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RESEARCH ARTICLE

Non-chemical approaches for effective weed management and productivity of transplanted rice (*Oryza sativa* L.)

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Abstract

A field experiment was conducted at the wetland farm, Tamil Nadu Agricultural University, Coimbatore, during *rabi* 2022 and *kharif* 2024 to evaluate the non-chemical weed management practices in transplanted rice. The study aimed to assess weed parameters including weed flora, total weed density, total weed dry weight, Weed Control Efficiency (WCE) and Weed Index (WI), along with their impact on grain yield. The experiment consisted of twelve treatments laid out in a Randomized Block Design (RBD) with three replications. The findings revealed that hand weeding at 20 and 40 Days After Transplanting (DAT) recorded the lowest total weed density with 19.9, 34.0, 46.0, 44.0 weeds m^{-2} in *rabi* 2022 and 24.3, 41.0, 58.1, 51.9 weeds m^{-2} in *kharif* 2024, the lowest total dry weight with 5.22, 5.89, 8.91, 10.15 g m^{-2} in *rabi* 2022 and 5.39, 6.33, 9.40, 10.92 g m^{-2} in *kharif* 2024, the highest WCE with 72.60 %, 79.22 %, 66.37 %, 68.73 % in *rabi* 2022 and 71.16 %, 77.02 %, 64.35 %, 64.47 % in *kharif* 2024, the lowest WI of 1.6 % in *rabi* 2022 and 1.4 % in *kharif* 2024 at 30, 45, 60, 80 DAT respectively, resulting in the highest grain yields of 5326 kg ha^{-1} in *rabi* 2022 and 5245 kg ha^{-1} in *kharif* 2024. This was followed by Butachlor @ 1 kg/ha at 3 DAT as pre-emergence and Bispyribac sodium @ 25 g/ha at 25 DAT as post emergence. Among non-chemical practices, foliar spray of ITK-based farmers' practices (cow urine + lime solution + khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT was most effective with total weed density of 5.06, 6.09, 7.53, 7.56 weeds m^{-2} in *rabi* 2022 and 5.52, 6.7, 8.2, 8.2 weeds m^{-2} in *kharif* 2024, total weed dry weight of 5.82, 7.36, 9.71, 12.13 g m^{-2} in *rabi* 2022 and 5.97, 7.50, 9.86, 12.37 g m^{-2} in *kharif* 2024, WCE of 65.53, 67.09, 59.98, 55.25 % in *rabi* 2022 and 64.51, 67.53, 60.78, 54.38 % in *kharif* 2024, WI of 3.2 in *rabi* 2022 and 2.4 in *kharif* 2024 at 30, 45, 60, 80 DAT respectively, with grain yield of 5235 kg ha^{-1} in *rabi* 2022 and 5198 kg ha^{-1} in *kharif* 2024. The current study aims to evaluate the effect of non-chemical weed management in transplanted rice.

Keywords: mycoherbicide; transplanted rice; Weed Control Efficiency; weed density; Weed Index

Introduction

Rice (*Oryza sativa* L.) is a staple food for over 60 % of the global population, playing a crucial role in food security and global economy (1, 2). India has significantly expanded its rice cultivation area and production in recent years. The U S Department of Agriculture reported that according to India's Third Advance Estimates released on 4th June 2024, the harvested area for rice was 47.6 million hectares (3). Weeds compete with rice for essential resources which causes yield losses of 34-67 % across various cultivation system (1, 2) and hence, effective weed management strategies are crucial for improving rice productivity (2, 4). Conventional weed management methods rely heavily on herbicides, but their repeated and excessive use has led to environmental pollution, herbicide resistance and ecological imbalances (5). To mitigate these non-chemical weed management practices approach, which includes mechanical, cultural and biological methods, to prevent weed reproduction, reduce weed emergence and minimize competition with crops (5). These practices not only protect ecosystems by preserving beneficial insects and improving soil health but also help reduce long-term farming costs by decreasing dependence on expensive herbicides and synthetic fertilizers.

Mechanical techniques such as hand weeding and cono-weeding have shown effectiveness in reducing weed density although they are labor-intensive (6). Cultural practices such as stale seedbed techniques, crop rotation, flooding, transplanting, green manuring and intercropping with green manuring crops helps in suppressing weed emergence and enhances soil fertility (7, 8). Biological control involving use of insects and pathogens is considered as an eco-friendly alternative for weed control (9) and many fungal-based bioherbicides have been proven to be a successful biocontrol against major rice weeds like *Cyperus rotundus* and *Echinochloa spp* among other weeds (10, 11). Mycoherbicides such as *Colletotrichum gloeosporioides*, *Cochliobolus lunatus* and

Alternaria alternata have successfully controlled problematic weeds like northern joint vetch and barnyard grass without harming the rice plant (12, 13). The commercial success of Collego also highlights the potential of mycoherbicides for sustainable weed management (14).

As global demand for sustainable agriculture grows, non-chemical weed management is becoming a crucial strategy for ensuring healthier crops, safer food and a more resilient agricultural system. Non-chemical weed management requires a combination of various strategies based on the type and severity of weeds, which is essential for developing a holistic, sustainable and eco-friendly weed control across the cropping season. Therefore, the present study was carried out to evaluate the most effective non-chemical weed management strategy that ensures optimal weed control while enhancing rice productivity and sustainability.

Materials and Methods

A field experiment was conducted during *rabi* 2022 and *kharif* 2024 at wetland farm, Tamil Nadu Agricultural University, Coimbatore (11°N latitude and 77°E longitude, 426.7 m above mean sea level). The treatments comprised of T_1: foliar spray (FS) of ITK-based farmers' practices on 25 DAT + hand weeding at 40 DAT, T_2: mycoherbicide (1) @ 25 DAT + hand weeding at 40 DAT, T_3: rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT, T_4: intercropping dhaincha with rice (3:1 ratio) and incorporation at 40 DAT, T_5: azolla as a dual crop @ 1 t/ha and incorporation at 40 DAT, T_6: rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT, T_7: double green manuring @ 6.25 t/ha at transplanting (25 DAT), T_8: cono-weeding at 10-day intervals for four times (10, 20, 30, 40 DAT), T_9: Butachlor @ 1 kg/ha at 3 DAT as PE and Bispyribac sodium @ 25 g/ha at 25 DAT as POE, T_{10}: mycoherbicide2 @ 25 DAT + hand weeding at 40 DAT, T_{11}: Hand Weeding (HW) at 20 and 40 DAT and T_{12}: unweeded check. The mycoherbicide selected were *Bipoloris eleusines* and *Curvularia lunata.*

The rice variety CO 51 was used for the experiment. The soil of the experimental field was clay loam with a pH of 8.31, low in nitrogen (231.6 kg ha^{-1}), medium in phosphorus (21.74 kg ha^{-1}), high in potassium (454.2 kg ha^{-1}) and medium in organic carbon content (0.59 %). The recommended fertilizer dose of 150:50:50 kg ha^{-1} of nitrogen, phosphorus and potassium was applied in the form of urea (46 % N), single super phosphate (16 % P_2O_5) and muriate of potash (60 % K_2O). Fifty percent of nitrogen (75 kg) and the full dose of phosphorus (50 kg) and potassium (50 kg) were applied basally before transplanting. The remaining 50 % of nitrogen (75 kg) was top-dressed in two equal splits at active tillering and panicle initiation stages.

The pre-dominant weed flora in the experimental field was identified from the unweeded control plots and categorized into grasses, sedges and Broad-Leaved Weeds (BLW). Weed density was recorded in 4 quadrants (0.5 m × 0.5 m) placed randomly in each plot at 30, 45, 60 and 80 DAT. Weed density and dry weight were expressed as No. m^{-2} and g m^{-2}, respectively. Throughout the experiment, data were recorded on weed flora composition, weed density, weed dry weight and grain yield of rice. Manual hand weeding was carried out twice in the weed-free check plots, while an unweeded check was maintained to assess the natural weed infestation. The effectiveness of pre-emergence (PE) and post-emergence (POE) herbicides was evaluated against non-chemical weed control strategies.

Weed observation

Weed flora

Weed species present in the experimental plot were identified from unweeded check at flowering stage and have been grouped as grasses, sedges and broadleaved weeds.

