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Influence of Water Management and Weeding Practices on the Growth and Yield of Boro Rice (cv. BRRI dhan29)

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ABSTRACT **Original research paper**

A field experiment was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh, during the Boro season (December 2014–June 2015) to evaluate the effects of different water- and weed-management practices on the performance of the rice variety BRRI dhan29. The study employed a split-plot design with three replications. The main plots were assigned three irrigation strategies: the conventional farmers' method (M_1), alternate wetting and drying (AWD) (M_2), and the system of rice intensification (SRI) (M_3). The subplots tested six weed-control treatments: no weeding (W_0); pyrazosulfuron-ethyl 10WP alone (W_1); pyrazosulfuron-ethyl 10WP combined with one hand weeding at 30 days after transplanting (DAT) (W_2); pendimethalin 33 EC alone (W_3); pendimethalin 33 EC with one hand weeding at 30 DAT (W_4); and a combination of pendimethalin 33 EC and pyrazosulfuron-ethyl 10WP (Panida + Manage) (W_5).The predominant weeds observed across the treatments included Paspalum scrobiculatum, Echinochloa crus-galli, Cyperus difformis, Scirpusjuncoides, and Digitariasetigera. Water-mangement practices had a significant influence on key yield-related traits, including the total and effective number of tillers per hill, panicle length, grain number per panicle, and harvest index. Among the irrigation methods, SRI produced the highest grain yield, largely due to its promotion of increased total and effective tillers.n terms of weed management, the combined application of pendimethalin 33 EC and pyrazosulfuron-ethyl 10WP (W_5) resulted in the best yield, performing comparably to W_1 and W_2. The interaction between water and weed management revealed that SRI coupled with the W_5 herbicide mixture provided the most effective weed suppression and the highest grain yield overall.n conclusion, adopting the SRI method in combination with the integrated use of pendimethalin 33 EC and pyrazosulfuron-ethyl 10WP is a highly effective approach for enhancing weed control and maximizing productivity in Boro rice cultivation.

Keywords: Boro rice, BRRI dhan29, Herbicide, Water management, Weed management, Yield.

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Introduction

Rice (*Oryza sativa* L.) serves as the primary staple food of Bangladesh and plays a crucial role in maintaining the country's food security. Approximately 54% of the population is involved in agricultural activities, with nearly 89% of farming households operating on landholdings smaller than 1 hectare (about 2.5 acres). In contrast, around 14% of households rely on sharecropping due to the absence of their own cultivable land (BRRI, 2008).

This fragmented agrarian structure struggles to meet the country's growing food demand. Consequently, agricultural land is under intense pressure, and cropping intensity has risen steadily over the decades, reaching an average of 197% nationwide (BBS, 2023).

Water is one of the most essential resources for sustaining life, yet it is becoming increasingly scarce worldwide, and Bangladesh is no exception. As surface water availability continues to decline, irrigation demands are shifting toward groundwater extraction. However, groundwater is a finite resource, and in areas with intensive tube-well irrigation, the water table is falling steadily each dry season. Therefore, efficient and judicious water management is imperative to ensure both sustainable crop production and long-term groundwater security. Although Bangladesh is often regarded as a water-abundant country, several regions, especially the northwestern districts, face water shortages during the *Boro* rice-growing season. Since groundwater is the principal irrigation source for *Boro* rice in these regions, the intensification of irrigation has placed immense pressure on underground water reserves.

Bangladesh has three main rice-growing seasons: *Aus* (pre-monsoon or early summer rice), *Aman* (monsoon rice), and *Boro* (dry season irrigated rice). Among these, *Boro* rice typically produces the highest yield. During the 2023–2024 season, *Boro* rice covered 4.85 million hectares and produced 20.77 million metric tons (BBS, 2023), contributing more than 50% of the nation's total annual rice output (BBS, 2024). Consequently, irrigated *Boro* rice plays a pivotal role in maintaining Bangladesh's food security.

However, the environmental consequences of intensive *Boro* rice cultivation are significant. Continuous groundwater pumping for irrigation lowers the water table each year because monsoon rainfall is insufficient to fully recharge aquifers (Imran et al., 2025; Faisal and Parveen, 2004; Ali et al., 2010). On average, producing one kilogram of rice globally requires about 3,400 liters of water (Hoekstra, 2008), making rice one of the most water-demanding crops. Nevertheless, studies have shown that rice plants can achieve optimal physiological growth with less water than this traditional requirement.

