2.3 Experimental design, varietal characteristics and agronomic practices

A field experiment was conducted in a randomized block design with 12 treatments and three replications during *rabi* 2022 and *kharif* 2024. The gross and net plot sizes were 5.0 m × 4.0 m and 4.5 m × 3.5 m respectively, with four sample rows per plot. A 60 cm buffer channel separated adjacent plots and 1.0 m irrigation channels were laid between replications. The rice variety CO 51, released in 2013 through the cross ADT 43/RR 272-1745, was used. It is a medium-duration, semi-dwarf variety maturing in

TABLE 2 Physio–chemical characteristics of the experimental area

Particulars	Cropping season	
	Rabi 2022	Kharif 2024
I. Textural composition		
Clay (%)	46	45.8
Silt (%)	11.1	11.3
Fine sand (%)	15.4	15.25
Coarse sand (%)	27.5	27.65
Textural class (%)	Clay loam	Clay loam
II. Chemical properties		
pH	7.9	7.95
EC (dS m ⁻¹)	0.53	0.48
Organic carbon (g kg ⁻¹)	0.64	0.7
Organic matter	0.11	0.12
Available N (kg ha ⁻¹)	230	240
Available P (kg ha ⁻¹)	24	22.5
Available K (kg ha ⁻¹)	580	645

105–110 days, with 50% flowering in 75–80 days. Suitable for multiple seasons, it features droopy panicles, produces 250–300 grains per panicle and has a 1,000-grain weight of ~16g. CO 51 yields about 6,623 kg ha⁻¹ under optimal conditions, contains 7.5% protein and shows moderate resistance to blast, BPH and GLH. The experimental field was prepared by plowing twice with a tractor-drawn cultivator to a depth of 20–25 cm, followed by rotavator and thorough puddling using a cage wheel-fitted tractor to achieve a well-leveled, puddled surface for transplanting. Seeds were sown at a recommended seed rate of 60 kg ha⁻¹. After soaking the seeds overnight, seeds were broadcasted in the nursery by hand and 14 days old seedlings were transplanted into the main field at 20 × 20 cm spacing, maintaining 2.5 cm water depth until panicle initiation and 5 cm thereafter. Fertilizers were applied at a recommended dose of 150:50:50 NPK kg ha⁻¹, with nitrogen split based on the Leaf Color Chart (LCC), phosphorus applied fully as basal and potassium in four equal splits.

2.4 Treatments implementation

The treatments were implemented as follows: T₁ involved a foliar spray of ITK-based farmers' practices (cow urine, lime solution, khadi soap, and common salt) at 25 DAT, followed by hand weeding at 40 DAT. Cow urine were collected and were made to mature for 30 days. Khadi soap was added to the cow urine one night before it is sprayed in the field. Then, lime and common salt were added and mixed well and sprayed on the weeds. T₂ and T₁₀ treatments includes Mycoherbicide-1 and Mycoherbicide-2, respectively applied at 25 DAT and hand weeding at 40 DAT. Mycoherbicide organisms were collected from infected leaves of *Echinochloa* and was isolated, identified and inoculated and preliminary experiment was conducted before the main field trial. T₃ treatment involved rice bran (5 t ha⁻¹) at

transplanting and hand weeding at 40 DAT, while T₄ treatment involved intercropping of *dhaincha* at 3:1 ratio. *Dhaincha* were cut and incorporated in the plot at 40 DAT. T₅ involved incorporation of Azolla at 1 t ha⁻¹ at 40 DAT. T₆ included application of rice hull solution (50% spray) at 15 DAT and hand weeding at 40 DAT where, rice hull was taken and soaked overnight in water and the hull solution was applied. T₇ treatment was double green manuring of *dhaincha* (6.25 t ha⁻¹) at transplanting and 25 DAT. T₈ involved cono-weeding by conoweeder at 10-day intervals (10, 20, 30 and 40 DAT). T₉ included application of Butachlor (1 kg ha⁻¹) at 3 DAT as pre-emergence, followed by Bispyribac sodium (25 g ha⁻¹) at 25 DAT as post-emergence. T₁₁ involved hand weeding twice (15 and 40 DAT) and T₁₂ was taken as the non-treated control treatment. The selected mycoherbicides, *Bipolaris eleusines* and *Curvularia lunata*, were isolated from infected *Echinochloa crusgalli* leaves and sub-cultured for inoculation.

2.5 Experimental observations

2.5.1 Growth parameters

Plant height was recorded by measuring the distance from the base of the plant to the tip of the longest leaf on tagged plants at 30, 60, and 90 days after transplanting (DAT) and at harvest. The number of tillers was determined by placing a 0.25 m² quadrat randomly at four locations within each plot and all tillers within the quadrat were counted at the same intervals (30, 60, 90 DAT and at harvest), with the values averaged and expressed as tillers per square meter. Leaf Area Index (LAI) was estimated by measuring the length and maximum breadth of the top third leaf from five representative plants per plot and calculated using the formula (Palaniswamy and Gomez, 1974).

$$LAI = \frac{L \times W \times K \times \text{Number of leaves per hill}}{\text{Area occupied by the plants (cm}^2\text{)}} \quad (1)$$

Where,

L - Length of the leaf (cm),

W - Maximum width of the leaf (cm)

K - Constant factor (0.75)

Crop Growth Rate (CGR), representing the increase in dry matter per unit area and time, was calculated using the formula given by Watson (1958) and expressed in g m⁻² day⁻¹.

$$CGR = \frac{W_2 - W_1}{P(t_2 - t_1)} \quad (2)$$

Where,

W₂ and W₁ - whole plant dry weight (g) at time t₁ and t₂, respectively

P - Area occupied by the plant

t₁ and t₂ - time interval in days

Relative Growth Rate (RGR), indicating the efficiency of biomass accumulation per unit of existing biomass, was computed following Radford (1967) using the logarithmic increase in dry weight between two time intervals and expressed in g g⁻¹ day⁻¹.

$$RGR = \frac{\log_e W_2 - \log_e W_1}{t_2 - t_1} \quad (3)$$

Where,

W_1 - dry weight of the whole plant at time t_1

W_2 - dry weight of the whole plant at time t_2

$t_2 - t_1$ - Time interval (days)

Net Assimilation Rate (NAR), a measure of photosynthetic efficiency per unit leaf area, was calculated using Enyi (1962) formula at three growth intervals (30-60 DAT, 60-90 DAT and 90 DAT-harvest) and expressed in $\text{mg m}^{-2}\text{day}^{-1}$.

$$\text{NAR} = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{\log_e L_2 - \log_e L_1}{L_2 - L_1} \quad (4)$$

Where,

W_1 and W_2 - Plant dry weight (g) at time (t_1 and t_2)

$t_2 - t_1$ - Time interval in days

$L_2 - L_1$ - Leaf area (cm^2) between the interval of t_1 and t_2

For assessment of dry matter production (DMP), five plants from each plot were randomly pulled out from outside the net plot area at 30, 60, 90 DAT and at harvest. The samples were shade dried initially and then oven-dried at $65 \pm 5^\circ\text{C}$ for 72 h till the constant weight as attained and then weighed. The DMP was expressed in kg ha^{-1} .

2.5.2 Yield parameters

The number of productive tillers per square meter were assessed at the harvest stage by counting the total number of tillers from five randomly tagged plants in each treatment plot. These values were then averaged and expressed as the number of productive tillers per m^2 , which is a key indicator of the rice plant ability to support grain formation. For estimating the number of filled grains per panicle, 10 representative panicles were collected from each plot. The number of completely filled grains in each panicle was counted separately and the mean was calculated to represent the average number of filled grains per panicle, which reflects the efficiency of grain filling and reproductive success. Test weight was measured by randomly selecting a filled sample of 1,000 grains from each plot. These grains were dried to a standard moisture content of 14% and weighed accurately using a digital balance. The test weight was expressed in grams and provides insight into grain density and overall quality. Grain yield was estimated by harvesting the crop from the designated net plot area in each treatment. After manual threshing, cleaning and drying the grains to 14% moisture, the grain yield was computed and expressed in kilograms per hectare (kg ha^{-1}), representing the economic yield of the crop.

