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RESEARCH ARTICLE

Integrated weed management approaches for sustainable weed suppression and yield optimization in aerobic rice

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Abstract

Aerobic rice, grown in well-drained, non-puddled and non-saturated soils, is a promising water saving approach that can reduce water consumption compared to traditional methods, but weed infestation remains a major constraint that significantly limits crop growth and yield. A two-year field study was conducted to evaluate effective combinations of physical and chemical methods along with various agronomic practices to analyse the impact of various weed management methods for aerobic rice cultivation. The study was conducted using a randomized block design, with three replications in ten treatment combinations. Among the different weed control strategies, the weed-free treatment recorded the lowest weed density (2.48 weeds/m^2 at maximum tillering and 3.39 weeds/m^2 at panicle initiation stage), highest weed control efficiency (94.7 % at maximum tillering and 93.2 % at panicle initiation stage), lowest weed index and highest grain yield (4977 kg/ha). This was followed by Pre-Emergence (PE) application of pendimethalin (0.75 kg/ha) at 5 DAS (Days After Sowing) followed by mechanical weeding at 30 DAS resulted in reduced weed density (5.37 weeds/m^2 at tillering and 9.12 weeds/m^2 at panicle initiation), improved weed control efficiency (73.76 % and 48.52 %) and a grain yield of 4833 kg/ha, this treatment also recorded the highest Benefit-Cost (B:C) ratio (2.23), establishing it as the most economically viable and profitable approach for weed management in aerobic rice cultivation. It was comparable to the chemical control using PE pendimethalin followed by Early Post-Emergence (EPoE) application of bispyribac sodium (25 g/ha) at 25 DAS, which recorded a B:C ratio of 2.00.

Keywords: bispyribac sodium; cultural methods; economics; mechanical methods; pendimethalin; yield attributes

Introduction

Rice (*Oryza sativa*) is a vital staple food for over half of the world's population, contributing over 20 % of worldwide calorie intake, particularly in Asia. It is grown in over 100 countries, with approximately 90 % of its production occurring in Asia (1). India cultivates rice across 47.83 million hectares, yielding approximately 135.76 million tonnes, with a productivity rate of 2838 kg/ha (2). Rice cultivation is highly water-intensive, requiring between 3000 and 5000 L of water to produce just 1 kg of rice, which is about 2 to 3 times more than the amount needed for other cereal crops like wheat or maize (3). To tackle this problem, researchers have developed water-saving techniques, including the aerobic rice system (4). Aerobic rice, which thrives in well-aerated, non-flooded and unsaturated soils, is considered a promising "strategy to decrease" water consumption by up to 50 % compared to traditional methods (5). This system requires only 470-650 mm of water input, significantly less than conventional rice cultivation (6). Weeds are a major constraint in aerobic rice cultivation, significantly limiting crop growth and yield. In aerobic direct-seeded rice, the reduction in grain yields due to weed competition ranged from 38 % to 92 % (7).

Integrated weed management is vital for achieving sustainable and cost-effective weed management in aerobic rice cultivation. Herbicides have become increasingly important in global agriculture, offering numerous benefits over traditional weed control methods, including labour and cost savings, improved weed control efficiency (52-96 %), increased crop yields (19-372 %) and providing economic benefits of $305–867 compared to unweeded controls (8). They efficiently control a wide range of weeds, reduce labour costs and save time, especially in areas facing labour shortages. Herbicides are particularly suitable for large-scale farming and conservation tillage systems, helping to reduce soil erosion, fuel use and greenhouse gas emissions (9). Overall, herbicides have largely replaced manual weeding in many countries, proving more cost-effective and efficient (10). Herbicides are important in modern agriculture but have notable disadvantages. Their repeated use can lead to the development of herbicide-resistant weeds, necessitating integrated weed management practices. Environmental concerns include soil and water contamination, adverse effects on biodiversity and potential harm to non-target vegetation (11). Long-term reliance on herbicides may undermine sustainable farming practices and promote monoculture. The development of crops with stacked herbicide resistance may exacerbate these challenges, potentially increasing herbicide use and resistant weed populations (12).