To help farmers reduce water, energy, and fuel consumption in irrigated rice systems, the Alternate Wetting and Drying (AWD) technique was introduced by the International Rice Research Institute (IRRI) in 2004 as a water-efficient practice for lowland rice cultivation. This method involves applying irrigation intermittently only after the standing water in the field has drained for a specified number of days instead of keeping the field continuously flooded. Another effective approach for conserving water is the System of Rice Intensification (SRI), originally developed in Madagascar by Father Henri de Laulanié (Stoop *et al.*, 2002).

Studies have shown that intermittent or saturated irrigation can save 20–50% of water compared to conventional continuous flooding (Lek and Yongyod, 1989). Intermittent irrigation involves applying water up to 5 cm deep at intervals that maintain soil moisture near field capacity, from about 20 days after transplanting until panicle initiation, while saturated soil management keeps the soil constantly at field capacity during this period.

Weed pressure is one of the most critical biotic constraints affecting rice cultivation globally. Weeds compete directly with rice plants for light, nutrients, water, and physical space, which leads to reduced plant growth, limited tillering, and ultimately lower yields (Halder et al., 2024a; Humaira et al., 2024). In Bangladesh, the impact is particularly severe: weed-related yield losses may reach 70–80% in Aus rice, 30–40% in transplanted Aman, and 22–36% in modern Boro varieties (Mia et al., 2024; Mamun, 1990). The country's soil and climatic conditions encourage the rapid spread and domination of numerous problematic weed species (Halder et al., 2024b).

Although manual weeding is still the primary method used by farmers, it is expensive, labor-demanding, and prone to delays, especially with the declining availability of rural labor due to increased migration to urban areas (Fiza et al., 2024; Ahmed et al., 2005). As a result, weeds often inflict greater yield losses than insects and diseases combined. To mitigate these issues, both mechanical methods and herbicides have been introduced. Herbicides, whether used alone or alongside hand weeding, can effectively suppress weed growth (Ahmed et al., 2005). Combining herbicide application with one timely hand weeding can improve yield while reducing labor requirements and production costs (Hossain et al., 2024; Islam et al., 2024a; Sathyamoorthy et al., 2004). Determining the most effective and cost-efficient weed management approach is therefore crucial for reducing yield losses associated with weed competition (Islam et al., 2024b).

Although the individual benefits of improved water and weed management practices are well established, limited research has examined how these two factors interact under Boro rice production conditions in Bangladesh. Hence, this study was undertaken with the following objectives:

i. To determine how different water management techniques influence Boro rice growth and yield.
ii. To evaluate the performance of various weed control practices in Boro rice.
iii. To investigate the combined effects of water and weed management on the growth and yield attributes of Boro rice.

Materials and Methods

Experimental Site Description

The experiment was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University (BAU), Mymensingh, during the Boro season from December 2014 to June 2015. The objective was to measure the influence of water and weed management strategies on the growth and productivity of Boro rice.

The field site is located at 24°75′ N latitude and 90°50′ E longitude, with an elevation of roughly 18 meters above sea level. The soil belongs to the Sonatala series within the Old

Brahmaputra Floodplain Agro-Ecological Zone (AEZ-9). It is a dark grey, non-calcareous floodplain soil with slightly acidic properties, featuring a pH of approximately 6.5 (UNDP & FAO, 1988).

Climate

The experimental area has a subtropical climate with distinct seasonal patterns. The Kharif season (April–September) is characterized by high temperatures, elevated humidity, and substantial rainfall, often accompanied by strong winds. Conversely, the Rabi season (October–March) brings cooler temperatures, limited rainfall, and higher sunshine hours—conditions that are favorable for successful Boro rice cultivation (Figure 1).