Straw yield, which contributes to the total biological productivity of the crop, was determined after separating the straw from the grains post-threshing. The straw was sun-dried until a constant weight was achieved and the total dry weight was recorded and expressed in kg ha^{-1} . Finally, the harvest index (HI), a measure of the efficiency with which the plant converts total biomass into economic yield, was calculated as the ratio of grain yield to total above ground biomass (grain yield + straw yield), by using the formula given by Donald and Hamblin (1976). This value, expressed as a percentage, indicates the proportion of

assimilated resources allocated to the harvested grain.

$$\text{Harvestindex} = \frac{\text{Economic yield (kg/ha)}}{\text{Biological yield (kg/ha)}} \times 100 \quad (5)$$

2.6 Statistical analysis

The analysis of variance (ANOVA) for all measured traits was conducted using R software (version 4.2.1) through R Studio (R Core Team, 2020). Mean comparisons were made using Fisher's Least Significant Difference (LSD) test at a 5% significance level, and non-significant results were indicated as "NS" (Gomez and Gomez, 2010). Pearson correlation coefficients were calculated to examine the relationships among different treatments.

3 Result

3.1 Growth parameters

The plant height, number of tillers and dry matter production of transplanted rice were significantly influenced by different weed management practices during *rabi* 2022 and *kharif* 2024 as mentioned in Tables 3–5. The application of Butachlor @ 1 kg ha^{-1} at 3 DAT as pre-emergence (PE) + Bispyribac sodium (BS) @ 25 g ha^{-1} at 25 DAT as post-emergence (POE)- T_9 consistently recorded the highest values across all growth stages (34.3, 77.8, 98.7 and 109.3 cm in *rabi* 2022 and 34.9, 76.4, 99.0, and 107.3 cm in *kharif* 2024 at 30, 60, 90 DAT and at harvest respectively) which was followed by hand weeding (HW) twice at 20 and 40 DAT (T_{11}) (33.7, 76.9, 97.9 and 106.2 cm in *rabi* 2022 and 34.5, 76.2, 97.2, 105.1 cm in *kharif* 2024 at 30, 60, 90 and at harvest respectively).

Among the non-chemical weed management practices, foliar spray (FS) of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding (HW) at 40 DAT (T_1) showed marked improvements in all parameters with values of 33.5, 75.3, 97.2, and 106.6 cm in *rabi* 2022 and 34.1, 74.8, 96.4, and 105.7 cm in *kharif* 2024 at 30, 60, 90 and at harvest respectively). Cono-weeding at 10, 20, 30, and 40 DAT (T_8) also proved effective. Azolla as dual crop @ 1 t ha^{-1} + incorporation at 40 DAT (T_5) also enhanced growth parameters. The unweeded check (T_{12}) consistently exhibited the lowest values in *rabi* 2022 and *kharif* 2024 respectively.

3.2 Physiological parameters

The leaf area index (LAI) of transplanted rice was significantly influenced by various non-chemical weed management practices during both *rabi* 2022 and *kharif* 2024 at 30 DAT and mentioned in Table 6. Among all the treatments, T_9 recorded the highest LAI in both *rabi* 2022 and *kharif* 2024 and was closely followed by T_{11} . Among the non-chemical treatments, T_1 , T_5 , and T_8 recorded high LAI values in both the seasons. Both the mycoherbicide treatments and unweeded check recorded the lowest LAI values.

The crop growth rate (CGR), among all treatments, T_9 recorded the highest CGR with value of $6.73 \text{ g m}^{-2} \text{ day}^{-1}$ in *rabi* 2022 and

TABLE 3 Effect of non- chemical weed management practices on plant height (cm) at 30, 60, 90 and harvest in transplanted rice (rabi 2022 and kharif 2024)

T.No	Treatments	rabi 2022				kharif 2024			
		30 DAT	60 DAT	90 DAT	Harvest	30 DAT	60 DAT	90 DAT	Harvest
T ₁	Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT	33.5	75.3	97.2	106.6	34.1	74.8	96.4	105.7
T ₂	Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT	28.4	62.8	83.8	89.2	29.3	62.1	82.6	88.1
T ₃	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	30.3	69.6	90.8	98.8	30.8	68.7	89.3	97.6
T ₄	Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT	29.8	68.4	89.6	97.1	30.6	67.6	88.6	96.2
T ₅	Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT	32.1	73.6	96.1	104.7	32.7	72.8	95.2	103.8
T ₆	Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT	29.2	67.5	88.8	96.4	29.9	66.7	87.6	95.3
T ₇	Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT	29.5	69.1	90.2	97.9	30.2	68.3	89.4	96.7
T ₈	Cono-weeding 4 times on 10, 20, 30 and 40 DAT	32.7	74.1	96.6	105.3	33.4	73.5	95.7	104.4
T ₉	Butachlor @ 1 kg ha ⁻¹ at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE	34.3	77.8	98.7	109.3	34.9	76.4	99.0	107.3
T ₁₀	Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT	28.1	61.9	82.9	88.4	28.8	60.8	82.1	87.5
T ₁₁	Hand weeding twice at 20 and 40 DAT	33.7	76.9	97.9	106.2	34.5	76.2	97.2	105.1
T ₁₂	Unweeded check	26.7	56.8	76.8	81.7	28.8	58.2	76.1	82.2
S.Ed		1.72	2.97	3.87	4.96	1.68	4.09	4.28	4.23
SE		1.22	2.10	2.74	3.51	1.19	2.89	3.03	2.99
CD (P=0.05)		3.570	6.16	8.02	10.3	3.49	8.48	8.88	8.78

(S.Ed, Standard error of difference; SE, Standard error of mean; CD, Critical Difference; NS, Non-significant; DAT, Days After Transplantation). Mean comparisons were performed using Fisher's LSD ($\alpha = 0.05$), using the mean square error (MSE) from the ANOVA. The common standard error was $SE = \sqrt{(MSE/n)}$, and the standard error of the difference was $S.Ed = \sqrt{(2 \cdot MSE/n)}$.

6.53 g m⁻² day⁻¹ in *kharif* 2024 at 30-60 DAT. Among the non-chemical treatments, T₁ showed higher CGR with 5.93 g m⁻² day⁻¹ in *rabi* 2022 and 5.70 g m⁻² day⁻¹ in *kharif* 2024 at 30-60 DAT reflecting its efficacy in sustaining growth followed by T₅ with CGR value of 6.00 g m⁻² day⁻¹ in *rabi* 2022 and 5.98 g m⁻² day⁻¹ *kharif* 2024 30-60 DAT.

The relative growth rate (RGR) followed a similar trend. T₁ recorded the highest RGR with value of 25.75 mg g⁻¹ day⁻¹ in *rabi* 2022 and 25.60 mg g⁻¹ day⁻¹ in *kharif* 2024 at 30-60 DAT. T₁ recorded the highest RGR value among non-chemical treatments with 23.26 mg g⁻¹ day⁻¹ in *rabi* 2022 and 22.88 mg g⁻¹ day⁻¹ *kharif* 2024 at 30-60 DAT followed by T₅ and T₈.

The net assimilation rate (NAR) also showed T₉ recorded the highest NAR with 9.95 mg g⁻¹ day⁻¹ in *rabi* 2022 and 9.69 mg g⁻¹ day⁻¹ *kharif* 2024 at 30-60 DAT. Among the non-chemical methods, T₅ and T₈ showed strong early-stage NAR at 30-60 DAT)

with 9.20 and 9.09 mg g⁻¹ day⁻¹ respectively in *rabi* 2022 and 9.21 and 9.05 mg g⁻¹ day⁻¹ respectively in *kharif* 2024.