Although herbicides are useful, excessive use can lead to resistance, making it necessary to adopt alternative approaches that reduce reliance on herbicides (13). A need to reduce the herbicide dependence due to environmental concerns has led to increased interest in bio-intensive weed management strategies that incorporate mechanical, cultural and biological control methods (14). The application of pendimethalin as a PE herbicide, followed by bispyribac-sodium as a post-emergence treatment, significantly decreased the weed density and biomass, resulting in improved weed control and enhanced grain yield (15). Mechanical weeder provide an efficient and cost-effective alternative to manual weeding in rice cultivation, enhancing productivity while reducing labour costs. Power-operated rotary weeders exhibit high weeding efficiency (84-91 %) and field capacity (0.14 ha/hr) (16). When compared to hand weeding, mechanical weeder can reduce weeding costs by as much as 48.7 % (17). Integrated weed management that combines agronomic practices, manual weeding and judicious herbicide use can effectively control weeds in aerobic rice production. The present study was conducted to find out the suitable physical and chemical combinations simultaneously incorporated with different agronomic practices to provide a comprehensive weed management options for aerobic rice cultivation.

While integrated weed management involving agronomic practices has proven effective in aerobic rice cultivation, there is limited research on the combined effectiveness of physical and chemical methods with agronomic approaches under aerobic conditions. To address this research gap, the present study was conducted to identify effective combinations that can offer a comprehensive and sustainable weed management strategy for aerobic rice.

Materials and Methods

Site description

A field experiment was carried out at the Department of Rice, TNAU, Coimbatore, Tamil Nadu, during *Kharif* season of 2021 and 2022. The experimental site consisted of clay loamy soil, with a pH of 8.02, an EC of 0.53 dS m^{-1} and an organic carbon content of 0.55 %. The average temperature during the cropping season was 28.7 °C, ranging from a high of 34.1 °C to a low of 23.2 °C.

Experimental design and treatments

The study was laid out in a randomized block design with three replications. The treatments included various weed management strategies: T_1 - mulching with crop residue at 5 t/ha during sowing; T_2 - mulching with crop residue at 5 t/ha during sowing followed by one post emergence herbicide application; T_3 - mechanical weeding using power weeder at 20 DAS and 45 DAS; T_4 - mechanical weeding once at 15 DAS followed by early post emergence herbicide application of bispyribac sodium (25 g/ha) on 25 DAS; T_5 - chemical weed control (PE- pendimethalin (0.75 kg/ha) on 5 DAS followed by EPoE application of bispyribac sodium (25 g/ha) on 25 DAS; T_6- PE- pendimethalin (0.75 kg/ha) on 5 DAS followed by one mechanical weeding at 30 DAS; T_7 - intercropping in rice with *Sesbania* (incorporation after 1 to 1½ month of sowing); T_8 - raised bed system of cultivation; T_9 - weed free and T_{10} - weedy check. The CO 53 variety was selected for the study and sowing was done in rows using the dibbling method, maintaining a spacing of 30 × 10 cm with a seed rate of 60 kg/ha. Fertilizers were applied as per the recommended rate of 150:50:50 kg NPK per hectare, utilizing urea, single superphosphate and muriate of potash. Nitrogen and potassium were administered in four equal splits at 21 DAS, as well as during the active tillering, panicle initiation and heading phases. The entire phosphorus was applied as a basal application before sowing. Treatments were imposed as per the programme schedule. Irrigation was given in alternate wetting and drying method during the entire crop period.

Data collection and statistical analysis

Observations on yield parameters including panicle number/m^2, panicle weight (g) and grain yield (kg/ha) were recorded at harvest. Total weed density was measured at the active tillering and panicle initiation stages using a 1 m^2 quadrat placed randomly in each plot. All weeds within the quadrat were uprooted, identified, counted and expressed as the number of weeds per square meter. The Weed Control Efficiency (WCE) and Weed Index (WI) were calculated using the following formulas:

$$\text{Weed Control Efficiency (\%)} = (W_c - W_t)/W_c \times 100$$

where as, W_c= weed density in the control plot and W_t= weed density in the treatment plot.

$$\text{Weed Index (\%)} = Yw-Yt/ Yw \times 100$$

where Yw = Grain yield in the weed-free plot (kg/ha) and Yt = Grain yield in the treated plot (kg/ha).