Weed density and weed dry weight

The total weed density and total dry weight was considered for each treatment and the effects of different weed control practices were worked out.

Weed Control Efficiency (WCE)

Weed control efficiency was worked out using the formula

$$WCE = \frac{DWC - DWT}{DWC} \times 100 \quad \text{(Eqn. 01)}$$

Where,

DWC - Dry weight of weeds in unweeded check (g m^{-2})

DWT - Dry weight of weed control treatments (g m^{-2})

Weed Index (WI)

WI is a measure of the crop yield loss across treatments in comparison to a minimum weed-infested plot such as two or three hand weeding (as good as weed free check) adopted in an experiment. WI was calculated by using the following formula.

$$WI = \frac{YWF - YT}{YWF} \times 100 \quad \text{(Eqn. 02)}$$

Where,

YWF - Crop yield in weed free plot (kg/ha),

YT - Crop yield in treated plot (kg/ha).

Yield parameters (grain yield and straw yield) were recorded from a net plot area and expressed in kg/ha.

Statistical analysis

The Analysis of Variance (ANOVA) for all measured traits was conducted using R software (version 4.2.1) through R Studio for Windows (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" (15).

Results and Discussions

Weed flora

The pre-dominant weeds observed in the experimental fields were *Echinochloa crus-galli*, *Echinochloa colona* and *Leptochloa chinensis* in grasses; *Cyperus rotundus*, *Cyperus difformis* and *Fimbristylis miliacea* in sedges; *Eclipta prostrata*, *Ammania baccifera* and *Acalypha indica* in broadleaved weeds. These weeds interfered with rice growth by competing for nutrients, water and light. The presence of diverse weed species highlights the complexity of weed management in transplanted rice systems and highlights the need for various non-chemical weed management approaches and taking integrated weed management under consideration. A similar kind of weed flora under transplanted conditions were also noticed previously (16, 17).

Weed density and weed dry weight

The highest total weed density was recorded in unweeded check for both the seasons (Table 1). All other weed management practices significantly reduced the total weed density and the total weed dry weight compared to the unweeded check. Weed dry weight is a crucial indicator for evaluating weed competition on crop growth and productivity.

The lowest total weed density was recorded with HW at 20 and 40 DAT which resulted in 19.9, 34.0, 46, 44 weeds/m^{-2} weeds m^{-2} in *rabi* 2022 and 24.3, 41.0, 58.1, 51.9 weeds m^{-2} in *kharif* 2024 at 30, 45, 60, 80 DAT respectively. Hand weeding physically removes both annual and perennial weeds, thereby minimizing weed-crop competition for essential resources such as nutrients, light, water and space during the early vegetative and tillering phases of rice. The timing of HW at 20 and 40 DAT is crucial, as it targets early germinating weeds and subsequent flushes, breaking the weed life cycle and reducing seed bank replenishment (18). HW twice at these intervals has been found to produce up to 81 % higher grain yield compared to unweeded controls (19). This was closely followed by Butachlor @ 1 kg/ha at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE which recorded 23.8, 35.2, 51, 51 weeds m^{-2} for *rabi* 2022 and 27.3, 44.8, 62.8, 59.5 weeds m^{-2} for *kharif* 2024 at 30, 45, 60, 80 DAT respectively. This may be due to the chemical combination of Butachlor (a pre-emergence herbicide) and Bispyribac sodium (a post-emergence herbicide) which acts through physiological pathways where Butachlor inhibits protein synthesis by affecting meristematic activity in germinating weeds and Bispyribac sodium inhibits acetolactate synthase (ALS), a key enzyme in the biosynthesis of branched-chain amino acids essential for weed growth (20). However, the efficacy of these herbicides is threatened by the increasing occurrence of resistant weeds (21).

Among the non-chemical weed management strategies, FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT showed a comparable reduction in weed density with 25.1, 36.6, 56.2, 30.1 weeds m^{-2} in *rabi* 2022 and 30.1, 44.8, 65.9 and 66.9 weeds m^{-2} in *kharif* 2024. ITK-based formulations, including cow urine, lime, soap and salt, act as bio-herbicides by disrupting cellular processes in weeds (22). It showed a notable reduction in weed density due to the synergistic action of both bioactive and physical weed control. The ITK formulation comprising cow urine, lime solution, khadi soap and common salt acts as a bio-herbicidal mixture. Cow urine contains urea and phenolic compounds that can disrupt cellular processes in weeds; lime raises the pH enhancing the caustic effect; soap aids in breaking the cuticle and improving penetration of active ingredients and salt exerts osmotic stress, leading to desiccation of weed tissues. This biochemical stress weakens the weed population prior to manual removal, making the subsequent HW at 40 DAT more effective and less laborious. This approach aligns with the growing need for sustainable, eco-friendly weed control methods that reduce reliance on chemical herbicides and address issues of labor scarcity and environmental concerns (23). Azolla as a dual crop @ 1 t/ha + incorporation at 40 DAT resulted in significant reduction in weed density. Azolla forms a dense mat on the water surface, shading the soil and reducing light availability required for weed seed germination. The dense azolla mat inhibits weed

Table 1. Effect of non- chemical weed management practices on total weed density (No. m^{-2}) at 30, 45, 60 and 80 DAT in transplanted rice (*rabi* 2022 and *kharif* 2024)

T.No	Treatments	*rabi* 2022				*kharif* 2024			
		30 DAT	45 DAT	60 DAT	80 DAT	30 DAT	45 DAT	60 DAT	80 DAT
T_1	FS of ITK-based farmers' practices on 25 DAT + hand weeding at 40 DAT	5.06 (25.1)	6.09 (36.6)	7.53 (56.2)	7.56 (56.0)	5.52 (30.1)	6.7 (44.8)	8.2 (65.9)	8.20 (66.9)
T_2	Mycoherbicide1 @ 25 DAT + hand weeding at 40 DAT	7.36 (53.7)	8.86 (78.0)	9.67 (93.0)	9.51 (90.0)	7.7 (58.8)	9.2 (84.8)	10.0 (99.2)	9.89 (97.3)
T_3	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	7.45 (55.1)	8.91 (79.0)	9.77 (95.0)	9.72 (94.0)	7.7 (59.2)	9.4 (88.6)	10.3 (105.1)	10.10 (101.7)
T_4	Intercropping dhaincha with rice (3:1 ratio) and incorporation at 40 DAT	7.83 (60.8)	9.41 (88.0)	10.32 (106.0)	10.37 (107.0)	8.1 (65.8)	9.9 (97.1)	10.6 (112.8)	10.79 (115.9)
T_5	Azolla as dual crop @ 1 t/ha and incorporation at 40 DAT	5.31 (27.7)	6.72 (44.6)	7.73 (59.2)	7.92 (66.2)	5.75 (32.6)	7.3 (53.1)	8.3 (68.7)	8.41 (70.0)
T_6	Rice hull solution (50 % FS spray) at 15 DAT + hand weeding at 40 DAT	8.44 (70.8)	9.92 (98.0)	10.79 (116.0)	10.88 (118.0)	8.8 (76.9)	10.4 (108.2)	11.0 (121.4)	11.30 (127.2)
T_7	Double green manuring @ 6.25 t/ha at transplanting (25 DAT)	7.36 (53.7)	8.86 (78.0)	9.72 (94.0)	9.87 (97.0)	7.7 (58.1)	9.3 (85.8)	10.0 (99.2)	10.28 (105.1)
T_8	Cono-weeding at 10 days interval for four times (10, 20, 30 and 40 DAT)	5.78 (32.9)	7.31 (53.0)	8.21 (67.0)	8.27 (68.0)	6.2 (37.9)	7.8 (59.9)	8.6 (73.6)	8.79 (76.7)
T_9	RH: Butachlor @ 1 kg/ha at 3 DAT as PE and Bispyribac sodium @ 25 g/ha at 25 DAT as POE	4.93 (23.8)	6.01 (35.2)	7.18 (51.0)	7.18 (51.0)	5.3 (27.3)	6.7 (44.8)	7.9 (62.8)	7.75 (59.5)
T_{10}	Mycoherbicide2 @ 25 DAT + hand weeding at 40 DAT	7.63 (57.7)	9.03 (81.0)	9.97 (99.0)	9.82 (96.0)	8.0 (63.5)	9.6 (91.2)	10.3 (105.3)	10.23 (104.3)
T_{11}	Hand weeding at 20 and 40 DAT	4.52 (19.9)	5.87 (34.0)	6.82 (46.0)	6.67 (44.0)	5.0 (24.3)	6.4 (41.0)	7.6 (58.1)	7.24 (51.9)
T_{12}	Unweeded check	9.71 (93.9)	11.07 (122.0)	11.93 (142.0)	12.34 (152.0)	9.9 (98.0)	11.5 (132.3)	12.4 (152.2)	12.72 (161.5)
S.Ed		**0.08**	**0.17**	**0.18**	**0.22**	**0.13**	**0.19**	**0.11**	**0.20**
CD (P=0.05)		**0.17**	**0.36**	**0.37**	**0.47**	**0.27**	**0.40**	**0.23**	**0.42**

germination by shading the soil surface and releasing allelochemicals (24). Upon incorporation into the soil, it further enhances soil fertility and microbial activity, which can indirectly suppress weeds by improving rice competitiveness.