3.3 Yield attributes

The combined results from *rabi* 2022 and *kharif* 2024 demonstrate that non-chemical weed management practices significantly influenced yield parameters at the harvest stage of transplanted rice and mentioned in Tables 7, 8. T₉ consistently recorded the highest values for parameters with number of filled grains per panicle of 163.6 in *rabi* 2022 and 159.3 in *kharif* 2024, panicle weight of 4.11 g in *rabi* 2022 and 4.13 g in *kharif* 2024, grain yield of 5427 kg ha⁻¹ in *rabi* 2022 and 5385 kg ha⁻¹ in *kharif* 2024 and straw yield of 7238 kg ha⁻¹ in *rabi* 2022 and 7189 kg ha⁻¹ in *kharif* 2024 indicating its effectiveness against

TABLE 4 Effect of non- chemical weed management practices on number of tillers at 30, 60, 90 and harvest in transplanted rice (rabi 2022 and kharif 2024).

T.No	Treatments	rabi 2022				kharif 2024			
		30 DAT	60 DAT	90 DAT	Harvest	30 DAT	60 DAT	90 DAT	Harvest
T ₁	Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT	248.0	345.0	356.0	362.0	248.0	351.0	364.0	361.0
T ₂	Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT	206.0	283.0	297.0	304.0	206.0	287.0	301.0	296.0
T ₃	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	231.0	315.0	328.0	332.0	231.0	320.0	332.0	328.0
T ₄	Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT	221.0	304.0	317.0	322.0	221.0	309.0	323.0	319.0
T ₅	Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT	236.0	332.0	343.0	248.0	236.0	341.0	352.0	349.0
T ₆	Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT	217.0	297.0	310.0	315.0	217.0	308.0	321.0	318.0
T ₇	Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT	228.0	307.0	319.0	326.0	228.0	315.0	327.0	320.0
T ₈	Cono-weeding 4 times on 10, 20, 30 and 40 DAT	242.0	344.0	356.0	363.0	242.0	351.0	364.0	359.0
T ₉	Butachlor @ 1 kg ha ⁻¹ at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE	256.0	368.0	377.0	382.0	256.0	373.0	386.0	381.0
T ₁₀	Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT	88.0	279.0	290.0	298.0	199.0	283.0	295.0	292.0
T ₁₁	Hand weeding twice at 20 and 40 DAT	198.0	357.0	371.0	379.0	239.0	361.0	374.0	369.0
T ₁₂	Unweeded check	176.0	257.0	274.0	285.0	176.0	264.0	277.0	280.0
S.Ed		4.96	15.2	15.5	19.9	11.3	15.4	22.9	21.2
SE		3.51	10.75	10.96	14.08	7.99	10.89	16.19	15.00
CD (P=0.05)		10.3	31.5	32.1	41.3	23.4	32	47.5	44.1

(S.Ed, Standard error of difference; SE, Standard error of mean; CD, Critical Difference; NS, Non-significant; DAT, Days After Transplantation)
Mean comparisons were performed using Fisher's LSD ($\alpha = 0.05$), using the mean square error (MSE) from the ANOVA. The common standard error was $SE = \sqrt{(MSE/n)}$, and the standard error of the difference was $S.Ed = \sqrt{(2 \cdot MSE/n)}$.

weed control resulting in good growth of the crop. However, non-chemical treatments like the ITK-based treatment, azolla dual cropping and cono-weeding treatment showed comparable results. These treatments consistently recorded high number of filled grain per panicle of 157.0, 152.1 and 154.7 respectively in *rabi* 2022 and 152.0, 147.9 and 151.6 respectively in *kharif* 2024, grain yields of 5235, 5076, and 5164 kg ha⁻¹ respectively in *rabi* 2022 and 5198, 4983, and 5121 kg ha⁻¹ respectively in *kharif* 2024 highlighting their potential as sustainable alternatives. Panicle length and test weight remained statistically non-significant across treatments.

The two mycoherbicide treatments (T₂ and T₁₀) and unweeded check (T₁₂) treatment performed poorly in both the seasons with lower panicle counts, fewer filled grains, reduced panicle weights and the lowest grain and straw yields, reflecting ineffective weed suppression. The harvest index remained relatively stable across treatments, mostly between 0.41 and 0.44, except in unweeded

check, which recorded the lowest harvest index of 0.36 due to poor resource partitioning because of heavy weed infestation. Overall, the study demonstrates that T₉ and T₁₁ resulted in the highest yield and superior yield parameters indicating their effectiveness in weed control and productivity enhancement in transplanted rice. Among the non-chemical weed management strategies, T₁, T₅ and T₈ resulted in substantial yield levels, demonstrating their potential as effective and eco-friendly alternatives to chemical herbicides.

3.4 Correlation between growth, physiology and yield parameters

The Pearson's correlation analysis revealed strong interrelationships among the growth, physiological and yield

TABLE 5 Effect of non- chemical weed management practices on dry matter production (g m⁻²) at 30, 60, 90 and harvest in transplanted rice (rabi 2022 and kharif 2024).

T.No	Treatments	rabi 2022				kharif 2024			
		30 DAT	60 DAT	90 DAT	Harvest	30 DAT	60 DAT	90 DAT	Harvest
T ₁	Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT	176.7	354.6	651.2	828.7	172.9	343.8	638.4	836.8
T ₂	Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT	149.6	277.2	540.6	608.9	185.3	281.7	529.0	602.9
T ₃	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	153.1	307.8	603.4	671.4	147.5	302.4	591.2	714.1
T ₄	Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT	158.2	296.2	768.4	820.8	151.4	291.6	758.6	879.9
T ₅	Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT	165.6	345.6	635.0	762.9	161.7	341.1	619.0	788.3
T ₆	Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT	160.0	299.7	777.8	863.8	155.2	293.4	759.6	966.8
T ₇	Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT	161.7	303.3	589.2	641.6	156.1	297.9	583.2	722.7
T ₈	Cono-weeding 4 times on 10, 20, 30 and 40 DAT	168.6	348.3	641.8	704.5	163.8	341.1	629.4	817.0
T ₉	Butachlor @ 1 kg ha ⁻¹ at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE	173.3	375.3	681.2	866.5	169.4	365.4	668.4	973.8
T ₁₀	Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT	148.4	269.2	516.4	646.5	145.3	263.7	512.8	753.2
T ₁₁	Hand weeding twice at 20 and 40 DAT	184.0	361.8	663.4	707.1	179.3	351.9	648.4	764.1
T ₁₂	Unweeded check	147.9	182.4	381.0	537.0	151.4	196.2	385.2	589.4
S.Ed		8.66	15.9	43.4	39.1	6.84	21.7	37.3	33.6
SE		6.12	11.24	30.69	27.65	4.84	15.34	26.37	23.77
CD (P = 0.05)		17.9	33	19	81.1	14.2	45	77.4	69.8

(S.Ed, Standard error of difference; SE, Standard error of mean; CD, Critical Difference; NS, Non-significant; DAT, Days After Transplantation). Mean comparisons were performed using Fisher's LSD ($\alpha = 0.05$), using the mean square error (MSE) from the ANOVA. The common standard error was $SE = \sqrt{(MSE/n)}$, and the standard error of the difference was $S.Ed = \sqrt{(2 \cdot MSE/n)}$

parameters of rice under different non-chemical weed control treatments during both *rabi* 2022 and *kharif* 2024 seasons (Figure 2). Positive correlations are represented in dark green and negative correlations in dark red, providing a visual insight into the trait associations. Significant positive relationships were recorded among plant height (PH), number of tillers per m² (NT), dry matter production (DMP), grain yield (GY) and straw yield (SY) under different non-chemical weed control practices, while physiological traits such as crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) exhibited weak or negative associations with most growth and yield parameters, as depicted in Figure 3.

In *rabi* 2022, significant and positive associations were observed among plant height (PH), number of tillers per square meter (NT), dry matter production (DMP) and leaf area index (LAI). LAI exhibited a perfect correlation with PH (1.00) and strong

positive correlations with DMP (0.69) and NT (0.58), suggesting that a higher leaf area promotes better canopy development and biomass accumulation. Similarly, PH showed substantial positive correlations with DMP (0.69) and NT (0.60), reflecting its role in vegetative vigor. Grain yield (GY) was most strongly correlated with LAI (0.99), PH (0.99) and DMP (0.67), while straw yield (SY) also exhibited strong associations with PH (0.97), LAI (0.96) and NT (0.63), highlighting the importance of robust vegetative traits in determining productivity.