The weed count data were then square root transformed using the formula $\sqrt{(x + 0.5)}$, where x represents the actual weed count, to normalize the data for statistical analysis. The data were analyzed using the ANOVA method (18). A critical difference at a 5 % significance level was computed to compare the means of the treatments. Correlations between weed density, WCE, WI, number of panicles/m^2, number of grains per panicle and panicle weight with grain yield were assessed. All statistical analyses were performed using R software version 4.2.2.

Results and Discussion

Weed parameters

Weed density

Weed species found in the experimental field were identified and recorded as grasses, sedges and broad-leaf weeds. The dominant species of grasses were *Echinochloa colona, Digitaria arvensis, Panicum repens, Dinebra retroflexa, Cynodon dactylon*, *Eragrostis* spp. sedges viz., *Cyperus difformis, Cyperus iria* and broad-leaf weeds like *Tridax procumbens, Trianthema portulacastrum, Euphorbia hirta* and *Eclipta prostrata*. The experimental findings indicated that among various weed management practices, the weed free condition had the lowest weed density at the maximum tillering (2.48 no./m^2) and panicle initiation (3.39 no./ m^2) stages (Table 1). The weed free condition had the lowest

Table 1. Assessment of treatment effects on weed density (number/m²) at different growth stages in aerobic rice (mean of two season data)

Treatments	Total weed density at maximum tillering stage	Total weed density at panicle Initiation stage
T_1 – Mulching with crop residue @ 5 t/ha at the time of sowing	7.31 (53.00)	9.14 (83.00)
T_2 - Mulching with crop residue @ 5 t/ha at the time of sowing +PoE	6.89 (47.00)	7.80 (60.33)
T_3 – Mechanical weeding using weeder	7.04 (49.00)	9.35 (87.00)
T_4 – Mechanical weeding once followed by PoE	5.93 (34.67)	7.06 (49.33)
T_5 – Chemical weed control (PE followed by PoE)	5.43 (29.00)	6.99 (48.33)
T_6 – PE followed by one mech weeding	5.37 (28.33)	9.12 (82.67)
T_7 – Rice with *Sesbania* intercropping	6.42 (40.67)	9.76 (94.67)
T_8 – Raised bed system of cultivation	8.99 (80.33)	11.11 (123.00)
T_9 – Weed free	2.48 (5.67)	3.39 (11.00)
T_{10} – Weedy check	10.43 (108.33)	12.70 (160.67)
Mean	6.63 (47.60)	8.64 (80.00)
S.Ed	0.33	0.34
CD (0.05)	0.70	0.71

weed density at maximum tillering and panicle initiation stages because weeds were continuously and completely removed throughout the crop growth period, preventing any competition for nutrients, water and light during the critical growth stages.

This was followed closely by the application of PE pendimethalin (0.75 kg a.i./ha) at 5 DAS, followed by one mechanical weeding on the 30th DAS, leading to weed densities of 5.37 no./m² during the maximum tillering and 9.12 no./m² at the panicle initiation. This treatment was comparable to chemical weed control, where the application of PE pendimethalin (0.75 kg/ha) at 5 DAS, followed by EPoE bispyribac sodium at 25 g/ha, resulted in weed densities of 5.43 no./m² during the tillering phase and 6.99 no./m² during panicle initiation. The highest weed density was observed in the weedy check, with 10.43 no./m² at the maximum tillering p and 12.70 no./m² during the panicle initiation. Weed density was lowered because the PE herbicide controlled initial weed emergence and mechanical weeding removed subsequent weed growth. Power weeders are an effective and cost-efficient method for reducing weed density in paddy crops compared to manual weeding (19).The combined application of pendimethalin at 1 kg/ha, organic mulch and one hand weeding effectively reduced weed density in direct-seeded rainfed rice (20).The PE herbicide (pyrazosulfuron ethyl @ 20 g ha^{-1} at 3 DAS) and post-emergence herbicide (bispyribac sodium @ 25 g ha^{-1} at 20 DAS), or PE followed by power weeding at 30 DAS, proved effective for controlling weeds in direct-seeded puddled lowland rice, helping to address labour shortages and weed infestation challenges faced by farmers (21). Application of PE pendimethalin at 1kg/ha followed by EPoE bispyribac sodium at 30 g a.i./ha resulted in more than an 80 % reduction in weed density compared to the control as weedy check (22). The PE application of pretilachlor (0.6-0.75 kg/ha) followed by the early EPoE herbicide application of bispyribac sodium (20-25 g a.i./ha) Substantially lowered weed density and enhanced grain yield (23).