The total weed dry weight in transplanted rice was significantly influenced by different weed management practices during *rabi* 2022 and *kharif* 2024 (Table 2). The lowest weed dry weight was recorded with HW at 20 and 40 DAT which resulted in 5.22, 5.89, 8.91, 10.15 g m^{-2} in *rabi* 2022 and 5.39, 6.33, 9.40, 10.92 g m^{-2} in *kharif* 2024 at 30, 45, 60, 80 DAT respectively. Early weed removal at 20 DAT minimizes initial weed-crop competition during the sensitive early vegetative phase, while the second weeding at 40 DAT targets late-emerging weeds. This approach not only reduces weed biomass but also enhances crop nutrient uptake and dry matter production in rice (25), ultimately leading to higher grain and straw yields (26). This was closely followed by Butachlor @ 1 kg/ha as PE + Bispyribac sodium @ 25 g/ha as POE, which recorded 5.68, 6.72, 9.48, 11.67 g m^{-2} in *rabi* 2022 and 5.81, 6.97, 9.84, 12.01 g m^{-2} in *kharif* 2024 at 30, 45, 60, 80 DAT, respectively. Among the non-chemical weed management practices, ITK-based farmers' practices on 25 DAT + HW at 40 DAT significantly reduced weed dry weight recording 5.82, 7.36, 9.71, 12.13 g m^{-2} in *rabi* 2022 and 5.97, 7.50, 9.86, 12.37 g m^{-2} in *kharif* 2024 at 30, 45, 60, 80 DAT, respectively. Similarly, azolla as dual crop @ 1 t/ha + incorporation at 40 DAT recorded values of 6.02, 7.86, 10.43, 12.72 g m^{-2} in *rabi* 2022 and 6.14, 8.11, 10.73, 13.16 g m^{-2} in *kharif* 2024 at 30, 45, 60, 80 DAT indicating its effectiveness as an eco-friendly alternative. The highest weed dry weight was recorded in the unweeded check with 9.94, 12.85, 15.42, 18.12 g m^{-2} in *rabi* 2022 and 9.99, 13.16, 15.72, 18.37 g m^{-2} in *kharif* 2024 at 30, 45, 60, 80 DAT respectively indicating severe weed interference. These results emphasized the necessity of sustainable and eco-friendly weed management approaches, where manual, chemical and biological methods play a crucial role in maintaining lower weed biomass and ensuring better crop growth in transplanted rice systems. These results were strongly supported by various studies conducted in rice. The integrated weed management practices significantly reduce weed density and biomass in transplanted rice (27-29). Chemical methods, particularly combinations of pre-emergence and post-emergence herbicides like pretilachlor followed by bispyribac sodium, showed promising results in reducing weed density and improving crop yield (27, 28) but its long-term use is not sustainable and eco-friendly. Azolla incorporation and ITK-based farmers' practices also demonstrated effectiveness in weed management.

Weed Control Efficiency (WCE)

The highest WCE was observed under HW at 20 and 40 DAT recording 72.60 %, 79.22 %, 66.37 %, 68.73 % in *rabi* 2022 and 71.16 %, 77.02 %, 64.35 %, 64.47 % in *kharif* 2024 at 30, 45, 60, 80 DAT respectively confirming its superiority in weed suppression (Table 3). Multiple manual weeding at 20-21 and 40-42 DAT significantly reduced weed density and increased WCE. The effectiveness of manual weeding is attributed to its direct elimination of weed biomass without relying on environmental conditions or herbicide selectivity (30). Manual weeding not only suppresses weed growth but also enhances nutrient uptake by rice plants, leading to superior grain yields compared to chemical treatments (31).

Butachlor @ 1 kg/ha as PE + Bispyribac sodium @ 25 g/ha as POE exhibited higher efficiency with 67.31 %, 72.67 %, 62.01 %, 58.57 % in *rabi* 2022 and 66.54 %, 71.95 %, 60.80 %, 56.94 % in *kharif* 2024 at 30, 45, 60, 80 DAT making it an effective chemical approach. Sequential application of these herbicides has demonstrated high weed control efficiency and increased grain yield in both transplanted and wet-seeded rice (32, 33). This combination addresses the challenge of multiple weed flushes throughout the growing season (33). However, the effect of prolonged use of chemical weed control is not a

Table 2. Effect of non- chemical weed management practices on total weed dry weight (g m^{-2}) at 30, 45, 60 and 80 DAT in transplanted rice (*rabi* 2022 and *kharif* 2024)

T.No	Treatments	*rabi* 2022				*kharif* 2024			
		30 DAT	45 DAT	60 DAT	80 DAT	30 DAT	45 DAT	60 DAT	80 DAT
T_1	FS of ITK-based farmers' practices on 25 DAT + hand weeding at 40 DAT	5.82 (33.4)	7.36 (53.7)	9.71 (93.8)	12.13 (146.7)	5.97 (35.2)	7.50 (55.8)	9.86 (96.7)	12.37 (152.7)
T_2	Mycoherbicide1 @ 25 DAT + hand weeding at 40 DAT	9.07 (81.8)	10.99 (120.2)	13.39 (179.3)	16.10 (258.8)	9.13 (82.9)	11.17 (124.7)	13.60 (184.6)	16.30 (265.2)
T_3	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	8.13 (65.8)	9.13 (82.8)	11.18 (124.5)	14.22 (201.8)	8.20 (66.7)	9.25 (85.3)	11.37 (128.8)	14.53 (210.6)
T_4	Intercropping dhaincha with rice (3:1 ratio) and incorporation at 40 DAT	8.52 (72.1)	9.65 (92.6)	11.81 (139.2)	14.90 (221.9)	8.59 (73.4)	9.83 (96.1)	12.07 (145.2)	15.27 (232.7)
T_5	Azolla as dual crop @ 1 t/ha and incorporation at 40 DAT	6.02 (35.8)	7.86 (61.3)	10.43 (108.4)	12.72 (161.7)	6.14 (37.2)	8.11 (65.2)	10.73 (114.6)	13.16 (173.1)
T_6	Rice hull solution (50 % FS spray) at 15 DAT + hand weeding at 40 DAT	8.63 (74.1)	10.19 (103.5)	12.15 (147.6)	15.27 (232.7)	8.77 (76.5)	10.41 (107.8)	12.50 (155.8)	15.56 (241.8)
T_7	Double green manuring @ 6.25 t/ha at transplanting (25 DAT)	8.37 (69.5)	9.35 (86.9)	11.49 (131.6)	14.55 (211.3)	8.47 (71.3)	9.46 (89.2)	11.83 (139.4)	14.97 (223.6)
T_8	Cono-weeding at 10 days interval for four times (10, 20, 30 and 40 DAT)	7.89 (61.8)	7.57 (56.8)	10.16 (102.7)	12.46 (154.8)	8.01 (63.7)	7.79 (60.3)	10.54 (110.7)	12.92 (166.5)
T_9	RH: Butachlor @ 1 kg/ha at 3 DAT as PE and Bispyribac sodium @ 25 g/ha at 25 DAT as POE	5.68 (31.8)	6.72 (44.8)	9.48 (89.4)	11.67 (135.8)	5.81 (33.2)	6.97 (48.1)	9.84 (96.4)	12.01 (143.9)
T_{10}	Mycoherbicide2 @ 25 DAT + hand weeding at 40 DAT	9.17 (83.5)	11.27 (126.5)	13.75 (188.5)	16.41 (269.3)	9.26 (85.4)	11.44 (130.4)	14.03 (196.9)	16.76 (280.4)
T_{11}	Hand weeding at 20 and 40 DAT	5.22 (26.7)	5.89 (34.2)	8.91 (78.9)	10.15 (102.5)	5.39 (28.6)	6.33 (39.6)	9.40 (87.8)	10.92 (118.7)
T_{12}	Unweeded check	9.94 (98.5)	12.85 (164.8)	15.42 (237.9)	18.12 (327.8)	9.99 (99.3)	13.16 (172.8)	15.72 (246.8)	18.37 (337.8)
S.Ed		**0.25**	**0.26**	**0.43**	**0.37**	**0.17**	**0.32**	**0.32**	**0.37**
CD (P=0.05)		**0.52**	**0.55**	**0.89**	**0.77**	**0.36**	**0.67**	**0.67**	**0.78**