During *kharif* 2024, a similar pattern was observed. PH was positively and strongly correlated with NT (0.98), DMP (0.63) and LAI (1.00). LAI emerged as a central trait, closely linked to GY (0.98) and SY (0.96). NT showed strong associations with LAI (0.96) and DMP (0.60), reinforcing the significance of tiller density. GY was significantly associated with PH (0.98), NT (0.94) and LAI (0.98), while SY followed similar trends with PH (0.97), NT (0.99)

TABLE 6 Effect of non- chemical weed management practices on leaf area index (LAI) at 30 DAT, crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (RGR) at 30-60 DAT respectively in transplanted rice (rabi 2022 and kharif 2024)

T.No	Treatments	rabi 2022				kharif 2024			
		60 DAT	30-60 DAT	30-60 DAT	30-60 DAT	60 DAT	30-60 DAT	30-60 DAT	30-60 DAT
T ₁	Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT	2.25	5.93	23.26	8.87	2.24	5.70	22.88	8.64
T ₂	Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT	1.95	4.25	20.46	7.56	1.91	3.21	14.12	5.78
T ₃	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	2.08	5.16	23.11	8.35	2.08	5.16	23.99	8.50
T ₄	Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT	2.05	4.60	20.88	7.63	2.04	4.67	21.71	7.88
T ₅	Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT	2.21	6.00	24.58	9.20	2.21	5.98	24.69	9.21
T ₆	Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT	2.03	4.66	20.96	7.87	2.03	4.61	21.23	7.81
T ₇	Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT	2.06	4.72	21.03	7.77	2.06	4.73	21.41	7.86
T ₈	Cono-weeding 4 times on 10, 20, 30 and 40 DAT	2.22	5.99	24.21	9.09	2.22	5.91	24.43	9.05
T ₉	Butachlor @ 1 kg ha ⁻¹ at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE	2.30	6.73	25.75	9.95	2.29	6.53	25.60	9.69
T ₁₀	Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT	1.93	4.03	19.87	7.19	1.90	3.95	19.83	7.24
T ₁₁	Hand weeding twice at 20 and 40 DAT	2.27	5.93	22.56	8.77	2.27	5.75	22.36	8.60
T ₁₂	Unweeded check	1.70	1.15	7.04	2.42	1.68	1.49	8.45	3.04
S.Ed		0.100	0.66	2.78	1.14	0.10	0.70	2.59	1.20
SE		0.070	047	1.97	0.81	0.07	0.49	1.83	0.85
CD (P = 0.05)		0.208	1.380	5.770	2.36	0.208	1.460	5.370	2.49

(S.Ed, Standard error of difference; SE, Standard error of mean; CD, Critical Difference; NS, Non-significant; DAT, Days After Transplantation). Mean comparisons were performed using Fisher's LSD ($\alpha = 0.05$), using the mean square error (MSE) from the ANOVA. The common standard error was $SE = \sqrt{(MSE/n)}$, and the standard error of the difference was $S.Ed = \sqrt{2 \cdot MSE/n}$.

and LAI (0.96). Physiological traits such as relative growth rate (RGR) and net assimilation rate (NAR) exhibited inconsistent or negative correlations with growth and yield traits in both *rabi* 2022 and *kharif* 2024 seasons. These traits showed negative associations with plant height (PH), leaf area index (LAI) and grain yield (GY) suggesting that higher physiological efficiency did not lead to improved biomass or yield under non-chemical weed management systems. This may be attributed to the stress imposed by weed competition, which limits resource availability and alters source-sink relationships. Although RGR and NAR reflect early growth efficiency, they did not maintain productivity throughout the crop cycle resulting in lower yield. Crop growth rate (CGR) however, showed positive correlations with DMP, RGR and NAR, indicating its relevance in biomass dynamics.

3.5 Interrelationship between combinations of different weed management strategies based on yield attributes

The cluster analysis illustrates the relationship between various weed management strategies and yield attributes during the *rabi* 2022 and *kharif* 2024 seasons and mentioned in Figure 4. The heatmaps visualizes the outcome of hierarchical clustering where Euclidean distance was employed to assess the similarity between data points based on their principal component scores. To ensure optimal grouping with minimal variance within clusters, Ward's linkage method was applied. The dendrograms along the top and left sides of each heatmap depict the clustering of yield attributes and treatment strategies, uncovering key patterns and associations.

TABLE 7 Effect of non- chemical weed management practices on yield parameters at harvest stage in transplanted rice (rabi 2022).

T.No	Treatments	rabi 2022							
		No. of panicles	Panicles length	No. of filled grains/panicle	Panicle weight (g)	Test weight (g)	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index
T ₁	Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT	290.8	19.6	157.0	3.92	23.2	5235	6949	0.43
T ₂	Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT	241.3	19.0	112.0	3.08	23.3	3965	5435	0.42
T ₃	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	270.6	19.6	135.3	3.59	22.8	4785	6086	0.44
T ₄	Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT	259.7	19.2	127.1	3.47	22.7	4416	5776	0.43
T ₅	Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT	284.7	19.2	152.1	3.89	23.6	5076	6712	0.43
T ₆	Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT	263.7	19.8	130.0	3.58	23.4	4537	5864	0.44
T ₇	Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT	268.1	19.3	132.2	3.50	23.1	4626	5938	0.44
T ₈	Cono-weeding 4 times on 10, 20, 30 and 40 DAT	287.6	19.0	154.7	4.00	23.2	5164	6774	0.43
T ₉	Butachlor @ 1 kg ha ⁻¹ at 3 DAT as PE + Bisparybac sodium @ 25 g/ha at 25 DAT as POE	297.8	19.3	163.6	4.11	22.9	5427	7238	0.43
T ₁₀	Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT	237.2	18.8	106.9	3.01	22.8	3781	5348	0.41
T ₁₁	Hand weeding twice at 20 and 40 DAT	294.7	19.4	161.4	4.09	23.0	5326	7147	0.43
T ₁₂	Unweeded check	192.5	19.3	97.0	2.59	22.8	2896	5048	0.36
S.Ed		12.30	0.42	7.44	0.08	0.52	280	264	0.02
SE		8.70	0.29	5.26	0.06	0.37	198	186	0.01
CD (P=0.05)		25.60	NS	15.40	0.17	NS	580	547	NS

(S.Ed, Standard error of difference; SE, Standard error of mean; CD, Critical Difference; NS, Non-significant; DAT, Days After Transplantation)