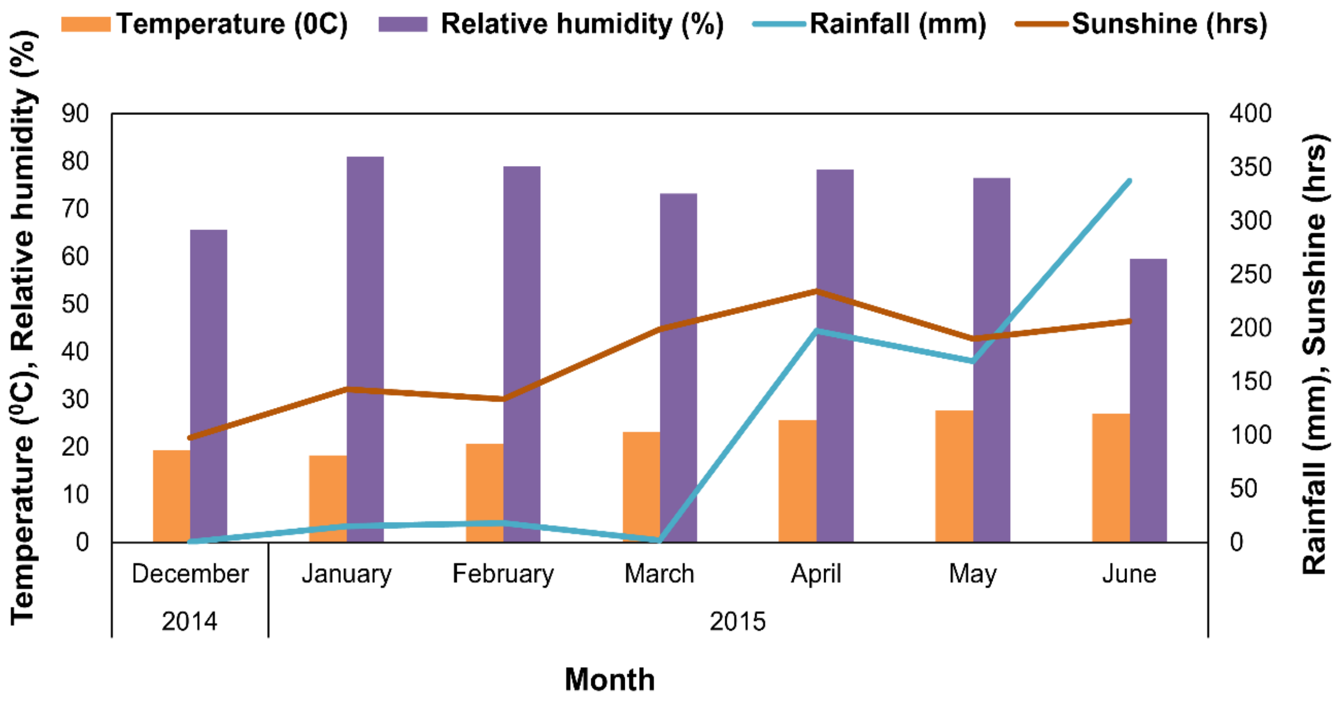

Figure 1. Monthly average temperature, relative humidity, sunshine duration, and rainfall at the experimental site during the crop-growing period.

Experimental Treatments

The experiment involved two factors and a total of 18 treatment combinations.

Factor A: Water Management Practices (3 levels)

i. M_1: Conventional farmer method (continuous flooding)
ii. M_2: Alternate Wetting and Drying (AWD)
iii. M_3: System of Rice Intensification (SRI)

Factor B: Weed Management Options (6 levels)

i. W_0: No weeding (control)
ii. W_1: Early post-emergence application of Pyrazosulfuron-ethyl 10WP (Manage 10WP)
iii. W_2: Pyrazosulfuron-ethyl 10WP (Manage 10WP) followed by one hand weeding
iv. W_3: Pre-emergence application of Pendimethalin 33 EC (Panida)
v. W_4: Pendimethalin 33 EC (Panida) plus one hand weeding at 30 days after transplanting (DAT)
vi. W_5: Combined application of Pendimethalin 33 EC and Pyrazosulfuron-ethyl 10WP (Panida + Manage)

Experimental Design and Layout

A split-plot design with three replications was used for the study. Water management practices (Factor A) were assigned to the main plots, and weed management treatments (Factor B) were allocated to the subplots.

The total number of experimental plots was:

3 water management levels × 6 weed control methods × 3 replications = 54 plots

Crop Establishment

Seed Source

Seeds of the Boro rice variety *BRRI dhan29* were collected from the Agronomy Field Laboratory at Bangladesh Agricultural University (BAU), Mymensingh.