Table 3. Effect of non-chemical weed management practices on weed control efficiency (WCE) (%) at 30, 45, 60 and 80 DAT in transplanted rice (*rabi* 2022 and *kharif* 2024)

T.No	Treatments	***rabi* 2022**				**k*Kharif* 2024**			
		30 DAT	**45 DAT**	**60 DAT**	**80 DAT**	**30 DAT**	**45 DAT**	**60 DAT**	**80 DAT**
T_1	FS of ITK-based farmers' practices on 25 DAT + hand weeding at 40 DAT	65.53	67.09	59.98	55.25	64.51	67.53	60.78	54.38
T_2	Mycoherbicide1 @ 25 DAT + hand weeding at 40 DAT	15.88	26.60	23.33	21.05	16.40	28.02	25.06	20.81
T_3	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	33.00	49.48	47.01	38.43	32.84	50.36	47.71	37.09
T_4	Intercropping dhaincha with rice (3:1 ratio) and incorporation at 40 DAT	25.88	43.47	40.84	32.32	25.87	44.07	40.98	30.48
T_5	Azolla as dual crop @ 1 t/ha and incorporation at 40 DAT	63.21	62.54	53.77	50.68	62.44	62.07	53.42	48.00
T_6	Rice hull solution (50 % FS spray) at 15 DAT + hand weeding at 40 DAT	24.61	36.85	37.27	29.01	22.96	37.10	36.76	27.77
T_7	Double green manuring @ 6.25 t/ha at transplanting (25 DAT)	28.56	46.98	43.94	35.53	28.19	48.43	43.35	33.30
T_8	Cono-weeding at 10 days interval for four times (10, 20, 30 and 40 DAT)	35.96	65.37	56.35	52.78	35.82	64.91	55.19	50.14
T_9	RH: Butachlor @ 1 kg/ha at 3 DAT as PE and Bispyribac sodium @ 25 g/ha at 25 DAT as POE	67.31	72.67	62.01	58.57	66.54	71.95	60.80	56.94
T_{10}	Mycoherbicide2 @ 25 DAT + hand weeding at 40 DAT	14.13	23.06	19.80	17.83	14.13	23.87	20.44	16.06
T_{11}	Hand weeding at 20 and 40 DAT	72.60	79.22	66.37	68.73	71.16	77.02	64.35	64.47
T_{12}	Unweeded check	-	-	-	-	-	-	-	-

Data statistically not analysed

sustainable approach for long term effect.

Among the non-chemical practices, ITK-based farmers' practices at 25 DAT + HW at 40 DAT and Azolla as a dual crop @ 1 t/ha + incorporation at 40 DAT recorded a considerable WCE. ITK-based farmers' practices at 25 DAT + HW at 40 DAT showed WCE of 65.53 %, 67.09 %, 59.98 %, 55.25 % in *rabi* 2022 and 64.51 %, 67.53 %, 60.78 %, 54.38 % in *kharif* 2024 while Azolla as a dual crop @ 1 t/ha + incorporation at 40 DAT recorded WCE of 63.21 %, 62.54 %, 53.77 %, 50.68 % in *rabi* 2022 and 62.44 %, 62.07 %, 53.42 %, 48.00 % in *kharif* 2024 at 30, 45, 60, 80 DAT highlighting their potential as sustainable alternatives. ITK-based control demonstrated notable weed control efficiency highlighting their potential as sustainable alternatives to herbicide-based strategies. It can be attributed to the combined action of traditional foliar applications and manual weeding. Studies have demonstrated that azolla can effectively control various weed species, including *Monochoria vaginalis* and *Echinochloa glabrescens* by forming a dense mat on the water surface (34, 35).

Weed Index

WI quantifies yield reduction due to weed competition with lower values indicating better weed control efficiency and minimal yield loss. HW at 20 and 40 DAT recorded the lowest WI of 1.6 % in *rabi* 2022 and 1.4 % in *kharif* 2024, confirming its effectiveness in minimizing yield losses (Table 4). This was followed by the ITK-based farmers' practices + HW at 40 DAT which recorded a WI of 3.2 % in *rabi* 2022 and 2.4 % in *kharif* 2024 and cono-weeding at 10, 20, 30, 40 DAT with WI of 4.5 % in *rabi* 2022 and 3.8 % in *kharif* 2024, highlighting their efficiency in reducing weed competition. Azolla as a dual crop + incorporation at 40 DAT also recorded effective weed suppression with a WI of 6.7 % in *rabi* 2022 and 6.5 % in *kharif* 2024. In contrast, the highest WI was observed in the unweeded check with 50.2 % in *rabi* 2022 and 52.1 % in *kharif* 2024, indicating severe yield loss due to uncontrolled weed growth. These findings emphasize that HW, ITK-based practices, cono-weeding and azolla incorporation significantly

Table 4. Effect of non-chemical weed management practices on WI in transplanted rice (*rabi* 2022 and *kharif* 2024)

T.No	Treatments	***rabi* 2022**	***kharif* 2024**
T_1	FS of ITK-based farmers' practices on 25 DAT + hand weeding at 40 DAT	3.2	2.4
T_2	Mycoherbicide1 @ 25 DAT + hand weeding at 40 DAT	26.9	26.8
T_3	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	11.8	10.3
T_4	Intercropping dhaincha with rice (3:1 ratio) and incorporation at 40 DAT	18.3	18.1
T_5	Azolla as dual crop @ 1 t/ha and incorporation at 40 DAT	6.7	6.5
T_6	Rice hull solution (50 % FS spray) at 15 DAT + hand weeding at 40 DAT	16.4	15.9
T_7	Double green manuring @ 6.25 t/ha at transplanting (25 DAT)	14.7	14.8
T_8	Cono-weeding at 10 days interval for four times (10, 20, 30 and 40 DAT)	4.5	3.8
T_9	RH: Butachlor @ 1 kg/ha at 3 DAT as PE and Bispyribac sodium @ 25 g/ha at 25 DAT as POE	0.0	0.0
T_{10}	Mycoherbicide2 @ 25 DAT + hand weeding at 40 DAT	30.2	30.2
T_{11}	Hand weeding at 20 and 40 DAT	1.6	1.4
T_{12}	Unweeded check	50.2	52.1

Data statistically not analysed

reduced yield losses whereas poor weed control results in substantial productivity declines in transplanted rice (36, 37).

Growth and yield of rice

Significant variations were observed among the weed management treatments in terms of plant height, Leaf Area Index (LAI) at 90 DAT and grain yield during both *rabi* 2022 and *kharif* 2024 (Table 5). Among the treatments, Butachlor @ 1 kg/ ha as PE + Bispyribac sodium @ 25 g/ha as POE recorded the highest plant height (109.3 cm in *rabi* 2022 and 107.3 cm in *kharif* 2024), LAI (3.58 and 3.56) and grain yield (5427 kg ha^{-1} and 5385 kg ha^{-1}) indicating its superiority in weed control efficiency and positive impact on crop growth. The enhanced crop growth can be scientifically attributed to the effective suppression of early and late-emerging weed populations by the dual-action herbicide strategy, which minimizes competition for essential resources such as light, water, nutrients and space during the critical early stages of crop development. Timely herbicide application significantly reduces weed density and biomass, allowing rice plants to allocate more resources towards vegetative and reproductive growth (38), leading to increased biomass accumulation (as indicated by higher LAI) resulting in taller and healthier plants. Furthermore, improved LAI enhances photosynthetic capacity, directly contributing to better grain filling and higher yields. This results in improved physiological traits such as increased plant height, tiller number and LAI, which contribute to enhanced photosynthetic capacity and higher grain yield (38, 39).