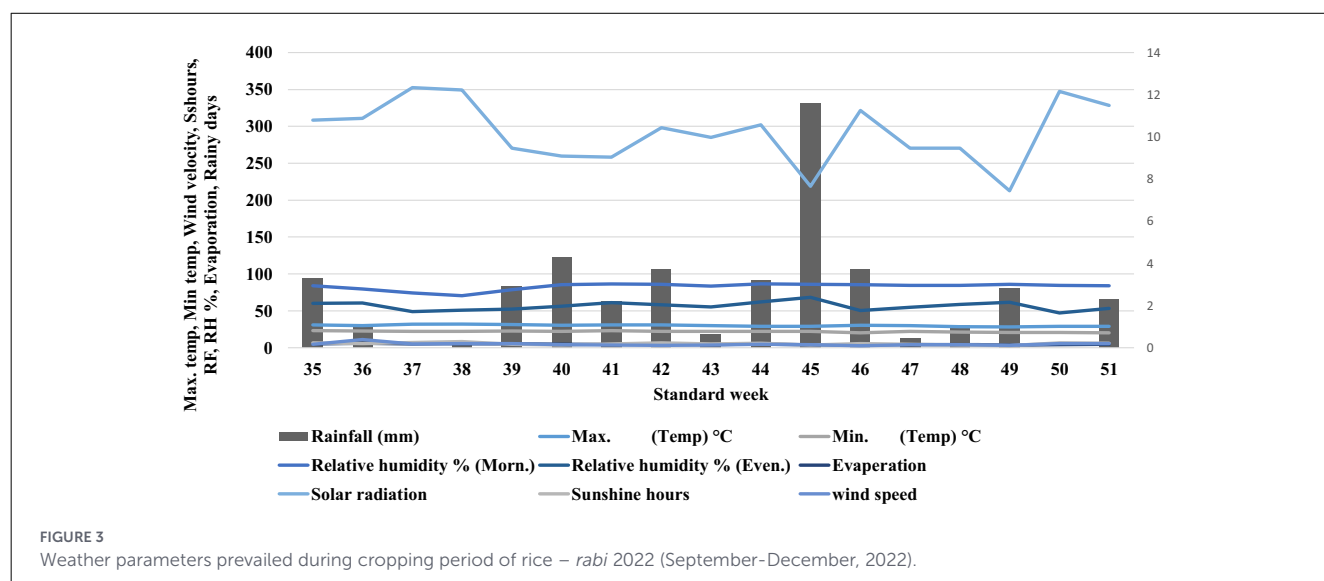
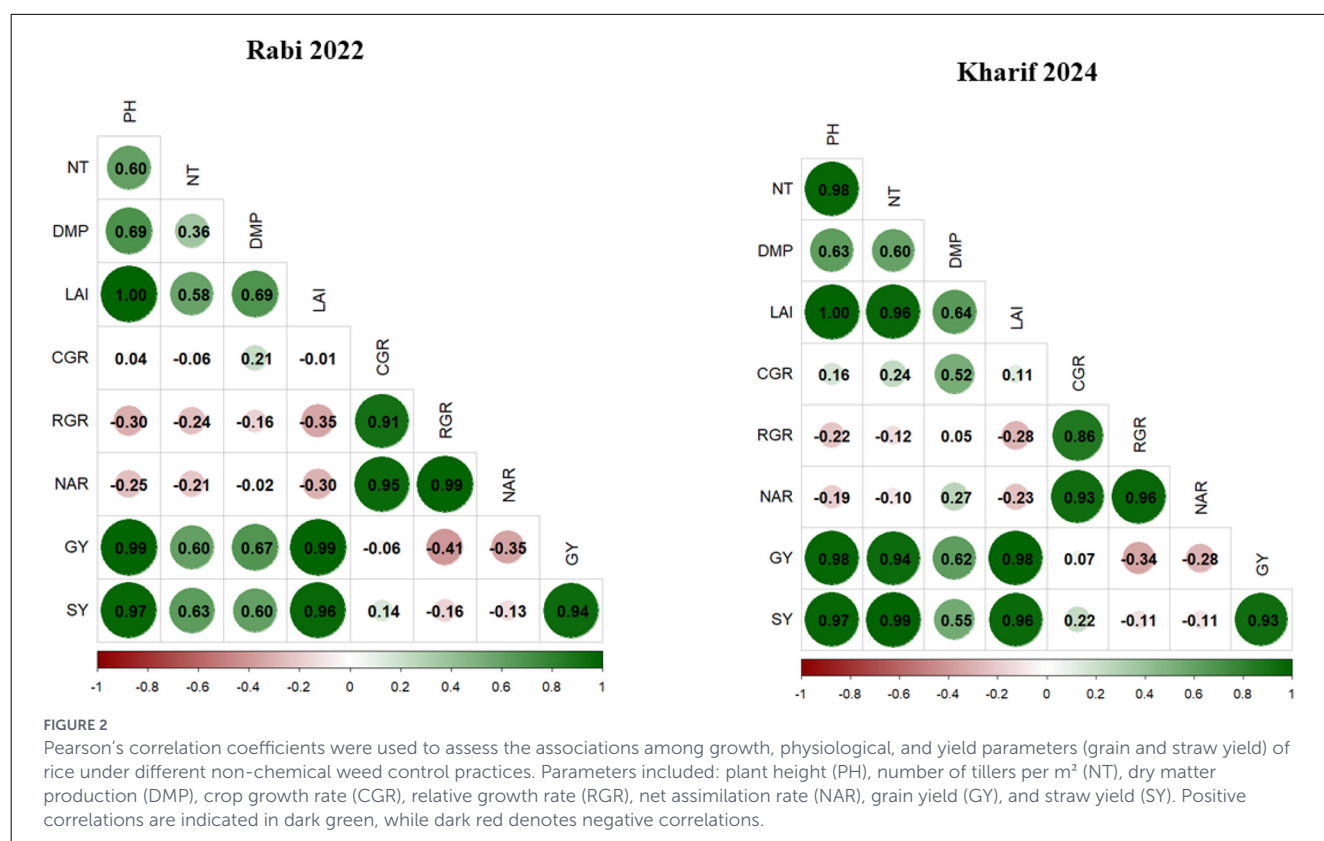
Mean comparisons were performed using Fisher's LSD ($\alpha = 0.05$), using the mean square error (MSE) from the ANOVA. The common standard error was $SE = \sqrt{(MSE/n)}$, and the standard error of the difference was $S.Ed = \sqrt{(2 \cdot MSE/n)}$

TABLE 8 Effect of non- chemical weed management practices on yield parameters at harvest stage in transplanted rice (kharif 2024)

T.No	Treatments	<i>kharif 2024</i>							
		No. of panicles	Panicles length (cm)	No. of filled grains/panicle	Panicle weight (g)	Test weight (g)	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index
T ₁	Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT	299.4	19.9	152.0	3.96	23.1	5198	6912	0.43
T ₂	Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT	307.4	19.4	109.1	3.13	22.8	3,932	5,384	0.42
T ₃	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	312.3	19.2	137.7	3.67	23.4	4,755	6,034	0.44
T ₄	Intercropping dhaincha with rice (3:1 ratio) + incorporation at 40 DAT	244.1	19.4	125.2	3.51	22.9	4,387	5,721	0.44
T ₅	Azolla as dual crop @ 1 t/ha + incorporation at 40 DAT	248.9	19.6	147.9	3.91	23.6	4,983	6,685	0.43
T ₆	Rice hull solution (50% foliar spray) at 15 DAT + hand weeding at 40 DAT	238.5	19.5	127.5	3.61	23.3	4,479	5,812	0.44
T ₇	Double green manuring @ 6.25 t/ha at transplanting + at 25 DAT	294.9	19.4	129.9	3.56	23.4	4,586	5,895	0.44
T ₈	Cono-weeding 4 times on 10, 20, 30 and 40 DAT	278.4	19.4	151.6	4.02	23.0	5,121	6,721	0.43
T ₉	Butachlor @ 1 kg ha ⁻¹ at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE	287.6	19.5	159.3	4.13	23.5	5,385	7,189	0.43
T ₁₀	Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT	182.0	19.4	105.1	3.08	23.2	3,716	5,303	0.41
T ₁₁	Hand weeding twice at 20 and 40 DAT	188.7	19.3	156.1	4.11	23.6	5,245	7,098	0.43
T ₁₂	Unweeded check	192.5	19.7	94.2	2.67	22.9	2,816	5,013	0.36
S.Ed		10.00	0.19	8.35	0.06	0.59	274	340	0.02
SE		7.07	0.13	5.90	0.04	0.42	194	241	0.01
CD (P = 0.05)		20.80	NS	17.30	0.13	NS	568	705	0.04

(S.Ed, Standard error of difference; SE, Standard error of mean; CD, Critical Difference; NS, Non-significant; DAT, Days After Transplantation)