Seed Germination

Healthy seeds were selected using the specific gravity technique. The selected grains were soaked for 24 hours, drained, and then placed in moist gunny bags to facilitate sprouting. Approximately 72 hours later, the seeds germinated and were ready for sowing in the nursery.

Nursery Bed Preparation and Sowing

Seedlings were raised on a well-prepared and properly drained nursery bed. The soil was puddled thoroughly with a traditional plough and leveled to ensure uniform emergence.

For the conventional (M_1) and AWD (M_2) treatments, sprouted seeds were sown on 22 December 2014.

For the SRI (M_3) treatment, seed sowing was carried out on 18 January 2015.

During the nursery stage, the beds were irrigated as needed and hand-weeded regularly to maintain healthy seedling growth.

Field Preparation Before Transplanting

Prior to transplanting, the main experimental field underwent one pass of ploughing using a power tiller, followed by four additional ploughings with a traditional plough. The field was then leveled using a ladder to achieve a fine tilth suitable for transplanting. All remaining stubble, weeds, and crop residues were removed, and the plots were marked according to the experimental layout after completing the final land preparation.

Fertilizer Application

Fertilizer management was carried out according to the recommendations of the Bangladesh Rice Research Institute (BRRI, 2013) for the Boro rice variety *BRRI dhan29*. The fertilizers and their application rates were as follows (kg ha^{-1}):

i. Urea: 300
ii. Triple Superphosphate (TSP): 100
iii. Muriate of Potash (MoP): 120
iv. Gypsum: 100
v. Zinc Sulphate: 10

The entire quantities of TSP, MoP, gypsum, and zinc sulphate were incorporated into the soil during the final land preparation. Urea was applied in three equal portions at 15, 30, and 45 days after transplanting (DAT) to maintain a steady supply of nitrogen throughout the crop growth period.

Seedling Uprooting

To facilitate easier removal, the nursery beds were irrigated one day prior to uprooting. Seedlings were carefully removed on 30 January 2015, taking care to minimize root damage. After uprooting, seedlings were sorted, and healthy, uniform ones were selected for transplanting into the main field.

Transplanting of Seedlings

Seedlings were transplanted on 31 January 2015 into the well-prepared puddled plots:

i. For the farmers' practice (M_1) and AWD (M_2) treatments, two seedlings per hill were transplanted, maintaining a spacing of 25 cm × 15 cm between rows and hills.
ii. For the SRI (M_3) treatment, single 14-day-old seedlings were transplanted at wider spacing to promote robust root development and higher tillering.

Weeding

Weeding was performed as per the specific treatment requirements to maintain the experimental plots free from unwanted vegetation.

i. In the no-weeding treatment (W_0), no weeding operations were carried out throughout the growing period.
ii. For all other treatments, weeds were removed whenever they appeared in plots designated as weed-free.
iii. Generally, weeding was performed once per week, depending on weed emergence.
iv. In W_2 and W_4 treatments, one manual hand weeding was conducted at 30 days after transplanting (DAT), in addition to other herbicide or management measures as per the treatment design.

Herbicide Application

Herbicides were applied according to the requirements of each weed management treatment:

i. **Pre-emergence application:** Pendimethalin 33 EC (Panida) was used at a rate of 2.5 L ha^{-1} in the W_3, W_4, and W_5 treatments. The herbicide was applied 5 days after transplanting (DAT).
ii. **Early post-emergence application:** Pyrazosulfuron-ethyl 10WP (Manage 10WP) was applied at 125 g ha^{-1} in the W_1, W_2, and W_5 treatments. This application was carried out 13 DAT when the plots had 5–7 cm of standing water.

A knapsack sprayer fitted with a flat-fan nozzle was used for all treatments to ensure consistent and uniform herbicide coverage across the experimental plots.

Description of Water Management Methods

Traditional Farmers' Practice (M_1)

In the conventional transplanting method, two rice seedlings were placed in each hill within well-puddled soil. The crop was arranged at a spacing of 25 × 15 cm (row × hill). A shallow layer of water, about 4–5 cm deep, was maintained continuously from transplanting up to the hard dough stage to support plant establishment and growth. Before harvesting, irrigation was stopped to allow the field to dry, making harvesting operations easier.