This was closely followed by T_{11} (hand weeding twice at 20 and 40 DAT), which recorded a plant height of 106.2 cm and 105.1 cm, LAI of 3.55 and 3.54 and grain yield of 5326 kg ha-^{1} and 5245 kg ha^{-1} in *rabi* 2022 and *kharif* 2024 respectively, exhibiting the effectiveness of hand weeding. HW minimizes the competition during the critical stages, allow the rice plants to fully utilize available resources. This promotes better tillering, enhanced photosynthetic area (higher LAI) and robust vegetative growth, which ultimately leads to improved reproductive development and higher grain yield (40).

ITK-based farmers' practices + HW at 40 DAT recorded a plant height of 106.6 cm and 105.7 cm, LAI of 3.52 and 3.51 and grain yield of 5235 kg ha^{-1} and 5198 kg ha^{-1} while econo weeding at 10, 20, 30, 40 DAT recorded a plant height of 105.3 cm and 104.4 cm, LAI of 3.50 and 3.49 and grain yield of 5164 kg ha^{-1} and 5121 kg ha^{-1} in *rabi* 2022 and *kharif* 2024, respectively indicating a good plant growth and yield. Azolla as a dual crop + incorporation at 40 DAT also recorded a good growth and yield with a plant height of 104.7 cm and 103.8 cm, LAI of 3.49 and 3.47 and grain yield of 5076 kg ha^{-1} and 4983 kg ha^{-1} suggesting its potential for weed suppression and soil fertility enhancement and microbial activity, which can indirectly suppress weeds by improving rice competitiveness (41).

Correlation analysis

The correlation matrices for *rabi* 2022 and *kharif* 2024 (Fig. 1 and Fig. 2) provides critical insights into the interactions between weed parameters and crop performance traits under varying seasonal conditions and weed management practices. During *rabi* 2022, a clear and consistent negative correlation was observed between weed matrices i.e., total weed density and total weed dry weight at 30, 45, 60, 80 DAT and yield parameters like the number of panicles (r = - 0.90), filled grains per panicle (r = - 0.98), panicle weight (r = - 0.99) and grain yield (r = - 0.97). This strong inverse relationship highlights the critical role of timely and effective weed suppression in enhancing yield attributes. HW at 20 and 40 DAT and FS of ITK-based farmers' practices at 25 DAT + HW at 40 DAT recorded superior efficacy in reducing weed competition as substantiated by the lower weed biomass and a high positive correlation between grain yield and yield components (panicle weight, r = 0.99; filled grains per panicle, r = 0.99). Negative correlations between weed parameters and crop productivity highlights the detrimental effects of weed competition on yield (42).

However, during *kharif* 2024, although a negative correlation between weed management practices and crop productivity was still evident, it was comparatively less intense (r values ranging from - 0.85 to - 0.94 for grain yield and weed management practices) potentially due to higher

Table 5. Effect of non-chemical weed management practices on plant height (cm), LAI and grain yield (kg ha^{-1}) in transplanted rice

T.No	Treatments	*rabi* 2022			*kharif* 2024		
		Plant height (cm) at harvest	LAI at 90 DAT	Grain yield (kg ha^{-1})	Plant height (cm) at harvest	LAI at 90 DAT	Grain yield (kg ha^{-1})
T_1	FS of ITK-based farmers' practices on 25 DAT + hand weeding at 40 DAT	106.6	3.52	5235	105.7	3.51	5198
T_2	Mycoherbicide1 @ 25 DAT + hand weeding at 40 DAT	89.2	2.99	3965	88.1	2.98	3932
T_3	Rice bran @ 5 t/ha as basal at transplanting + hand weeding at 40 DAT	98.8	3.27	4785	97.6	3.26	4755
T_4	Intercropping dhaincha with rice (3:1 ratio) and incorporation at 40 DAT	97.1	3.23	4416	96.2	3.22	4387
T_5	Azolla as dual crop @ 1 t/ha and incorporation at 40 DAT	104.7	3.49	5076	103.8	3.47	4983
T_6	Rice hull solution (50 % FS spray) at 15 DAT + hand weeding at 40 DAT	96.4	3.23	4537	95.3	3.21	4479
T_7	Double green manuring @ 6.25 t/ha at transplanting (25 DAT)	97.9	3.26	4626	96.7	3.25	4586
T_8	Cono-weeding at 10 days interval for four times (10, 20, 30 and 40 DAT)	105.3	3.50	5164	104.4	3.49	5121
T_9	RH: Butachlor @ 1 kg/ha at 3 DAT as PE and Bispyribac sodium @ 25 g/ha at 25 DAT as POE	109.3	3.58	5427	107.3	3.56	5385
T_{10}	Mycoherbicide2 @ 25 DAT + hand weeding at 40 DAT	88.4	2.96	3781	87.5	2.94	3716
T_{11}	Hand weeding at 20 and 40 DAT	106.2	3.55	5326	105.1	3.54	5245
T_{12}	Control	81.7	2.61	2896	82.2	2.59	2816
S.Ed		**4.96**	**0.159**	**0.159**	**4.23**	**0.159**	**274**
CD (P=0.05)		**10.3**	**0.3**	**0.33**	**8.78**	**0.33**	**568.00**

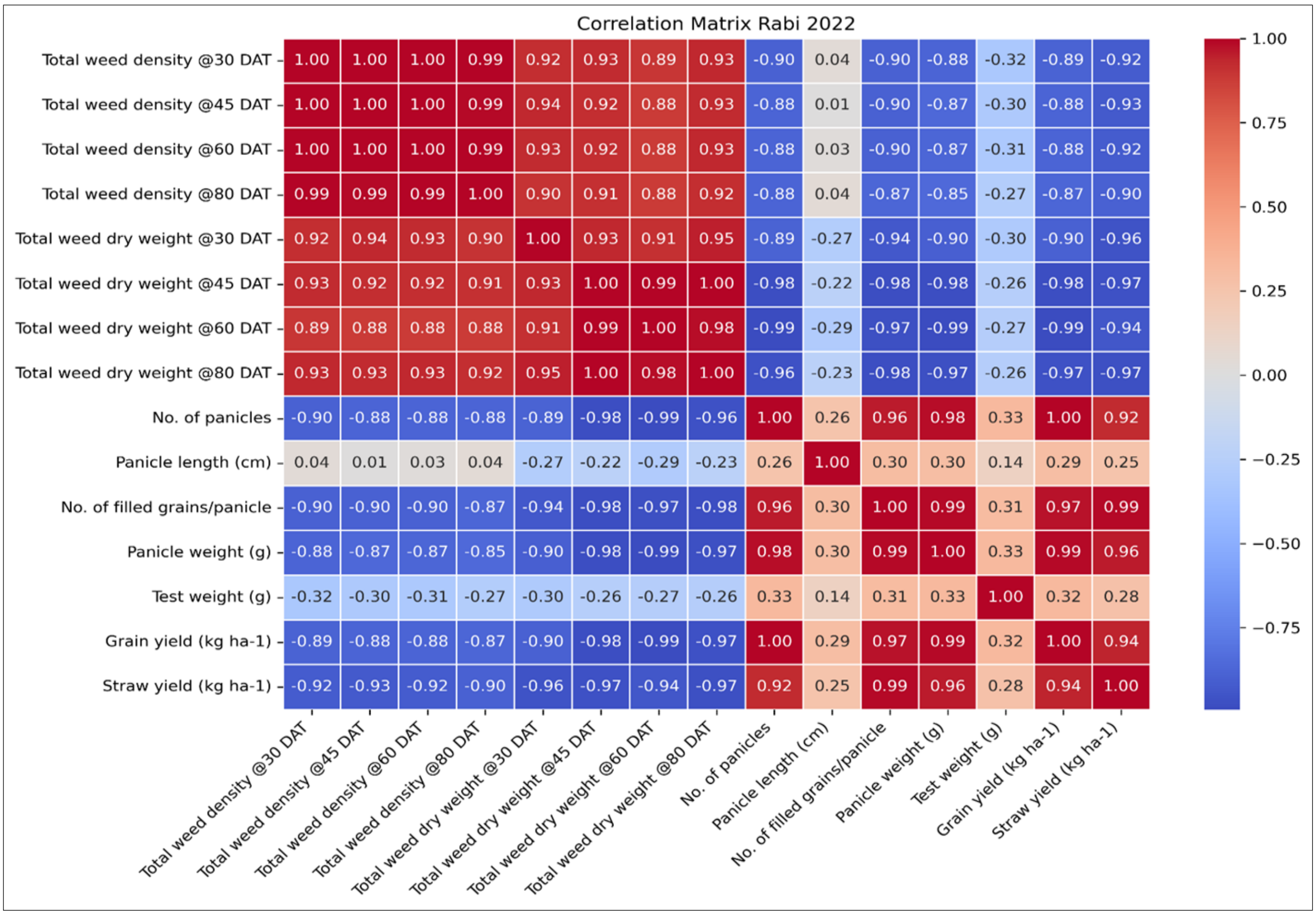

Fig. 1. Correlation matrix *rabi* 2022.