WCE and WI

Among the different weed management approaches, the weed-free treatment exhibited the highest WCE at the maximum tillering stage (94.73 %) and the panicle initiation stage (93.15 %) (Table 2). This was followed by PE pendimethalin (0.75 kg/ha) applied at 5 DAS followed by one mechanical weeding which was on par with chemical weed control, where PE pendimethalin (0.75 kg/ha) at 5 DAS followed by EPoE bispyribac sodium at 25 g a.i/ha. Maximum WCE was achieved with PE herbicide application followed by mechanical weeding (power weeder), leading to a significant reduction in weed biomass in comparison to the weedy check (17). Pendimethalin (1 kg/ha) followed by bispyribac sodium (40 g/ha) recorded the greatest WCE (71.2 %) and the lowest WI. This was closely followed by the weed-free treatment, which achieved the highest WCE (73.0 %) and the lowest WI (24). Pendimethalin at 1 kg ha^{-1} combined with farm waste mulch (7.5 t ha^{-1}) and supplemented by one hand weeding at 45 DAS achieved the highest WCE (91.3 %), comparable to the farmers' practice of manual weeding (20). Power weeders can increase WCE (73.8 %) in cauliflower crops (25).

Additionally, the weed-free condition exhibited the lowest WI, signifying effective weed management (26). Maintaining a weed-free environment throughout the crop's growth period results in the minimal weed density and optimum WCE, but it

Table 2. Analysis of different treatments on weed control efficiency (%) and weed index (%) in aerobic rice (mean of two years data)

Treatments	Weed control efficiency (%)		Weed index (%)
	At tillering stage	At panicle initiation stage	
T_1 – Mulching with crop residue at 5 t/ha during sowing	51.01	48.31	18.17
T_2 - Mulching with crop residue at 5 t/ha during sowing + EPoE bispyribac sodium (25 g a.i./ha) on 25 DAS	56.40	62.44	15.89
T_3 – Mechanical weeding using power weeder at 20 DAS and 45 DAS	54.84	45.80	11.69
T_4 – Mechanical weeding once at 15 DAS followed by EPoE bispyribac sodium (25 g a.i./ha) on 25 DAS	67.86	69.31	6.55
T_5 – Chemical weed control (PE– pendimethalin 0.45 kg a.i./ha) on 5 DAS followed by EPoE bispyribac sodium (25 g a.i./ha) on 25 DAS	73.42	69.90	2.90
T_6 – PE- Pendimethalin(0.45 kg a.i./ha) on 5 DAS followed by one mechanical weeding at 30 DAS	73.76	48.52	9.02
T_7 – Rice with *Sesbania* intercropping	62.26	41.08	13.04
T_8 – Raised bed system of cultivation	25.32	23.45	23.44
T_9 – Weed free	94.73	93.15	0
T_{10} – Weedy check	0.00	0.00	49.54
Mean	55.96	50.19	15.02
S.Ed	2.89	2.67	0.86
CD (0.05)	6.07	5.62	1.82

(PE - Pre Emergence; EPoE - Early Post Emergence; DAS -Days After Sowing) requires higher labour expenses (27). Therefore, weed management options, which combine chemical and mechanical methods, such as the application of PE pendimethalin (0.75 kg/ha) at 5 DAS followed by mechanical weeding, effectively reduce the weed density and WI while enhancing WCE. This approach minimizes reliance on herbicides and provides a sustainable alternative to weed-free conditions, ensuring optimal crop performance and long-term weed management.