Alternate Wetting and Drying (AWD) Method (M_2)

The AWD technique was implemented following the recommendations of the International Rice Research Institute (IRRI) to enhance water-use efficiency. A water-level monitoring tube (often called a "magic pipe") was installed 10 days after transplanting to track the groundwater depth.

After each irrigation event, the standing water was allowed to naturally decline through percolation and evapotranspiration. When the water level inside the tube dropped to 15 cm below the soil surface, irrigation was applied again to raise the water depth to roughly 5 cm. At the maximum tillering stage, a constant 5-cm water layer was maintained. During flowering, grain filling, and ripening, the field was again managed under AWD, allowing the water level to fall to 15 cm before re-irrigation. This approach significantly conserved water while still providing adequate soil moisture to sustain healthy plant growth and preserve yield potential.

Figure 2: AWD device installed in the soil.

SRI Water Management Method

Water Management Under the System of Rice Intensification (SRI)

Managing water was one of the most challenging aspects of practicing the System of Rice Intensification. The core idea behind SRI is to give the rice plants only the amount of water they actually need, instead of keeping the field constantly flooded. In SRI plots, the land was kept moist during the early growth period but never fully submerged. Small amounts of water were added only to maintain a damp, aerated soil environment. During the tillering stage, the soil surface was occasionally allowed to dry for two to four days. This slight drying improved air circulation in the root zone and encouraged stronger root development.

From panicle initiation up to the hard dough stage, a shallow layer of waterusually about 2 to 3 cmwas maintained across the field. Once the crop reached the hard dough stage, irrigation was stopped altogether, and any remaining water was drained to ensure even ripening and to make harvesting easier.

Sampling, Harvesting, and Processing

Harvesting and Yield Measurement

Rice plants were harvested once they reached full maturity, which was determined when roughly 90% of the grains had turned golden yellow. Harvest timing differed across water management practices. The plots under the farmers' traditional method (M_1) and under alternate wetting and drying (M_2) were harvested on 30 May 2015, which corresponded to 155 days after sowing (DAS). The SRI plots (M_3) matured slightly later and were harvested on 8 June 2015, at 145 DAS.

After cutting, the harvested plants from each plot were tied into bundles, properly labeled, and moved to the threshing area. Threshing was done manually to separate grains from the straw, and yields of both were recorded. Grain samples were cleaned and adjusted to a standardized moisture content of 14%, while straw samples were sun-dried before weighing. Both grain and straw yields were expressed in tonnes per hectare (t ha^{-1}). Before harvest, five hills from each plot were randomly selected to document yield-related traits.

Data Collection

Throughout the experiment, observations were recorded for the major growth and yield attributes of Boro rice, including:

1. Plant height (cm)
2. Total number of tillers per hill
3. Number of productive tillers per hill
4. Panicle length (cm)
5. Number of grains per panicle
6. Number of sterile spikelets per panicle
7. Thousand-grain weight (g)
8. Grain yield (t ha^{-1})
9. Straw yield (t ha^{-1})
10. Harvest index (%)

Statistical Analysis

All data gathered during the study were compiled and analyzed using the MSTAT-C statistical software. Analysis of variance (ANOVA) was applied to determine whether the treatments differed significantly. Whenever significant differences were detected, treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% significance level, following the procedures described by Gomez and Gomez (1984).

Weed Infestation in the Experimental Field

The environmental conditions favorable for Boro rice also encourage rapid weed growth, which can compete heavily with the crop for nutrients, water, and sunlight, ultimately reducing productivity. In the experimental area, ten weed species representing five botanical families were identified. These included four grasses, three broad-leaved species, and three sedges. The most commonly encountered weeds were *Paspalum scrobiculatum*, *Echinochloa crus-galli, Leersia hexandra*, *Oxalis europaea*, *Monochoria vaginalis*, *Ludwigia hyssopifolia*, *Cyperus difformis*, *Scirpus juncoides*, *Digitaria setigera*, *Fimbristylis miliacea*, and *Commelina diffusa*.

These observations align with earlier findings by Mamun et al. (1993), who reported similar dominant weed speciessuch as *Fimbristylis miliacea*, *Lindernia antipoda*, and *Eriocaulon cinereum*in transplanted Boro rice fields in the same agro-ecological zone (AEZ-9). This consistency suggests that certain weed species are persistently dominant in this region.