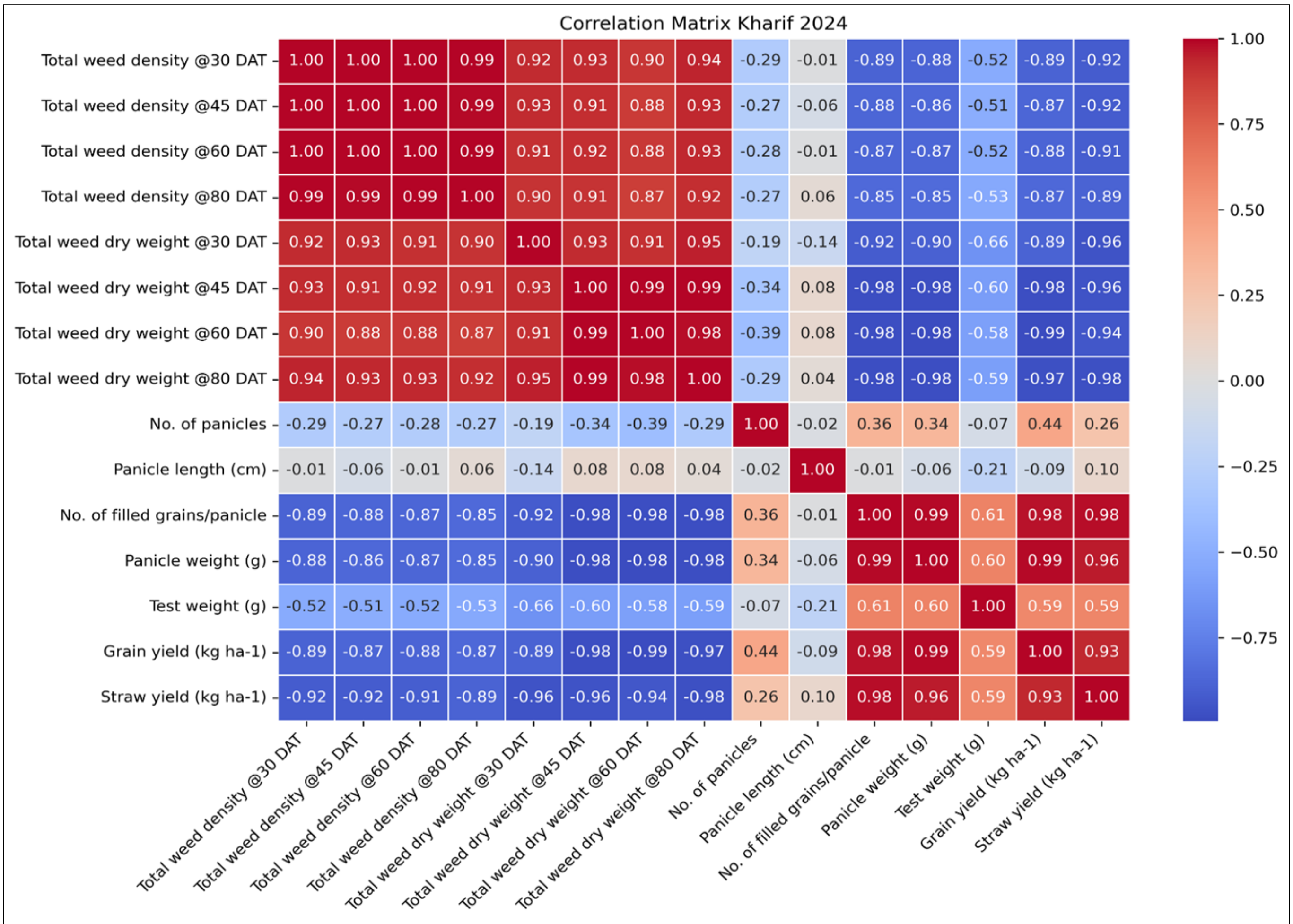

Fig. 2. Correlation matrix *kharif* 2024.

rainfall, temperature fluctuations and increased weed density. While HW at 20 and 40 DAT and FS of ITK-based farmers' practices at 25 DAT + HW at 40 DAT showed to be more effective, the crop physiological performance was relatively more challenged leading to reduced correlation strength between panicle number and grain yield (r = 0.44) suggesting that grain yield correlated more with grain filling efficiency than with panicle density under *kharif* condition. Notably, weed competition had a stronger adverse impact on grain quality parameters such as test weight (r = -0.66), indicating compromised assimilate partitioning under prolonged stress. These results highlight the importance of season specific, integrated weed management approaches emphasizing non-chemical weed management approaches, which suggests early and sustained weed control during the critical tillering and reproductive phase to maintain optimum crop productivity under diverse agroclimatic scenario.

Regression analysis

In both *rabi* 2022 and *kharif* 2024, linear regression (Fig. 3 & Fig. 4) of grain yield against weed density at 30, 45, 60, 80 DAT revealed highly significant ($p < 0.01$) negative relationship with R^2 values of 0.78-0.84 in *rabi* and 0.72-0.80 in *kharif*. The steeper slope coefficients in *rabi* (-24 to -21 kg ha^{-1} per additional weed m^{-2}) compared to *kharif* (-22 to -19 kg ha^{-1} per weed m^{-2}) indicates more intense crop-weed competition under *rabi* condition. The lowest weed density was recorded in HW at 20 and 40 DAT and Butachlor @ 1 kg/ha at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE, clustered at the left-upper quadrant of each scatterplot, consistently recording grain yield above 5200 kg ha^{-1} by maintaining weed counts below 40 m^{-2}. Among non-chemical weed management strategies, FS of ITK-based farmers' practices at 25 DAT + HW at 40 DAT and azolla as dual crop @ 1 t/ha + incorporation at 40 DAT fell along the regression line, showing moderate yield losses with increasing weed density. These results highlight the necessity of early and sustained weed suppression particularly, prior to and during the tillering phase, to mitigate yield losses and optimize transplanted rice productivity across different seasons.

Principal Component Analysis (PCA)

The PCA analysis (Fig. 5 and 6) illustrates the relationships among the treatments and their contributions to rice growth and yield characteristics for both *rabi* 2022 and *kharif* 2024. The biplots integrate a wide range of yield attributes and weed parameters to assess treatment performance comprehensively. Key yield attributes considered across both seasons includes panicle length (cm), panicle weight (g), grain yield (kg ha^{-1}), straw yield (kg ha^{-1}), test weight (g), number of panicles m^{-2} and number of grains/panicles. Weed parameters such as total weed dry weight and total weed density recorded at 30, 45, 60, 80 DAT were incorporated to obtain the influence of weed pressure on yield. In *rabi* 2022, principal component 1 (PC1) accounted for 82.5 % of the total variation, while in *kharif* 2024, PC1 and PC2 together explained 78.3 % and 7.7 % of the variability, respectively. Parameters like grain yield, straw yield, panicle weight, test weight and number of panicles contributed positively to PC1 in both seasons and were strongly correlated, especially in Butachlor @ 1 kg/ha as PE + Bispyribac sodium @ 25 g/ha as POE and HW at 20 and 40 DAT, indicating superior performance under these management practices. On the other hand, weed parameters had negative loadings on PC1, particularly in HW at 20 and 40 DAT, rice hull solution (50 % FS) at 15 DAT + HW at 40 DAT and FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT which aligned with higher weed densities and lower yield attributes. Additionally, panicle length showed a negative contribution in both the seasons, suggesting its inverse relationship with yield traits in the given datasets. These findings clearly differentiated high-performing weed management treatments from those with poor weed control, emphasizing the critical role of integrated weed management in enhancing rice productivity across both *rabi* and *kharif* seasons.