Yield parameters

Yield attributes

Among the various weed management practices, the highest panicle number/m^2 (284) and panicle weight (2.85 g) were recorded under weed free conditions due to minimal weed-crop competition. This was followed by the PE pendimethalin (0.75 kg/ha) at 5 DAS with one mechanical weeding at 30 DAS, which recorded a panicle number (273) and panicle weight (2.82 g). These values were statistically on par with PE pendimethalin (0.75 kg/ha) at 5 DAS followed by EPoE bispyribac sodium (25 g/ha), which resulted in a panicle number (267) and panicle weight (2.82 g) which emphasize the importance of effective weed management in reducing weed-crop competition and improving both panicle number and panicle weight. Herbigation with PE pendimethalin at 1 kg/ha, followed by Post-Emergence (POE) bispyribac sodium at 25 g/ha at 20 DAS, recorded a significantly higher number of panicles (446/m^2) and filled grains (130.4 per panicle) compared to the other treatments in aerobic rice (28).

Grain yield (kg/ha)

A higher grain yield was obtained under weed-free conditions (4977 kg/ha) (Table 3). This was succeeded by the application of PE pendimethalin (0.75 kg/ha) at 5 DAS, followed by a single mechanical weeding at 30 DAS, which resulted in a grain yield of 4833 kg/ha, comparable to PE pendimethalin (0.75 kg/ha) at 5 DAS, followed by EPoE bispyribac sodium at 25 g/ha (4651 kg/ha). The lowest grain yield of 2512 kg/ha was observed in weedy check due to competition between weeds and the crop for resources, which reduced yield attributes and overall yield. In weed-free environments, rice plants receive optimal conditions for growth, resulting in higher yields and better crop growth. Power weeder usage exhibited the highest grain yield compared to other mechanical methods and hand weeding in rice cultivation (29). The integration of the stale seedbed technique with PE pendimethalin application, followed by mechanical weeding at 25 DAS and hand weeding at 45 DAS, resulted in a yield of 4.3 t/ha, which was comparable to the 4.4 t/ha yield achieved in a weed-free plot under aerobic rice cultivation (30). Sequential application of pendimethalin followed by bispyribac sodium or penoxsulam effectively reduced weed density, resulting in the highest paddy yield (2.79 t/ha) in dry seeded rice (20). Application of PE pendimethalin at 1 kg/ha through herbigation followed by POE bispyribac sodium at 25 g/ha at 20 DAS led to a significantly higher grain yield of 4583 kg/ha in aerobic rice (31). Mechanized dry direct seeding of rice sowing with pre emergence Pretilachlor and one mechanical weeding (power weeder)increases the grain yield of 6467 kg/ha (32). The combination of PE herbicide application followed using a paddy weeder led to enhanced weed control and maximum grain yield in transplanted summer rice (33).

Grain yield exhibited a strong negative correlation with weed-related parameters, particularly weed density (r = -0.790) and WI (r = -0.984), indicating that increased weed infestation significantly reduces yield potential in aerobic rice cultivation (Fig. 1). Conversely, grain yield showed a strong positive correlation with WCE (r = 0.861), suggesting that effective weed management plays a crucial role in enhancing rice productivity. Key yield-contributing traits, such as panicle number/m^2 r = 0.882) and panicle weight (r = 0.910), also showed significant positive associations with grain yield. This reflects the fact that better-developed yield components contribute substantially to final harvest outcomes.

WCE not only improved grain yield directly but also had a positive influence on yield traits, being significantly correlated with panicle number (r = 0.855) and panicle weight (r = 0.740). Overall, the results demonstrate that minimizing weed pressure and maximizing WCE are pivotal strategies for improving panicle development and grain yield in aerobic rice. These findings underscore the importance of integrated weed management practices tailored to aerobic conditions to achieve optimal crop performance.

Economics

Although the weed free treatment resulted in significantly higher yields compared to other treatments, it was not economically viable, with a B:C ratio of 1.78. Among the weed management practices, PE pendimethalin (0.75 kg/ha) at 5 DAS followed by one mechanical weeding at 30 DAS not only significantly reduced the weed density but also increased rice grain yield along with improvements in yield attributes. This approach resulted in the highest net returns (₹49590/ha) and a B:C ratio of 2.23 (Table 4). It was followed by PE pendimethalin (0.75 kg/ha) at 5 DAS followed by EPoE bispyribac sodium (25 g a.i./ha) at 25 DAS, resulting in

Table 3. Impact of various treatments on yield attributes and grain yield (kg/ha) in aerobic rice (mean of two years data)