Table 1. Infesting weed species grown in the experimental plots in *boro* Rice

Sl. no.	Common name	Scientific name	Family	Morphology	Life cycle
1.	Shama	*Echinochloa crus-galli* (L.) P. Beauv.	Poaceae	Grass	Annual
2.	Angta	*Paspalum scrobicultum* L.	Poaceae	Grass	Perennial
3.	Arail	*Leersia hexandra* Sw.	Poaceae	Grass	Perennial
4.	Chesra	*Scirpus juncoides* Roxb.	Cyperaceae	Sedge	Perennial
5.	Chhoto Angulighash	*Digiteria setigera* Roth	Poaceae	Grass	Annual
6.	Panikachu	*Monochoria vaginalis* (Burm. F.) C. Presl	Pontederiaceae	Broadleaf	Perennial
7.	Joina	*Fimbrystylis miliacea* L.	Cyperaceae	Sedge	Annual
8.	Sabuj Nakphul	*Cyperus difformis* L.	Cyperaceae	Sedge	Annual
9.	Amrul Shak	*Oxalis europea* L.	Oxalidaceae	Broadleaf	Annual
10.	Kanaibashi	*Commelina diffuza* Burm. F.	Commelinaceae	Broadleaf	Annual

Yield and Yield Contributing Characters

Effect of Methods of Water Management

Plant Height

Plant height is primarily a genetic trait and was not significantly affected by different methods of water management (Table 2). Although the variation was statistically non-significant, plants grown under the AWD (Alternate Wetting and Drying) method attained the greatest average height (95.52 cm), whereas the shortest plants (94.16 cm) were recorded under the SRI (System of Rice Intensification) method. Similar observations were made by Dhillon et al. (2020), who reported that variations in water management methods did not result in significant differences in plant height among rice genotypes.

Number of Total Tillers per Hill

A significant variation in the number of total tillers per hill was observed among the different water management treatments (Table 2). The System of Rice Intensification (SRI) (M_3) method produced the highest number of total tillers per hill (18.45), followed by the Alternate Wetting and Drying (AWD) (M_2) method with 17.20 tillers per hill. The lowest number of total tillers (15.06) was recorded under the farmers' conventional practice (M_1), which was statistically comparable to the AWD treatment (Figure 3).

The superior tiller production observed in the SRI plots can be attributed to the aerobic soil conditions maintained by intermittent irrigation. The practice of keeping the soil moist but not continuously flooded allowed oxygen to penetrate into the root zone, encouraging the development of stronger and deeper root systems. Robust roots enhance nutrient and cytokinin absorption, which in turn stimulates the initiation and growth of tillers (Uphoff, 2006).

Additionally, younger seedlings, wider spacing, and shallow transplanting used in the SRI method further contributed to enhanced tillering compared to conventional continuous flooding. Similar findings were reported by Pramanik et al. (2015), who observed a significant increase in total tiller production under SRI practices.

Number of Effective Tillers per Hill

The number of effective tillers per hill was also significantly influenced by the different water management methods (Table 2). The highest number of effective tillers (14.71) was recorded under the SRI (M_3) water management method, while the lowest number (11.44) was obtained from the farmers' practice (M_1). The latter was statistically similar to the AWD (M_2) treatment (Figure 3).

The superior performance of SRI in producing more effective tillers may be attributed to its intermittent irrigation and soil aeration, which create a favorable environment for root growth and nutrient uptake. The periodic drying of soil enhances microbial activity and oxygen availability in the rhizosphere, resulting in stronger and healthier root systems capable of supporting more productive tillers. In contrast, continuous flooding tends to induce anaerobic soil conditions, which can suppress root growth and limit nutrient absorption.

Moreover, the use of young seedlings (about 14 days old) in SRI allowed early tiller initiation. Wider spacing provided each plant with greater access to light, nutrients, and space, reducing interplant competition and promoting vigorous tiller formation. Chapagain and Yamaji (2010) also reported that SRI management practices enhance tiller development compared to conventional flooded conditions.

