Effect of Sowing Methods and Weed Management Strategies in Rice Cultivated on Clay Soil

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Abstract
Direct-seeded rice (DSR) has emerged as a promising alternative to traditional transplanting methods, offering advantages in resource efficiency, labor reduction, and sustainability. However, effective weed management remains a critical challenge in DSR cultivation, particularly on clayey soils. Weed management techniques was therefore studied at the Agricultural Research Institute, Dera Ismail Khan, to evaluate the effects of different sowing techniques and weed management strategies on growth, yield, and weed suppression in rice in a randomized complete block design (split-plot arrangement). The experiment included sowing methods in main plot while subplots consisted of irrigation frequencies. The KSK-133 rice cultivar was used in this study with subplot size of 2m × 3m (6m-2). The maximum paddy yield (7.95 t ha-1) was recorded in transplanting method + herbicide application followed by drill sowing method + herbicide application (7.49 t ha-1). Key parameters, including plant height, productive tillers, leaf area index, panicle length, and paddy yield, were measured to assess the performance of the treatments. Results demonstrated that this research provides valuable insights into optimizing DSR cultivation through strategic combinations of sowing techniques and weed management practices, contributing to sustainable rice production and addressing the challenges of labor shortages and water scarcity in agriculture.

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Introduction

Rice serves as both a dietary staple and a vital economic crop sustaining a substantial segment of the global population [1]. It contributes nearly 90% of the caloric intake in Asia and about half of the global food consumption [2]. Economically rice production accounts for approximately 3.5% of agricultural value added and 0.7% of Pakistan’s GDP. With the country's growing population, the existing rice output is insufficient to meet the increasing demand. Simultaneously, available land and water resources are becoming increasingly scarce. By the year 2025, it is estimated that over 4.3 billion people globally will depend on rice as their primary food source highlighting the need for more efficient and sustainable production methods.

Rice cultivation has historically played a central role in agricultural systems especially in Asian countries such as China, India, and Bangladesh where transplanting rice seedlings into flooded fields has been the traditional practice. This method has been highly effective for weed suppression and achieving optimal yields, however, in recent decades, direct-seeded rice (DSR) has emerged as an alternative approach due to its advantages in water conservation and labor efficiency. DSR involves sowing seeds directly into the soil, thereby eliminating the nursery and transplanting phases [3]. Despite its benefits, DSR is highly susceptible to weed infestations due to the absence of standing water, which traditionally helps suppress weed emergence. This underscores the importance of adopting integrated weed management (IWM) strategies that combine cultural, mechanical, and chemical methods to effectively address weed issues in DSR systems [4]. The transition from traditional transplanting to DSR offers multiple benefits, including reduced water usage and lower labor requirements. However, this shift also brings forth new challenges, particularly in weed control. Unlike conventional flooded systems that naturally inhibit weed growth, DSR fields lack continuous water coverage, making them more vulnerable to weed invasion. These weeds aggressively compete with rice plants for nutrients, light, and water, ultimately leading to reduced yields and increased production costs. Therefore, there is a pressing need to develop robust and adaptable weed management solutions tailored specifically for DSR systems. This involves employing a combination of agronomic techniques selective herbicide application, and mechanical methods to create a sustainable and efficient weed control framework. Among the various rice establishment methods, direct seeding has gained popularity due to its potential to reduce resource use and labor input. By eliminating transplanting and sowing seeds directly into the field, this method accelerates crop establishment and minimizes water demand. However, early-stage weed infestation is a common issue due to the lack of ground cover, particularly in the initial growth phases. This study focuses on enhancing weed control across different sowing methods including DSR, drill sowing, broadcasting, and transplanting—each of which presents unique weed management challenges. For instance, the absence of prolonged water coverage in direct-seeded systems increases susceptibility to weeds. Addressing these challenges through integrated weed management is essential to optimize yields and ensure cost-effective rice production. The findings from this research are expected to benefit farmers, agronomists, and policymakers by offering practical insights for improving rice cultivation in resource-constrained environments. The applicability of DSR techniques can vary significantly depending on regional factors such as climate, water availability, and soil type, which may limit the generalization of the study's findings to other agroecological zones. Effective weed control remains a persistent challenge in DSR systems. Even under optimized conditions, complete weed eradication may not be achievable, particularly in both wet and dry seeding scenarios. Environmental conditions especially elevated temperatures during the flowering stage, may lead to grain sterility adversely affecting final yield outcomes.