Treatments	Panicle number/m^2	Panicle weight (g)	Grain yield (kg/ha)
T_1 – Mulching with crop residue at 5 t/ha during sowing	237	2.79	4073
T_2 - Mulching with crop residue at 5 t/ha during sowing + EPoE bispyribac	255	2.80	4186
T_3 – Mechanical weeding using power weeder at 20 DAS and 45 DAS	246	2.80	4395
T_4 – Mechanical weeding once at 15 DAS followed by EPoE bispyribac sodium	229	2.76	4528
T_5 – Chemical weed control (PE- pendimethalin 0.45 kg a.i./ha) on 5 DAS followed by EPoE bispyribac sodium (25 g a.i./ha) on 25 DAS	267	2.82	4651
T_6 – PE– pendimethalin(0.45 kg a.i./ha) on 5 DAS followed by one mechanical weeding at 30 DAS	273	2.82	4833
T_7 – Rice with *Sesbania* intercropping	218	2.74	4327
T_8 – Raised bed system of cultivation	207	2.72	3809
T_9 – Weed free	284	2.85	4977
T_{10} – Weedy check	177	2.18	2512
Mean	239	2.73	4229
S.Ed	11	0.13	199
CD(0.05)	24	0.27	418

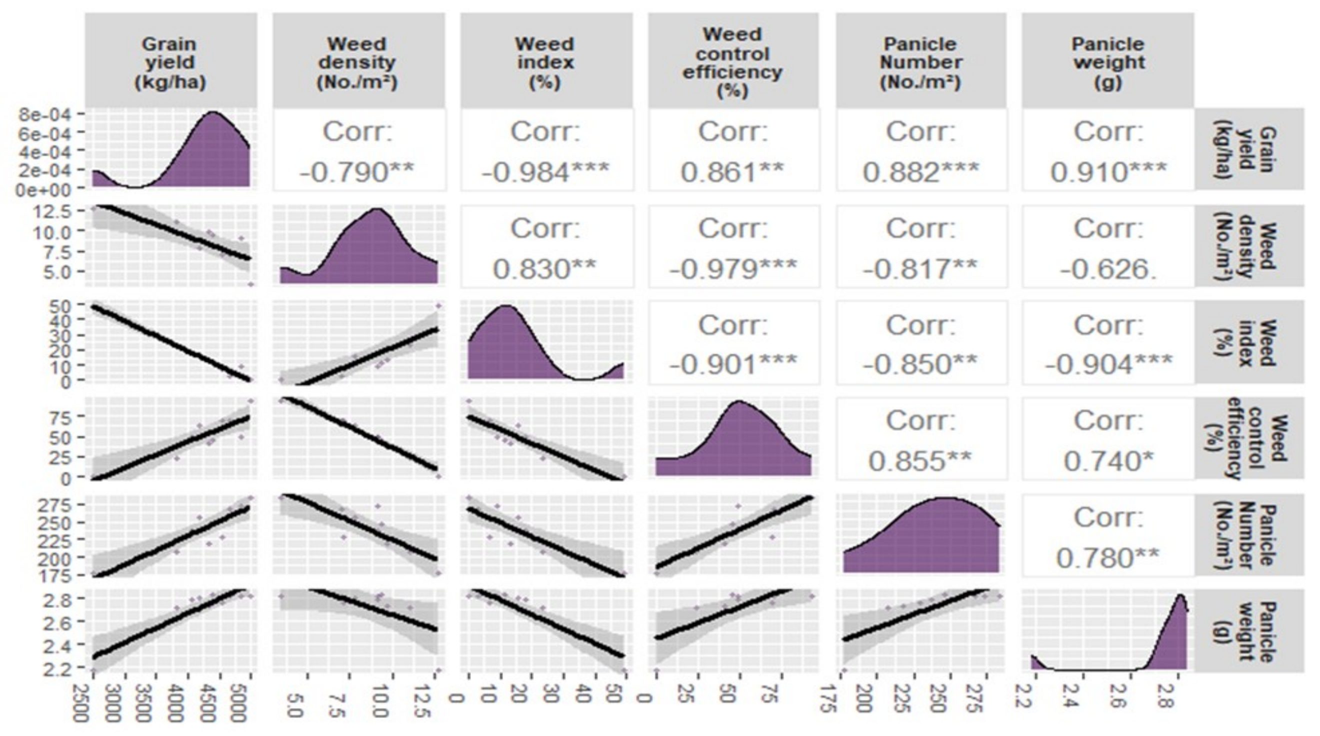

Fig. 1. Relationship analysis of weed parameters and yield attributes with grain yield in aerobic rice (mean of two season data).