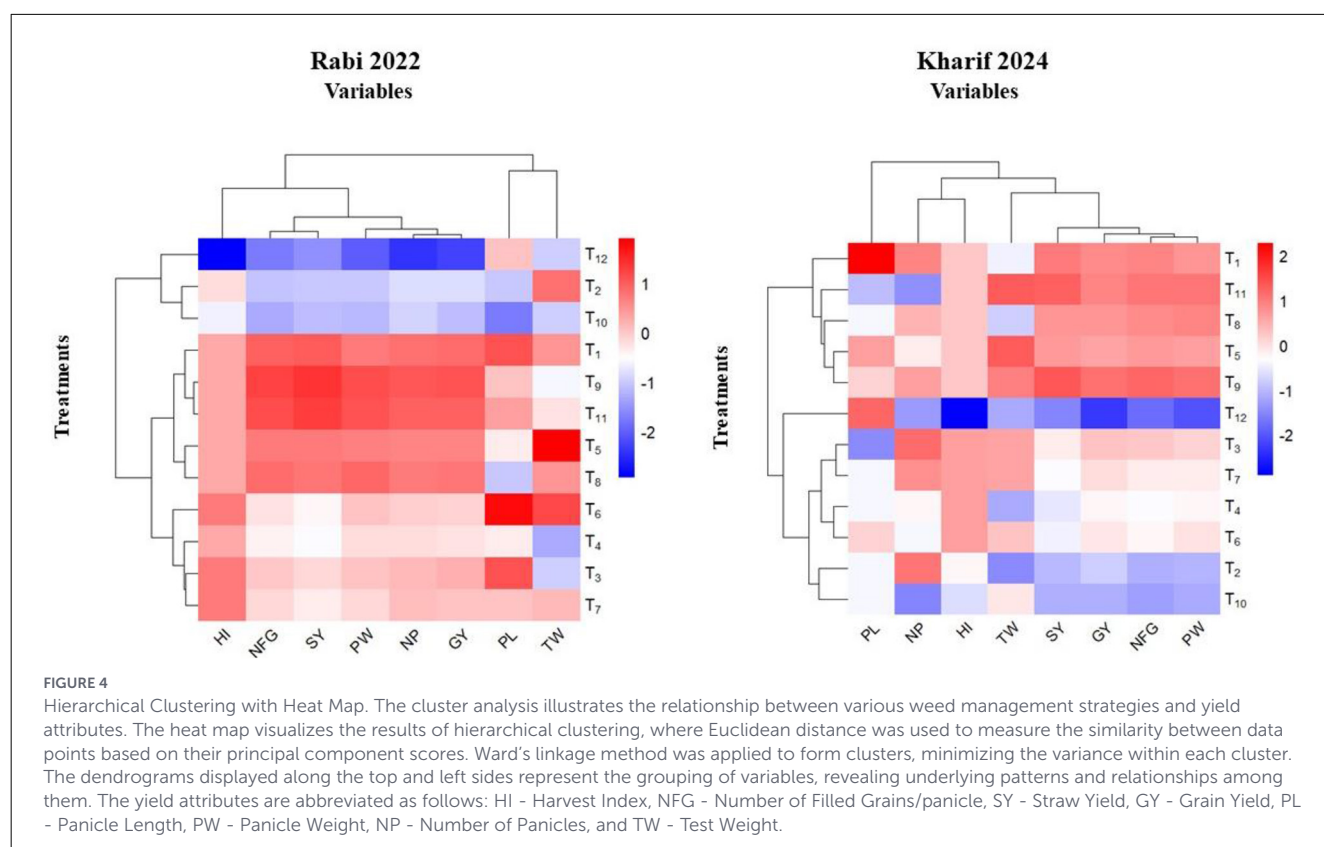
Mean comparisons were performed using Fisher's LSD ($\alpha = 0.05$), using the mean square error (MSE) from the ANOVA. The common standard error was $SE = \sqrt{(MSE/n)}$, and the standard error of the difference was $S.Ed = \sqrt{(2 \cdot MSE/n)}$.



In *rabi* 2022, three major treatment clusters were identified. The first cluster where T_{12} and T_2 showed predominantly negative associations across most yield traits, particularly with NP (Number of Panicles), GY (Grain Yield) and NFG (Number of Filled Grains/panicle), indicating poor performance under these weed management strategies. Similarly, T_{10} and T_1 exhibited neutral to negative effects across several attributes. The second cluster, consisting of T_9 , T_{11} , T_5 , T_8 and T_6 , was marked by strong positive associations with key yield traits including TW (Test Weight), SY (Straw Yield) and GY, with T_9 and T_{11} emerging as the

highest-performing treatments. A third sub-cluster involving T_4 , T_3 and T_7 showed moderately positive associations with traits like PL (Panicle Length) and PW (Panicle Weight) but less impact on grain yield traits.

In *kharif* 2024, the clustering showed a similar structure. The top-performing cluster included T_1 , T_{11} , T_8 , T_5 and T_9 , all showing strong positive relationships with SY, GY and NFG. T_1 and T_{11} demonstrated the highest level of performance, especially in PL and TW, reflecting consistent effectiveness across seasons. The second cluster which comprised of T_{12} and T_3 showed



negative associations with most attributes, including HI, SY and GY, indicating poor treatment responses. A third cluster, formed by T₇, T₄, T₆, T₂ and T₁₀, showed weak to moderate performance with generally negative or low associations, particularly in GY and NFG.

4 Discussion

4.1 Growth parameters

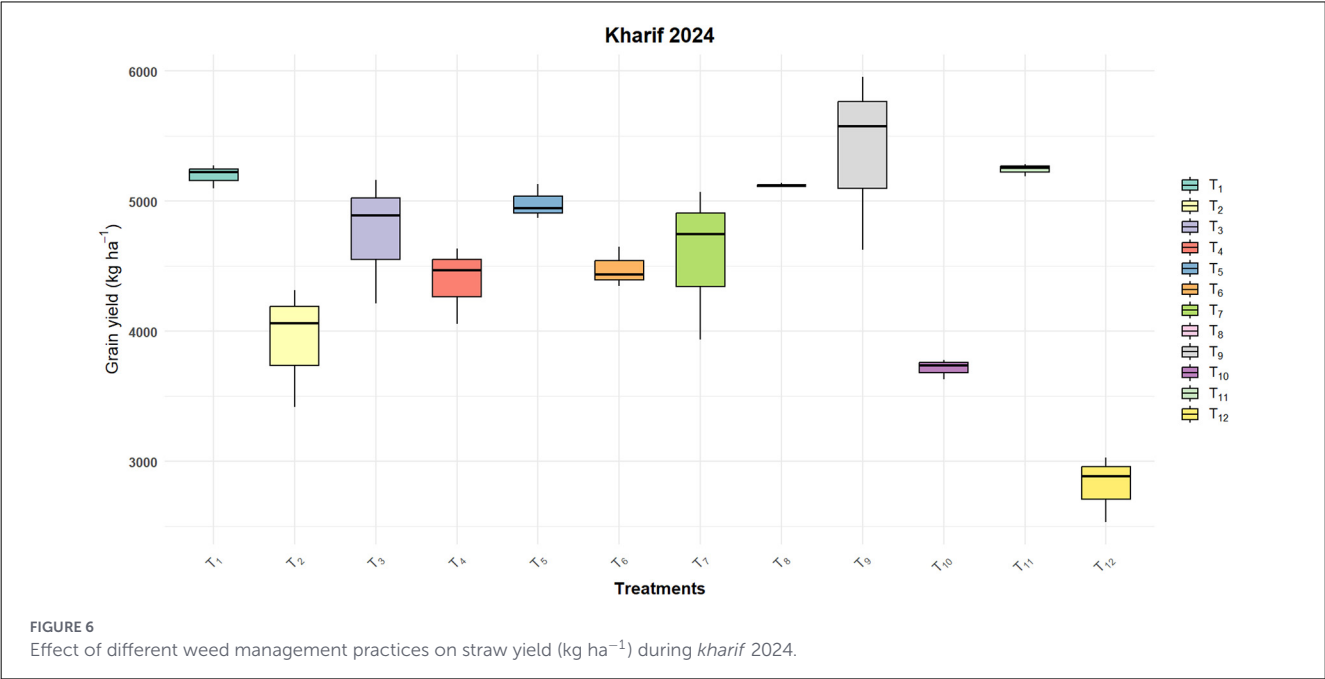
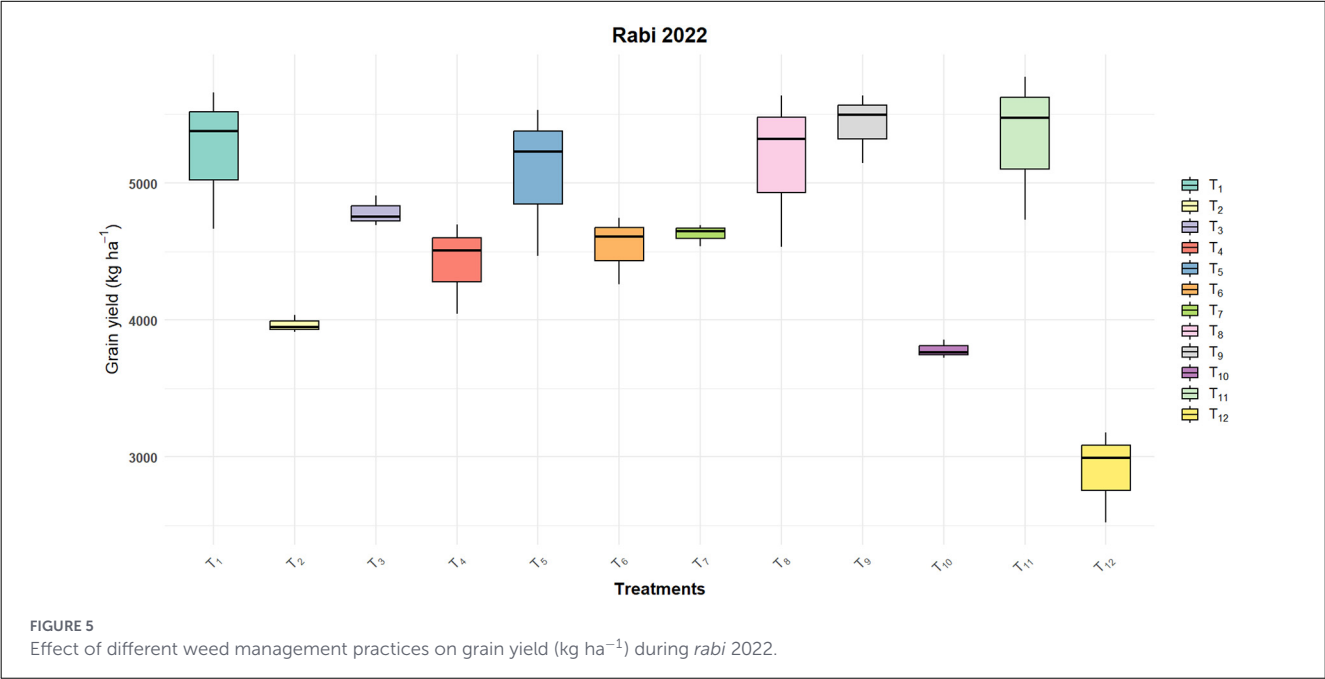
Growth parameters such as plant height, number of tiller and dry matter production (DMP) are fundamental indicators of a crop physiological performance and its capacity to efficiently utilize available resources while coping with biotic stress, particularly weed interference. In the present investigation conducted during *rabi* 2022 and *kharif* 2024, weed management practices significantly influenced these growth traits. The chemical weed management treatment, T₉, consistently recorded the highest plant height, number of tillers and DMP at all growth stages. This enhanced performance was due to effective early weed suppression, which minimized the competition for essential inputs like nutrients, light and soil moisture, thereby enabling uninterrupted vegetative growth and greater biomass partitioning (Khalid et al., 2018; Balaji et al., 2024). Manual methods, including hand weeding twice (T₁₁) and ITK-based practices combined with hand weeding (T₁), also contributed positively to growth, with comparable values to the chemical treatment. These approaches provided