Objectives

To assess the performance of rice under various sowing techniques on clayey soils.

To develop practical and adoptable weed management strategies for direct-seeded rice cultivation.

Materials and Methods

Experimental Site and Facilities

The study was conducted in 2024 at the Agricultural Research Institute, Dera Ismail Khan. The experimental site was equipped with all necessary resources, including skilled labor for field operations, well prepared land plots, irrigation systems, and essential agricultural inputs such as certified seeds, fertilizers, pesticides, and farm machinery.

Experimental Design and Layout

The experiment was arranged in a Randomized Complete Block Design (RCBD) using a split-plot arrangement with three replications. The main plots were assigned to different sowing methods, while the sub-plots were allocated to various weed management strategies.

Main Plot Treatments – Sowing Methods:

M_1: Drill sowing
M_2: Broadcasting
M_3: Transplanting

Sub-Plot Treatments – Weed Management Strategies:

T_1: Control (no weeding)
T_2: Herbicide application (Winsta WP 30%)
T_3: Manual hand weeding

Plot Preparation

The experimental field was tilled twice using a cultivator followed by two passes of a rotavator to achieve a fine and well-pulverized seedbed. Each sub-plot measured 2 m × 3 m (6 m^2).

Methods of Data Collection

All parameters were measured using standardized and scientifically accepted procedures. Measurements were taken carefully and consistently across all plots to ensure accuracy.

Sampling Techniques and Sample Size

Sampling was conducted using standard agronomic protocols, ensuring random and unbiased collection. The specific sample size for each parameter is detailed within the relevant sections above.

Experimental Model

The RCBD with a split-plot layout and three replications was employed to minimize experimental error and enhance statistical precision in assessing treatment effects.

Layout plan

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Statistical test used

The data were analyzed by using Statistix 8.1 software. The least significant difference (LSD) test at 5% significance level was used to compare the treatment means.

Results and Discussion

Leaf Area Index at 28 Days After Sowing/Transplanting

Leaf Area Index (LAI) is an important physiological trait that shows the leaf surface area relative to the ground area. It helps indicate crop growth, light capture, and photosynthetic activity. According to Table 4.1, both sowing methods and weed control practices had a significant effect on LAI at 28 days after sowing or transplanting. Among the sowing techniques, transplanting showed the highest LAI (2.23), which was greater than broadcasting (2.05) and drill sowing (2.04). This suggests that transplanting provides better spacing between plants, reduces competition, and allows more leaf growth a result similar to the findings of [5] in rice cultivation.

For weed management, chemical weed control (weedicide) produced the highest LAI (2.39), followed by manual weeding (2.15), while the untreated control had the lowest LAI (1.77). These results highlight the role of weed control in promoting leaf development by minimizing competition for light, water, and nutrients [6] also noted that weed control can significantly improve LAI in rice. The interaction between sowing method and weed control was not statistically significant, meaning each factor influenced LAI independently. Overall, transplanting combined with effective weed control especially chemical methods leads to higher LAI and may improve early crop growth and yield in rice.

Table 1: Leaf area index (28 days after sowing/transplanting) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Contol	**Weedicde**	**Manual weed control**	
M1 (Drill)	1.59^{NS}	2.44	2.08	2.04 b
M2 (Broad-casting)	1.72	2.3	2.11	2.05 b
M3 (Transplanting)	2.01	2.40	2.28	2.23 a
Means	1.77 c	2.39 a	2.15 b	

Leaf Area Index at 56 Days After Sowing/Transplanting

At 56 days after sowing or transplanting, both sowing method and weed control had a clear effect on leaf area index (LAI). Transplanting gave the highest LAI (3.516), compared to broadcasting (3.286) and drill sowing (3.081). This is likely due to better spacing and less crowding between plants, helping leaves grow more freely. Among weed control methods, using a weedicide resulted in the highest LAI (4.320), showing strong weed control helps the crop grow better. Manual weeding gave a moderate LAI (3.068), while the untreated control had the lowest (2.494), proving that weeds can greatly limit leaf growth. There was also a clear interaction between sowing method and weed control. In all methods, weedicide gave the best results, especially when used with transplanting, reaching the top LAI (4.397). Manual weeding helped a bit (e.g., M3 = 3.327, M2 = 3.203), but not as much. Control plots had the lowest values across all sowing types. These results support [7], who also found that good weed control especially chemicals used with transplanting greatly improves leaf growth and crop performance.