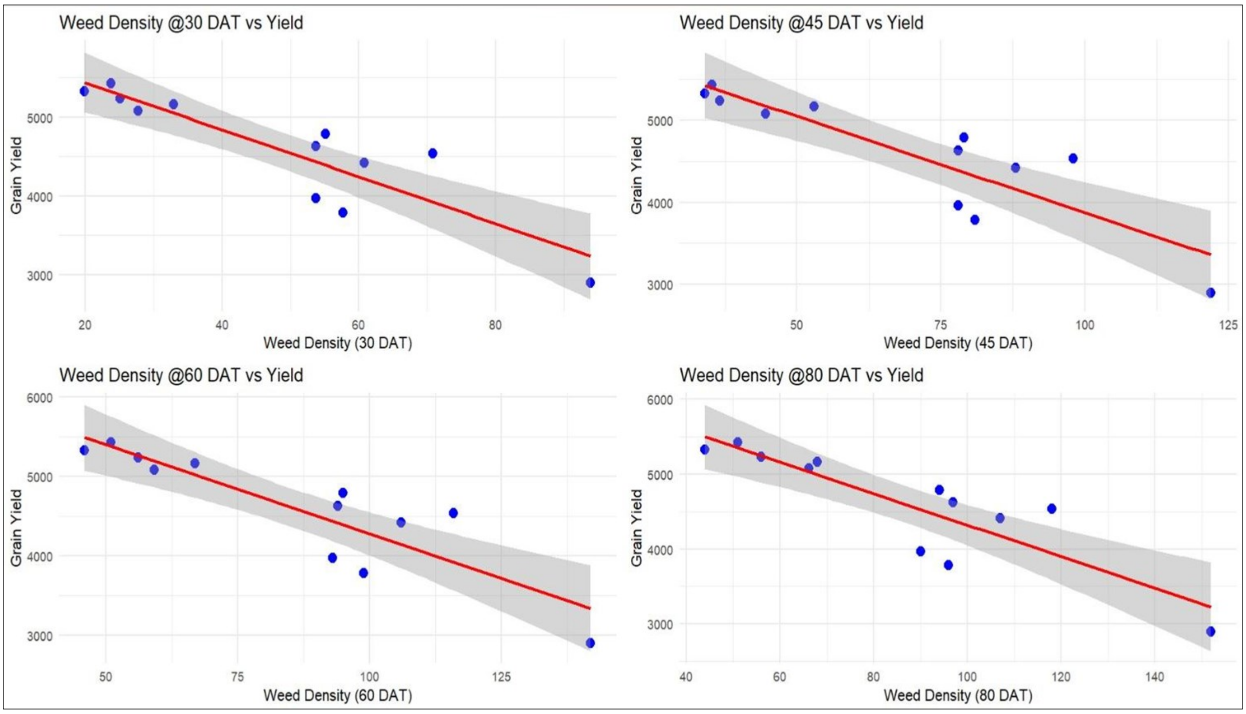

Fig. 3. Regression analysis (scatter plot) for *rabi* 2022.

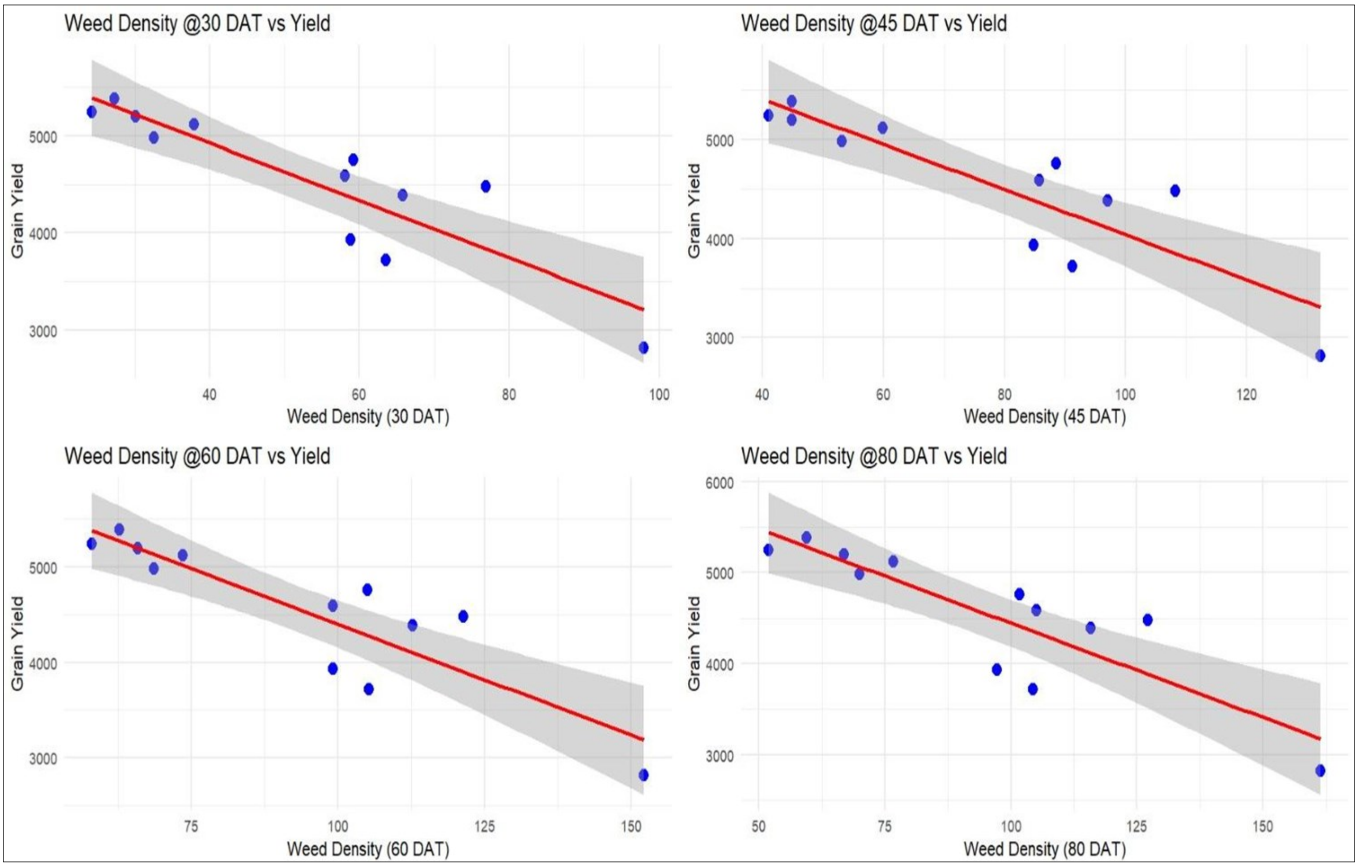

Fig. 4. Regression analysis (scatter plot) for *kharif* 2024.