timely weed removal at critical growth phases, ensuring optimal resource availability for crop development. These findings aligns with previous research demonstrating that effective weed control during early growth stages significantly improved plant vigor and structure (Choudhary and Dixit, 2018; Banu et al., 2016). ITK treatment containing cow urine, lime solution, khadi soap and common salt helps in controlling weed efficiently. Spraying ITK at 25 DAT targets younger weeds which are still in their seedling or early vegetative stage which are more susceptible to desiccation, scorching and metabolic disruption. Cow urine acts as a natural herbicide and growth suppressant. Cow urine contains ammonia which causes leaf scorching and disrupts cell membranes, phenolic compounds which inhibit weed growth and high pH which destabilizes leaf tissue on weeds. This was partially supported by Choudhary et al. (2024) by use of cow-based preparations i.e., jeevamrit (mixture of urine, dung, jaggery, chickpea flour, handful soil, and water) and ghanjeevamrit (mixture of urine, dung, jaggery and chickpea flour) which along with mulching showed better weed control and weed control efficiency compared to other treatments. Lime is observed to increase surface pH damaging epidermal tissues and enhancing sunlight-induced scorching. Common salt is known for controlling weeds as tested by Chatterjee et al. (2016) and Rathore et al. (2012). Non-chemical strategies such as Azolla dual cropping (T₅), rice hull extract application (T₆) and cono-weeding (T₈) exhibited moderate efficacy, showing improved growth performance over the unweeded control by suppressing weed density and potentially enhancing soil nutrient status and microbial interactions. However, the unweeded control (T₁₂) consistently exhibited the lowest values

for all growth parameters, highlighting the severe negative impact of unchecked weed infestation on crop performance. The presence of unmanaged weed flora resulted in intense competition for growth resources, leading to restricted plant growth, suppressed tillering and diminished dry matter production. These observations are in agreement with the earlier findings of [Ismail and Abdullah \(2020\)](#), emphasizing the critical role of weed management in influencing crop morphology and productivity.

4.2 Physiological parameters

The influence of various weed management practices on key physiological parameters in transplanted rice was substantial, as reflected in significant differences observed in the leaf area index (LAI), crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) during *rabi* 2022 and *kharif* 2024. T₉ consistently recorded the highest LAI at 30



DAT and CGR, RGR and NAR values at 30-60 DAT. This was statistically on par with hand weeding twice (T_{11}), suggesting that both approaches were equally effective in suppressing weed and enhancing physiological efficiency.

Non-chemical treatments like ITK-based (T_1), cono-weeding (T_8), azolla incorporation (T_5) and rice hull solution (T_6) combined with hand weeding (T_6) also recorded higher values. The unweeded control (T_{12}) consistently recorded the lowest physiological parameter values throughout due to delayed tillering. These findings are in accordance to those of [Shanmugapriya et al. \(2019\)](#), [Soren et al. \(2018\)](#) and [Goswami et al. \(2022\)](#), emphasizing

the important role of weed management in enhancing physiological efficiency and ultimately, rice yield.

LAI improvements under these treatments suggest more efficient light interception and enhanced photosynthetic surface area, promoting biomass accumulation. A higher LAI allows the crop to capture more light for photosynthesis boosting overall productivity. Higher CGR measures the increase in crop biomass per unit area per unit time and it reflects how fast the crop is growing which directly relates with efficient weed control. This was in accordance to the findings of [Rathod and Somasundaram \(2017\)](#). RGR is the increase in plant biomass relative to the existing