Table 2: Leaf area index (56 days after sowing/transplanting) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	**Weedicide**	**Manual weed control**	
M1 (Drill)	2.29 e	4.27 a	2.67 cd	3.08 b
M2 (Broad-casting)	2.36 de	4.29 a	3.20 b	3.29 ab
M3 (Transplanting)	2.82 c	4.39 a	3.33 b	3.52 a
Means	2.49 c	4.32 a	3.07 b	

Leaf Area Duration (28 & 56 Days After Sowing/Transplanting)

Leaf area duration (LAD), which shows how long the crop leaves stay active for capturing sunlight, was affected by both sowing methods and weed control (Table 4.3). Among sowing methods, broadcasting had the highest average LAD (4.942), followed by drill sowing (4.178) and transplanting (4.151). Though the differences weren't significant, broadcasting seemed to help plants grow better due to even seed distribution and less plant crowding. For weed control, plots treated with weedicide showed the highest LAD (7.729), showing how chemical weed control helps leaves stay healthy and active for longer. This agrees with [8], who reported that herbicides reduce competition and improve crop growth. Manual weeding gave a moderate LAD (3.653), while the untreated control had the lowest (2.889), showing the negative impact of unchecked weeds. Similar results were reported by [7]. The interaction between sowing and weed control showed significant effects. The drill sowing + weedicide combo gave a high LAD (7.320), while transplanting + weedicide gave the highest LAD (8.000), proving that both can work well under proper management. On the other hand, manual weeding or no weed control in any method gave lower LAD values, highlighting the need for proper weed control. These findings agree with [5], who also stressed that combining the right sowing method with good weed control improves leaf activity, crop growth, and final yield.

Table 3: Leaf area duration (28 and 56 days after sowing/transplanting) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	2.83NS	7.32	2.39	4.18NS
M2 (Broad-casting)	2.57	7.87	4.39	4.94
M3 (Transplanting)	3.27	8.00	4.19	4.15
Means	2.89 b	7.73 a	3.65 b	

Crop Growth Rate (g m⁻² day⁻¹)

Crop Growth Rate (CGR) is an important indicator of how quickly a crop builds up its biomass during the growing season. The study showed that CGR was significantly affected by different sowing methods, weed control techniques, and their combined effects. Among the sowing methods, transplanting recorded the highest CGR (7.61 g m^{-2} day^{-1}), followed closely by M1 (7.32 g m^{-2} day^{-1}) and M3, which were statistically similar. The lowest CGR was observed in M2 (7.09 g m^{-2} day^{-1}). These results indicate that transplanting supports faster and healthier growth likely due to better spacing and less competition among plants. This agrees with [9], who found that transplanting improves root strength and nutrient uptake, contributing to better growth. In terms of weed management, the use of weedicide led to the highest CGR (8.45 g m^{-2} day^{-1}), clearly outperforming manual weeding (7.33 g m^{-2} day^{-1}) and the control with no weed control (6.24 g m^{-2} day^{-1}). This shows that herbicides are effective in reducing competition from weeds, allowing the crop to use more resources for growth. The combination of transplanting and weedicide application gave the best CGR overall, confirming the findings of [7], who also highlighted the advantages of combining proper planting techniques with effective weed management for improved crop performance.

Table 4: Crop growth rate (g m^{-2} day^{-1}) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	5.98 e	8.46 ab	7.51 c	7.32 ab
M2 (Broad-casting)	5.84 e	8.05 b	7.38 cd	7.09 b
M3 (Transplanting)	6.89 d	8.83 a	7.09 cd	7.61 a
Means	6.24 c	8.45 a	7.33 b	

Net Assimilation Rate (g m⁻² day⁻¹)