Table 4. Effect of treatments on economics (₹/ha) in aerobic rice cultivation (mean of two years data)

Treatments	Net return (₹/ha)	Benefit :Cost ratio
T_1 – Mulching with crop residue at 5 t/ha during sowing	28380	1.67
T_2 - Mulching with crop residue at 5 t/ha during sowing + EPoE bispyribac sodium (25 g a.i./ha) on	31780	1.66
T_3 – Mechanical weeding using power weeder at 20 DAS and 45 DAS	40960	1.98
T_4 – Mechanical weeding once at 15 DAS followed by EPoE bispyribac sodium (25 g a.i./ha) on 25	42370	1.97
T_5 – Chemical weed control (PE- pendimethalin(0.45 kg a.i./ha) on 5 DAS followed by EPoE bispyribac sodium (25 g a.i./ha) on 25 DAS	43560	2.00
T_6 – PE- Pendimethalin(0.45 kg a.i./ha) on 5 DAS one mechanical weeding at 30 DAS	49590	2.23
T_7 – Rice with *Sesbania* intercropping	38740	1.87
T_8 – Raised bed system of cultivation	26630	1.56
T_9 – Weed free	40620	1.78
T_{10}–Weedy check	8900	1.38

net returns (₹43560/ha) and B:C ratio (2.00) which effectively reduced the manual labour and minimized man days spent on weeding, leading to significant cost savings and improved profitability. Mechanical weeding has been found to be more effective than manual weeding, reducing labour requirements and cost (34). Power weeding treatment proved to be more cost-effective, with operational costs ranging from ₹928 to ₹1580 per hectare, which is significantly lower than the manual weeding costs of ₹2346-5108 per hectare (19). Mechanical weeder lowered labour demands by 85 % and reduced weeding costs by 77.8 % compared to hand weeding, while producing comparable grain yields (35). Mechanical weeding techniques are effective in reducing weed population and provide significant economic and labour benefits, with cost reductions of up to 75.8 % and time savings of up to 95.8 % compared to manual weeding, making them a viable and efficient alternative for farmers (36). Herbigation using PE pendimethalin at 1 kg/ha, followed by POE bispyribac sodium at 25 g/ha at 20 DAS, recorded significantly higher net returns (₹32362/ha) and B:C ratio (2.02) compared to the other treatments (28). The application of Pretilachlor (0.75 kg a.i./ha) followed by bispyribac sodium (20 g a.i./ha) led to increased grain yields, net returns and B:C ratios in direct-seeded lowland rice (37). The PE application of herbicide followed mechanical weeding has been recognized as an effective and cost-efficient weed management strategy.

Conclusion

Based on the two years of study, among the different weed management methods evaluated, PE herbicide application of pendimethalin (0.75 kg/ha) at 5 DAS followed by one mechanical weeding at 30 DAS were effective in better weed control options in aerobic rice cultivation. This treatment was on par with PE application of pendimethalin (0.75 kg/ha) at 5 DAS, followed by an EPoE application of bispyribac sodium (25 g/ha), These methods exhibited performance in reducing weed density, improving WCE, increasing grain yield and enhancing the benefit:cost ratio in aerobic rice. Hence, the combination of chemical and mechanical weed control methods provide effective alternatives to traditional manual weeding method by reducing the labour costs and also enhancing rice yield due to better crop growth yield attributes, yield and economics in aerobic rice cultivation. However, the use of synthetic chemicals in agriculture is also associated with environmental concerns such as soil degradation, water pollution and negative impacts on beneficial organisms. Therefore, adopting integrated weed management practices that reduce reliance on herbicides can help balance productivity with ecological sustainability.

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Authors' contributions

GSK conceptualized and designed the study, performed data collection, formal analysis and prepared the original draft. NS and RS provided essential resources. SM participated in investigation, resource provision and supervision. GS contributed to data collection and visualization. KS contributed to formal analysis and draft editing. KR and SP provided resources. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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