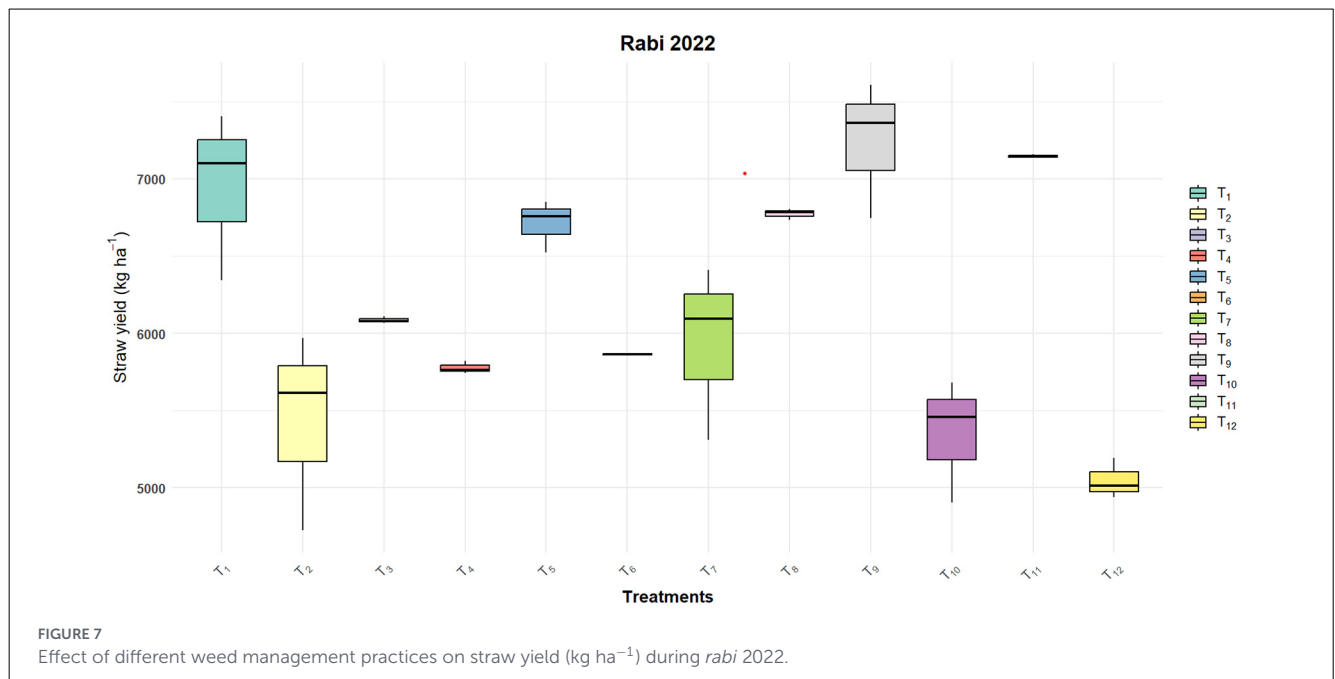


FIGURE 7
Effect of different weed management practices on straw yield (kg ha^{-1}) during *rabi* 2022.

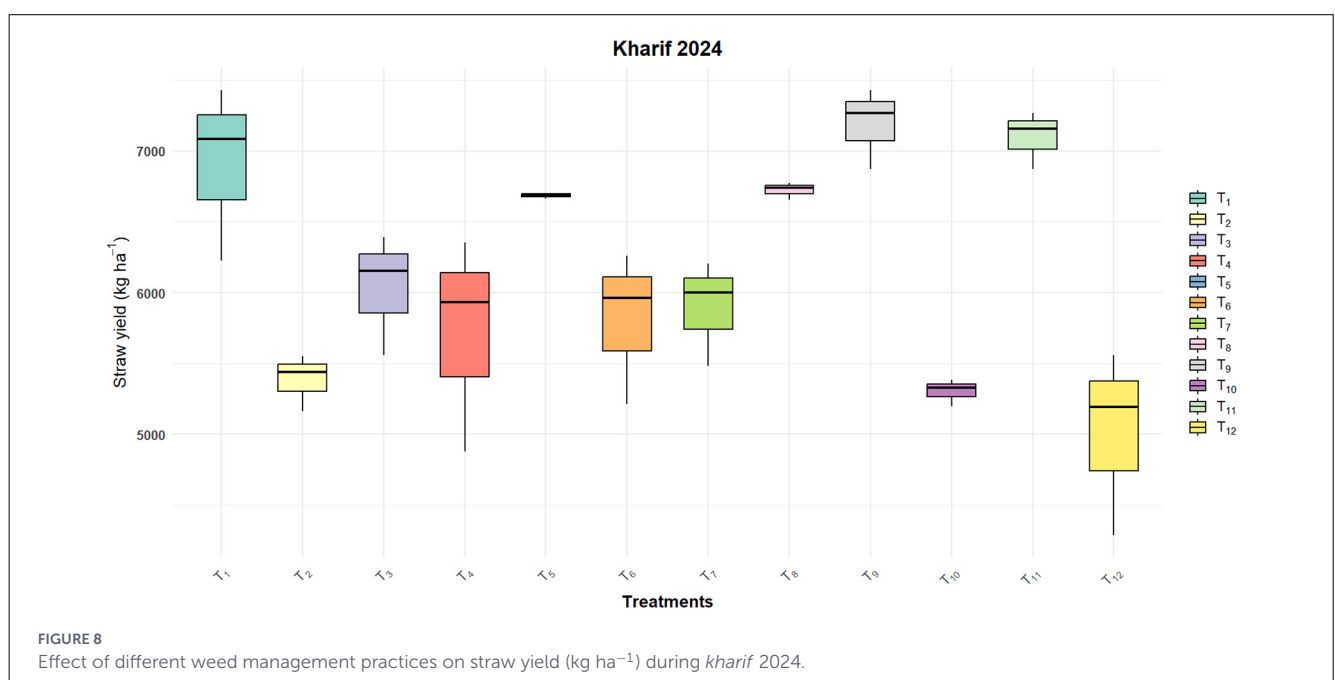


FIGURE 8
Effect of different weed management practices on straw yield (kg ha^{-1}) during *kharif* 2024.

biomass suggesting efficient growth directly to effect of good weed control. NAR is the rate of photosynthesis per unit leaf area where it measures the leaves efficiency in converting light into biomass. In weed-free and weed controlled condition, the rice leaves receive full sunlight maximizing photosynthesis rate. Higher photosynthetic efficiency results higher dry matter accumulation per unit leaf area leading to higher NAR.

4.3 Yield attributes

The yield performance of transplanted rice was significantly influenced by the weed management practices with both chemical and non-chemical interventions showing superior weed control over untreated control. The chemical weed control with Butachlor and Bispyribac sodium (T₉) and hand weeding twice (T₁₁) emerged as the most effective, achieving comparable and significantly superior yield parameters such as panicle number, filled grains, grain weight and grain yield in both the seasons. This highlights their efficacy in minimizing weed interference during critical crop stages. T₁ and T₈ showed the potential of integrating traditional and mechanical approaches for sustainable grain yield. T₅, T₃ and T₆ also recorded good productivity reflecting the value of organic interventions when supported by timely weed management. The consistently poor yield of the unweeded control (T₁₂) highlights the critical impact of weed pressure on yield loss. Although the test weight remained unaffected, improved harvest index in the other non-chemical treatments suggests better assimilate allocation toward grain, highlighting the role of integrated approaches in obtaining yield stability (Figures 5–8). These findings are consistent with those reported by Kumari et al. (2018) and Awan et al. (2019).

5 Conclusion

The study highlighted that effective weed management practices significantly influenced the growth, physiological and yield attributes of transplanted rice in both *rabi* 2022 and *kharif* 2024. Among the treatments, the chemical treatment (Butachlor @ 1 kg/ha at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE) consistently recorded the highest values across all growth stages. However, the non-chemical treatments also showed efficient in enhancing crop performance. T₁, T₅ and T₈ consistently recorded higher growth and yield. T₁ and T₅ recorded higher leaf area index, crop growth rate and net assimilation rate throughout the crop cycle suggesting their eco-friendly and sustainable role in integrated weed management. It may be due to nitrogen being fixed by azolla and nitrogen content in cow urine which attributed to better growth and yield of the rice plant in addition to suppressing weeds. The study highlights that non-chemical treatments can be effectively implemented for controlling weeds in transplanted rice offering a sustainable approach for improving productivity while reducing dependency on herbicides. These findings suggest the promotion of more study on non-chemical weed management practices for sustainable rice cultivation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LK: Funding acquisition, Formal analysis, Writing – review & editing, Software, Writing – original draft, Conceptualization, Data curation. ES: Validation, Methodology, Data curation, Supervision, Conceptualization, Investigation, Writing – original draft, Resources, Writing – review & editing, Visualization. KS: Writing – review & editing, Writing – original draft, Formal analysis, Software, Methodology, Data curation. MP: Supervision, Resources, Writing – review & editing. RK: Writing – review & editing, Resources. JP: Resources, Writing – review & editing, Supervision. RS: Resources, Writing – review & editing, Supervision. NE: Writing – review & editing. EC: Writing – review & editing.

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Conflict of interest

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Generative AI statement

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

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