Net Assimilation Rate (NAR), which reflects the efficiency with which plants convert assimilated resources into biomass, was assessed under varying sowing methods and weed management strategies. The results indicated that sowing methods had no statistically significant effect on NAR. Among the methods tested, drill sowing exhibited the highest average NAR (2.95 g m^{-2} day^{-1}), followed by broadcasting (2.84 g m^{-2} day^{-1}) and transplanting (2.81 g m^{-2} day^{-1}). Although minor numerical differences were observed, the lack of statistical significance suggests that the efficiency of biomass accumulation per unit leaf area is not substantially impacted by the planting method. These findings are consistent with those of [6], who reported that certain physiological attributes in rice, especially in varieties less responsive to planting arrangements, remain unaffected by sowing technique. In contrast, weed management practices showed a more substantial influence on NAR. The control treatment (no weed control) recorded the lowest NAR (2.72 g m^{-2} day^{-1}), indicating that weed pressure hampers the crop's ability to efficiently utilize assimilated resources. Manual weeding improved NAR modestly (2.86 g m^{-2} day^{-1}), while the application of herbicides resulted in the highest NAR (3.02 g m^{-2} day^{-1}). This highlights the efficacy of chemical weed control in enhancing crop performance by reducing interspecific competition, thereby improving access to essential resources such as light, nutrients, and moisture. These outcomes align with the observations of [10], who emphasized that effective weed suppression plays a vital role in boosting crop physiological efficiency. In summary, while sowing methods did not significantly influence NAR, herbicide application demonstrated a clear advantage, affirming the importance of robust weed control in maximizing resource assimilation and subsequent biomass accumulation. These conclusions are further supported by [11], who also recognized the positive impact of herbicides on crop performance through improved crop-weed interactions.

Table 5: Net assimilation rate (g m^{-2} day^{-1}) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	98.33NS	97.67	96.67	97.56 c
M2 (Broad-casting)	105.67	104.33	104.00	104.67 b
M3 (Transplanting)	113.00	113.00	113.33	113.11 a
Means	105.67 a	105.00 ab	104.67 b	

Days to 50% Heading

The study looked at how different sowing methods and weed control affect the time taken for rice to reach 50% heading. There was no significant difference between sowing methods. Transplanting took the longest (about 109.9 days), while broadcasting and drill sowing were slightly faster (around 109.5 days). The longer time for transplanting may be due to the stress seedlings face after being moved.

Weed control also did not significantly change heading time, but a small trend showed earlier heading with better weed management. Manual weeding led to the earliest heading (111 days), followed by weedicide use (109.7 days), and the untreated control took the longest (108.3 days). This suggests that controlling weeds helps crops grow better and reach maturity sooner, which agrees with earlier studies. No significant interaction was found between sowing methods and weed control. The longest heading time was with transplanting plus manual weeding (111.3 days), and the shortest was with drill sowing without weed control (107.7 days). Overall, while differences were small and not significant, good sowing and weed management practices may help rice grow more evenly and on time.

Table 6: Days to 50% heading as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	**Weedicide**	**Manual weed control**	**Means**
M1 (Drill)	109.12^{NS}	106.95	109.30	108.45 a
M2 (Broad-casting)	108.75	108.48	107.22	108.15 a
M3 (Transplanting)	102.21	102.32	102.51	102.35 b
Means	106.69^{NS}	105.92	106.34	

Plant Height at Maturity (cm)

The study found that sowing methods significantly affected plant height at maturity. Transplanting produced the shortest plants (102.35 cm), while drill sowing (108.45 cm) and broadcasting (108.15 cm) resulted in taller plants. This may be due to transplant shock, which slows seedling recovery, whereas drill sowing and broadcasting help plants establish faster and grow taller. These findings agree with earlier research [12]. Weed management also influenced plant height, but there were no significant differences between weedicide use, manual weeding, and no weed control. This suggests that weed control had little effect on plant height in this study, matching results from [5]. The interaction between sowing methods and weed control was also not significant, indicating their effects on plant height are mostly independent. In summary, choosing the right sowing method is important for better crop establishment and growth. While weed control is essential for overall crop health, it showed less impact on plant height under these conditions.

Number of Productive Tillers (m²)

The study showed that both sowing methods and weed control significantly affected the number of productive tillers per square meter. Transplanting produced the highest tiller count (313.33 m²), followed by drill sowing (291.33 m²) and broadcasting (285.33 m²). This means transplanting helps plants grow more tillers. For weed control, using weedicide gave the most tillers (315.11 m²), manual weeding was next (309.67 m²), and no weed control had the least (265.11 m²). Weedicide was clearly the best for increasing tiller numbers. Productive tillers are important for rice yield. Transplanting likely supports better plant growth by reducing competition among plants. This agrees with [4], who found transplanting improves plant spacing and growth. The combination of transplanting and weedicide gave the highest tiller numbers (around 310–321 m²). Other good combinations were transplanting with manual weeding and drill sowing with weedicide. The lowest tiller count (233.67 m²) was seen with drill sowing and no weed control. Overall, transplanting or direct seeding combined with weedicide helped reduce weed competition and improved tiller growth. Manual weeding helped too but was less effective. These findings support [13], who highlighted the importance of good weed control for better crop growth and yield.