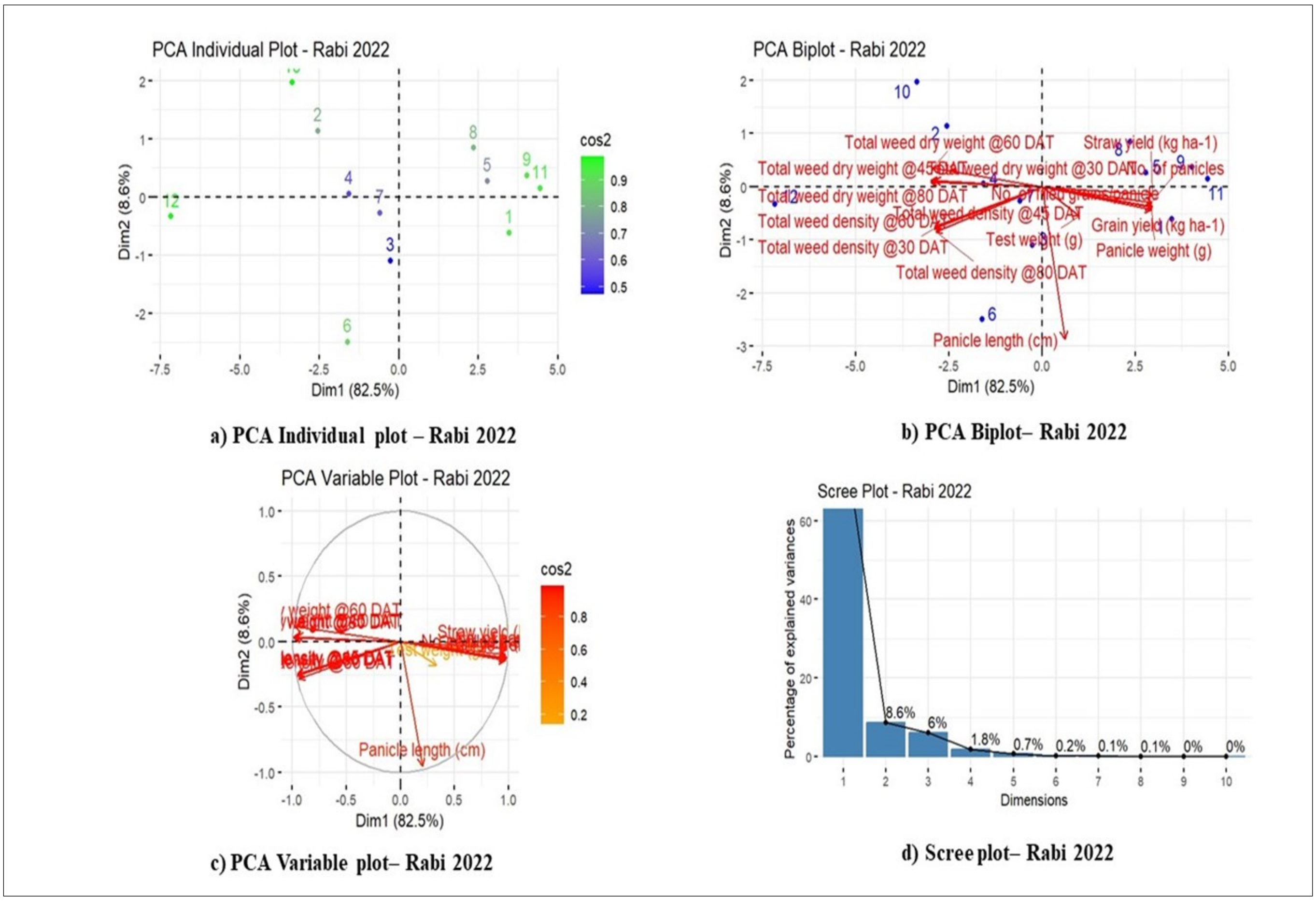

Fig. 5. Principle Component Analysis for *rabi* 2022.

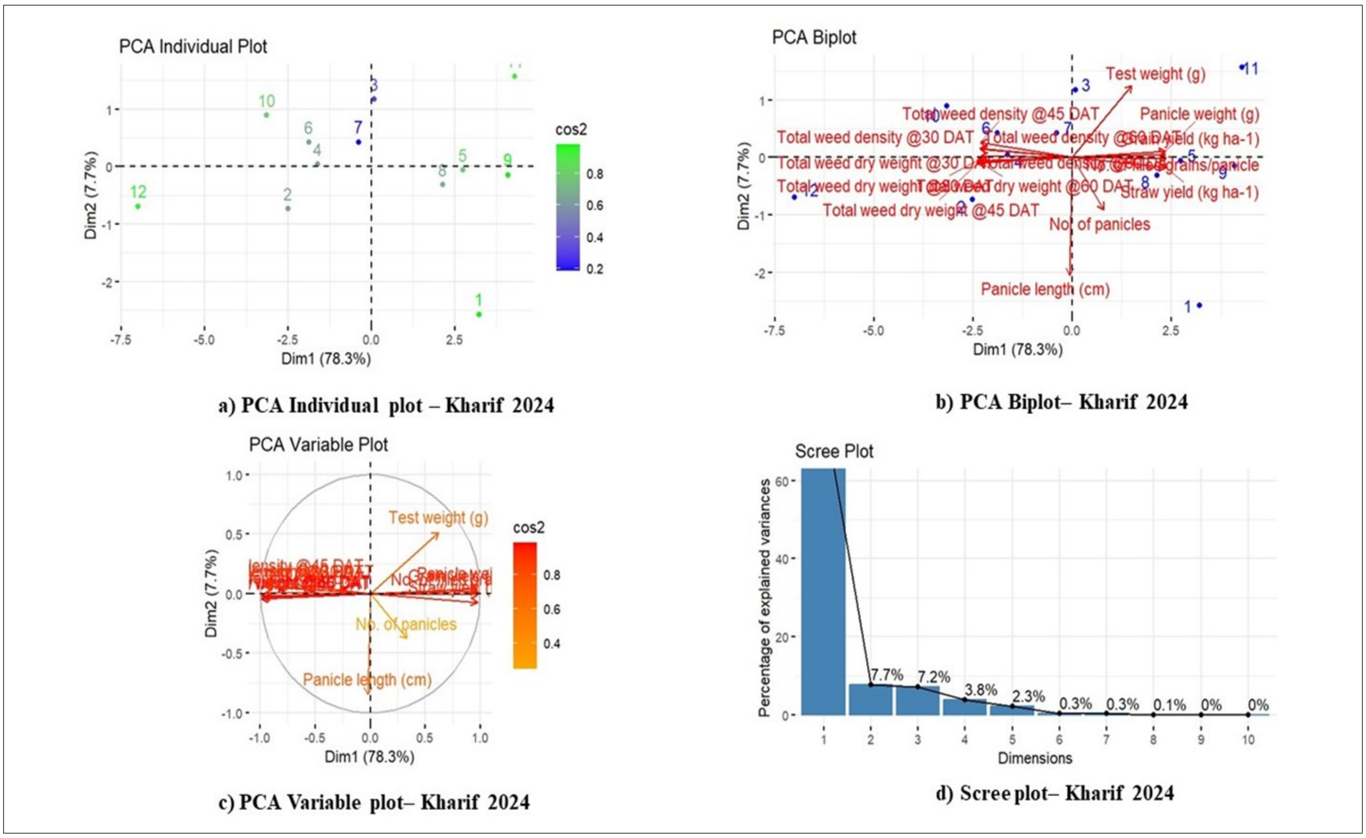

Fig. 6. Principle Component Analysis for *kharif* 2024.

Conclusion

The study showed the comprehensive evaluation of non-chemical weed management strategies in transplanted rice system during *rabi* 2022 and *kharif* 2024. The study concluded that hand weeding at 20 and 40 DAT recorded lowest weed density, lowest weed dry weight, highest weed control efficiency and highest grain yield. However, this approach has limited practical feasibility due to its labour intensive nature. Among the non-chemical treatments, foliar spray of ITK-based farmers' practices at 25 DAT + hand weeding at 40 DAT, cono-weeding at 10, 20, 30, 40 DAT and azolla as dual crop @ 1 t/ha + incorporation at 40 DAT confirmed significant potential for sustainable weed management, which recorded reduced weed density by 30-50 % and higher grain yield, which were comparably equivalent to butachlor @ 1 kg/ha at 3 DAT as PE + Bispyribac sodium @ 25 g/ha at 25 DAT as POE. Hence, for a sustainable and eco-friendly alternatives of farming practices, non-chemical weed management strategies can be recommended, taking into consideration the long-term impacts on soil health and weed resistance dynamics, which will aid in optimizing sustainable management strategies across diverse agroecosystems.

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Authors' contributions

LMK carried out the experiment, recording observations, analysis of data and preparation of the manuscript. ES guided the research by formulating the research concept and reviewed and approved the manuscript. PA shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript. RK, PJ, RS and SK shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript.

Compliance with ethical standards

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

Ethical issues: None

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