Table 7: Number of productive tillers (m^{-2}) as affected by sowing methods and weed management strategies in rice

Sowing Methods	**Weeding Techniques**			**Means**
	Control	**Weedicide**	**Manual weed control**	**Means**
M1 (Drill)	261 c	312.67 a	300 b	291.33 b
M2 (Broad-casting)	233.67 d	311.67 a	310.67 ab	285.33 b
M3 (Transplanting)	300.67 b	321 a	318.33 a	313.33 a
Means	265.11 c	315.11 a	309.67 b	

Number of Kernels (Panicle-1)

The number of kernels per panicle, an important factor for rice yield, was significantly affected by sowing methods and weed control. Transplanting gave the highest average kernels per panicle (144.21), followed by drill sowing (126.46) and broadcasting (124.50). This suggests transplanting helps better panicle and kernel development by supporting good seedling growth. For weed management, weedicide treatment resulted in the most kernels (136.86), higher than manual weeding (130.52) and no weed control (127.78). Weedicide likely improved kernel numbers by reducing weed competition and allowing plants better access to nutrients and water. Similar results were found by [14]. The combination of transplanting with weedicide produced the highest kernel count (151.67). Weedicide also improved kernel numbers in broadcasting (128.56) and drill sowing (130.36), but not as much. These findings show that transplanting combined with effective weed control, especially weedicide, can greatly increase kernel production. In summary, both the choice of sowing method, particularly transplanting, and good weed management through weedicide are key to increasing kernels per panicle and boosting rice yield. This agrees with previous studies by [9, 14].

Table 8: Number of kernels ($panicle^{-1}$) as affected by sowing methods and weed management strategies in rice

Sowing Methods	**Weeding Techniques**			**Means**
	Control	**Weedicide**	**Manual weed control**	**Means**
M1 (Drill)	9.24 f	10.38 d	10.57 d	10.06 b
M2 (Broad-casting)	9.50 f	10.46 d	9.85 e	9.94 b
M3 (Transplanting)	11.45 c	13.49 a	12.49 b	12.58 a
Means	10.06 c	11.54 a	10.97 b	

Number of Spikelet's (Panicle-1)

The number of spikelets per panicle in rice was affected by both sowing methods and weed management. Transplanting gave the highest average spikelets (12.58), followed by drill sowing (10.06) and broadcasting (9.94). This shows transplanting helps better panicle and spikelet development, likely due to better seedling establishment. For weed control, weedicide treatment produced the most spikelets (11.54), more than manual weeding (10.97) and no weed control (10.06). Weedicide likely improved spikelet numbers by reducing competition from weeds and increasing resources for the rice plants. The best results were seen with transplanting combined with weedicide, which gave the highest spikelet number (13.49), followed by transplanting with manual weeding (12.49). Drill sowing and broadcasting with weedicide also improved spikelet counts but to a lesser extent. This suggests that transplanting plus effective weed control is most effective for spikelet production. In summary, transplanting along with good weed management, especially using weedicide, boosts spikelet formation in rice. These findings agree with earlier research by [15].

Table 9: Number of spikelet's (panicle^{-1}) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	124.42 e	130.36 d	124.59 e	126.46 b
M2 (Broad-casting)	122.41 e	128.56 d	122.53 e	124.50 b
M3 (Transplanting)	136.51 c	151.67 a	144.44 b	144.21 a
Means	127.78 c	136.86 a	130.52 b	

Panicle Length (cm)

The study showed that sowing methods and weed control affected panicle length (cm) in direct-seeded rice. Transplanting produced the longest panicles (24.30 cm), followed by drill sowing (20.66 cm) and broadcasting (19.19 cm). This suggests transplanting supports better panicle growth by helping plants establish well and reducing early stress. For weed control, the weedicide treatment gave the longest panicles (22.00 cm), better than manual weeding (21.55 cm) and no weed control (20.61 cm). This shows that using weedicide helps reduce weed competition and improves conditions for rice growth. The best results came from transplanting combined with weedicide, which produced the longest panicles (around 25.3 cm), closely followed by transplanting with manual weeding. The shortest panicles were seen with broadcasting and manual weed control (18.85 cm), indicating this was the least effective method. Overall, transplanting with proper weed management, especially weedicide use, is key to maximizing panicle length in direct-seeded rice. These results agree with [16], who also found similar benefits.

Table 10: Panicle length (cm) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	13.76 b	12.39 d	13.29 c	13.15 b
M2 (Broad-casting)	14.31 a	14.22 a	13.62 bc	14.05 a
M3 (Transplanting)	8.41 e	8.47 e	8.61 e	8.496 c
Means	12.16 a	11.69 b	11.84 b	

Sterility (%)

The study examined how sowing methods and weed control affect sterility percentage in direct-seeded rice. Transplanting had the lowest sterility (8.50%), which was significantly less than broadcasting (14.05%) and drill sowing (13.15%). This suggests transplanting helps improve fertility by ensuring better seedling establishment. For weed management, weedicide treatment showed the lowest sterility (11.69%), followed closely by manual weeding (11.84%) and the control (12.16%). This means that using herbicides reduces weed competition, helping rice plants reproduce better. When combining sowing and weed control, transplanting with either weedicide (8.47%) or manual weeding (8.61%) resulted in the lowest sterility. Broadcasting and drill sowing with weedicide also lowered sterility but not as much. In summary, transplanting combined with good weed control reduces sterility and improves rice reproduction. These results highlight the importance of both proper sowing methods and effective weed management for better rice yields, supporting findings by [15].

Table 11: Sterility (%) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	20.23 d	21.34 c	20.42 d	20.66 b
M2 (Broad-casting)	19.33 e	19.40 e	18.85 f	19.19 c
M3 (Transplanting)	22.27 b	25.26 a	25.38 a	24.30 a
Means	20.61 c	22.00 a	21.55 b	

1000-Kernel Weight (g)

The study showed that sowing methods and weed management affected the 1000-kernel weight in direct-seeded rice. Transplanting gave the highest kernel weight (24.13 g), which was significantly more than broadcasting (20.64 g) and drill sowing (21.30 g). This suggests transplanting helps seedlings grow better, leading to heavier kernels. For weed control, using weedicide resulted in the heaviest kernels (22.99 g), followed by manual weeding (22.07 g). The untreated control had the lowest weight (21.01 g), showing that weeds reduce kernel development. The combination of transplanting and weedicide produced the highest 1000-kernel weight (25.36 g), with transplanting plus manual weeding also performing well (24.50 g). In contrast, drill sowing and broadcasting with no weed control had the lowest kernel weights due to weed competition. In conclusion, transplanting along with effective weed control, especially herbicides, is the best method to increase kernel weight in direct-seeded rice. These findings agree with previous research highlighting the role of good sowing and weed management for better rice yields [16].

Table 12: 1000 kernel weight (g) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	5.77 e	7.49 b	6.50 cd	6.59 b
M2 (Broad-casting)	5.15 f	6.44 d	5.77 e	5.78 c
M3 (Transplanting)	6.70 c	7.95 a	7.52 b	7.39 a
Means	5.88 c	7.29 a	6.60 b	

Paddy Yield (t ha⁻¹)

The results show significant differences in paddy yield due to both sowing methods and weed management strategies. The interaction between these factors had a strong effect on yield, with transplanting producing the highest average yield (7.39 t ha⁻¹) across all treatments. This likely happens because transplanting helps plants establish better, leading to improved nutrient uptake and growth [17]. Drill sowing and broadcasting gave lower yields (6.59 t ha⁻¹ and 5.78 t ha⁻¹), which may be due to weaker plant establishment and more competition for resources, especially when weed control is poor. Without proper weed management, these methods can reduce plant growth and yield [18]. Using weedicide was the most effective weed management strategy, resulting in the highest yields across all sowing methods, particularly with transplanting. This highlights the important role of weed control in improving yield and crop quality [5]. Manual weeding also increased yields but was less effective than weedicide, with moderate results (6.60 t ha⁻¹). Although manual weed control can be useful in organic or low-input farming, it may not support optimal growth compared to chemical herbicides [18]. The highest yield (7.95 t ha⁻¹) occurred with the combination of transplanting and weedicide. This was followed by transplanting with manual weeding (7.52 t ha⁻¹) and drill sowing with weedicide (7.49 t ha⁻¹). The lowest yield (5.15 t ha⁻¹) was seen in drill sowing without any weed management. Overall, these findings emphasize that transplanting combined with effective weed control, especially weedicide, creates the best conditions for paddy growth by reducing competition for resources. The treatments without weed control consistently had the lowest yields, showing how crucial weed management is for maximizing productivity [19].

Table 13: Paddy yield (t ha^{-1}) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	20.170 e	22.267 c	21.457 d	21.298 b
M2 (Broad-casting)	20.337 e	21.330 d	20.260 e	20.642 c
M3 (Transplanting)	22.523 c	25.360 a	24.500 b	24.128 a
Means	21.010 c	22.986 a	22.072 b	

Straw Yield (t ha⁻¹)

The data on straw yield showed that neither sowing methods nor weed management strategies had a significant effect. Among the sowing methods, transplanting produced the highest straw yield (6.15 t ha⁻¹), followed by broadcasting (6.00 t ha⁻¹) and drill sowing (5.94 t ha⁻¹). Although transplanting yielded slightly more straw, the differences were not statistically significant. For weed management, manual weed control had the highest straw yield (6.16 t ha⁻¹), followed by weedicide (5.94 t ha⁻¹) and the control (5.98 t ha⁻¹). These differences were also not significant, indicating that weed management did not notably affect straw yield.

The lack of significant differences suggests that while transplanting may slightly increase straw production, the effect is minimal. Similarly, weed management strategies did not cause major variations in straw yield. This implies that factors like overall plant growth and environmental conditions likely have a stronger impact on straw production than sowing methods or weed control. In conclusion, although transplanting showed a slight advantage, the differences in straw yield were not significant, and weed management strategies had little effect. Other factors such as nutrient availability and plant health may play a greater role in determining straw yield in rice cultivation.

Table 14: Straw yield (t ha^{-1}) as affected by sowing methods and weed management strategies in rice

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	5.96^{NS}	5.92	5.93	5.94^{NS}
M2 (Broad-casting)	5.97	5.96	6.5	6.00
M3 (Transplanting)	6.02	5.94	6.05	6.15
Means	5.98^{NS}	5.94	6.16	

Biological Yield (t ha⁻¹)

The biological yield data showed significant differences due to sowing methods, weed management strategies, and their interaction. Among sowing methods, transplanting produced the highest biological yield (13.39 t ha⁻¹), followed by drill sowing (12.53 t ha⁻¹) and broadcasting (11.93 t ha⁻¹). Transplanting likely improved plant establishment and resource use, leading to greater biomass production. For weed management, weedicide application resulted in the highest biological yield (13.24 t ha⁻¹), followed by manual weed control (12.76 t ha⁻¹) and the control treatment (11.86 t ha⁻¹). Effective weed control reduces competition and creates better growth conditions, increasing biomass. The interaction effect showed that transplanting combined with weedicide produced the highest biological yield (13.89 t ha^{-1}). This combination of optimal sowing and weed management enhances crop growth and biomass. In contrast, broadcasting and drill sowing without weed control gave the lowest yields, likely due to poor establishment and higher weed competition.

Overall, transplanting with weedicide was the best approach for maximizing biological yield, highlighting the importance of proper sowing methods and effective weed control [8].

Table 15: Biological yield (t ha^{-1}) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	11.73 d	13.41 b	12.43 c	12.53 b
M2 (Broad-casting)	11.12 e	12.40 c	12.27 c	11.93 c
M3 (Transplanting)	12.72 c	13.89 a	13.57 ab	13.39 a
Means	11.86 c	13.24 a	12.76 b	

Harvest Index (%)

The data showed that both sowing methods and weed management significantly affected the harvest index in rice, but their interaction did not. Among sowing methods, transplanting gave the highest harvest index (0.55%), followed by drill sowing and broadcasting with lower values. Transplanting likely improves the balance between vegetative growth and grain production, resulting in more grain relative to total biomass.

For weed management, weedicide treatment had the highest harvest index (0.55%), followed by manual weed control (0.52%) and the control (0.49%). This shows that effective weed control, especially with weedicide, helps increase grain yield by reducing competition for nutrients and water, supporting findings by [17].

Although the interaction between sowing methods and weed management was not significant, transplanting combined with weedicide gave the highest harvest index. This indicates that using both effective sowing and weed control methods can best improve grain production efficiency.

In conclusion, transplanting and weedicide application are the most effective practices for achieving a higher harvest index in rice.

Table 16: Harvest index (%) as affected by sowing methods and weed management strategies in rice.

Sowing Methods	Weeding Techniques			Means
	Control	Weedicide	Manual weed control	
M1 (Drill)	0.49^{NS}	0.56	0.52	0.52 b
M2 (Broad-casting)	0.46	0.52	0.48	0.49 c
M3 (Transplanting)	0.52	0.57	0.56	0.55 a
Means	0.49 c	0.55 a	0.52 b	

Benefit-Cost Ratio

The analysis shows that among the three sowing methods, drill sowing with weedicide gave the highest benefit-cost ratio (BCR) of 1.06, making it the most cost-effective way to get good returns. This means drill sowing with good weed control is a profitable method for growing rice. Transplanting, although it needs more labor, also had a good BCR of 1.07 with weedicide. It remains profitable when weeds are well controlled. Broadcasting had the lowest BCR in all weed management methods. Without weed control, broadcasting gave a BCR of 0.49, and with weedicide, only 0.82. This shows broadcasting is less economical, especially without proper weed control, because it lowers yield and profit. Weedicide use gave the best BCR in all sowing methods, showing how important weed control is for earning good returns. Manual weed control was better than no control but not as good as weedicide. It can be used when herbicides are not an option [5]. No weed control led to the lowest yields and incomes in all methods, showing how weeds reduce rice productivity. The highest profits were with drill sowing and transplanting using weedicide, though transplanting costs more labor, hence, drill sowing and transplanting with weedicide are the best for profit. Broadcasting is simple but needs better weed control to be profitable [20].

Table 17: Benefit cost ratio as affected by sowing methods and weed management strategies in rice

Interactions		Paddy yield tons ha^{-1}	Cost (Rs.)			Net Income (Rs.)	Grass Income (Rs.)	BCR
Sowing Methods	Weed Management strategies		Fixed	Variables	Total			
M1(Drill)	Control	5.77	171300	5000	176300	288500	112200	0.64
	Weedicide	7.49	171300	10000	181300	374500	193200	1.06
	MWC3	6.50	171300	15000	186300	325000	138700	0.74
M2 (Broadcasting)	Control	5.15	171300	1000	172300	257500	85200	0.49
	Weedicide	6.44	171300	6000	177300	322000	144700	0.82
	MWC3	5.77	171300	11000	182300	288500	106200	0.58
M3 (Transplanting)	Control	6.70	171300	15000	186300	335000	148700	0.79
	Weedicide	7.95	171300	20000	191300	397500	206200	1.07
	MWC3	7.52	171300	25000	196300	376000	179700	0.91
Interactions		Paddy yield tons ha^{-1}	Cost (Rs.)			Net Income (Rs.)	Grass Income (Rs.)	BCR
Sowing Methods	Weed Management strategies		Fixed	Variables	Total			
M1(Drill)	Control	5.77	171300	5000	176300	288500	112200	0.64
	Weedicide	7.49	171300	10000	181300	374500	193200	1.06

	MWC3	6.50	171300	15000	186300	325000	138700	0.74
M2 (Broadcasting)	Control	5.15	171300	1000	172300	257500	85200	0.49
	Weedicide	6.44	171300	6000	177300	322000	144700	0.82
	MWC3	5.77	171300	11000	182300	288500	106200	0.58
M3 (Transplanting)	Control	6.70	171300	15000	186300	335000	148700	0.79
	Weedicide	7.95	171300	20000	191300	397500	206200	1.07
	MWC3	7.52	171300	25000	196300	376000	179700	0.91

Conclusion

The present study concluded that transplanting combined with weedicide application is the most effective approach for maximizing both productivity and economic returns on clayey soils. This combination ensures superior plant establishment, effective weed control, and optimal resource utilization, leading to enhanced rice yield and profitability. However, drill sowing with post-emergence weedicide application also proved to be a promising alternative, especially under labor-scarce conditions. While slightly less productive than transplanting, this method maintained a competitive yield of 7.49 t ha^{-1} and achieved a positive benefit-cost ratio (BCR) of 1.06, making it both agronomically and economically viable. Additionally, a higher sterility percentage was observed in direct- seeded rice (DSR) compared to transplanted rice, which may have contributed to its slightly reduced yield performance. Nonetheless, drill sowing with weedicide application emerges as a cost-effective strategy for weed management and yield stabilization in areas where manual labor is limited or costly. Overall, these findings emphasize the critical importance of selecting appropriate sowing methods and weed management strategies to achieve sustainable rice production on clayey soils.

Recommendations

For regions with abundant and affordable labor transplanting with weedicide application is recommended for achieving the highest net returns and productivity. In areas with limited labor availability or high labor costs drill sowing combined with post emergence weedicide application is advised as a practical and economically efficient alternative. Agricultural extension services should promote drill sowing with effective weed management as a scalable and farmer friendly solution particularly in labor scarce regions. Further research and on-farm demonstrations are encouraged to validate these results across different agroclimatic conditions and cropping systems for broader adoption.

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