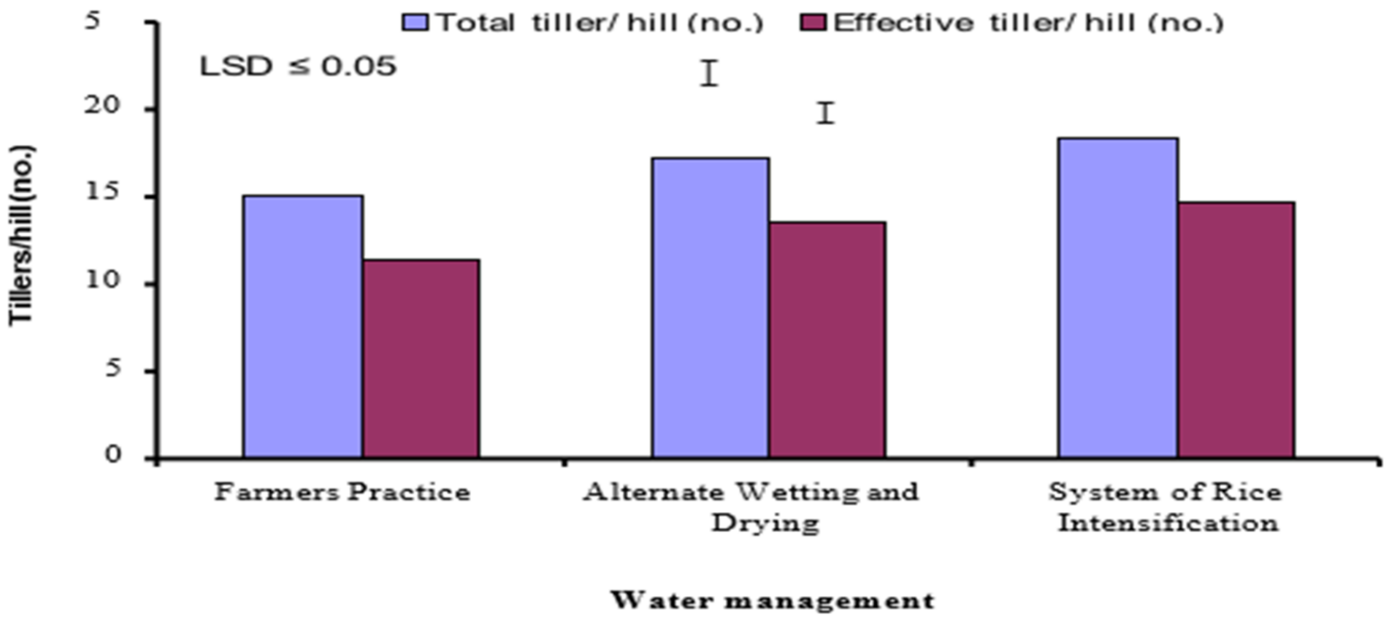

Figure 3: Number of total and effective tillers hill^{-1} as influenced by water management in *Boro* rice.

Panicle Length

Panicle length varied significantly across the different water management practices (Table 2). The longest panicles were produced under the conventional farmers' practice (M_1), measuring 24.39 cm. This value was statistically similar to the panicle length observed under the SRI method (M_3), which averaged 23.57 cm. The shortest panicles, measuring 23.42 cm, occurred in the AWD treatment (M_2).

These results agree with the findings of Farzana et al. (2021), who noted that continuous flooding generally supports the development of longer panicles compared to AWD. The relatively greater panicle length under conventional irrigation may be linked to a steady water supply, which limits excessive tillering and allows more carbohydrates to be directed toward the development of fewer, but longer, panicles. However, panicle length by itself does not define final grain yield, as yield also depends on the number of panicles, the number of grains each panicle carries, and grain weight.

Number of Grains per Panicle

Water management also had a significant impact on the number of grains per panicle (Table 2). The conventional farmers' practice (M_1) produced the highest grain count, with an average of 139.80 grains per panicle. Continuous flooding likely helped maintain a consistently saturated soil environment, ensuring steady nutrient and water availability during the reproductive stage, which in turn encouraged better grain formation.

The lowest grain counts were recorded under both AWD (M_2) and SRI (M_3), averaging 133.70 grains per panicle, and the difference between these two treatments was not significant. These observations match the findings of Zhao et al. (2010), who reported a slight decline in grains per panicle under SRI compared with continuous flooding.

Number of Sterile Spikelets per Panicle

The number of sterile spikelets per panicle was significantly influenced by the water management methods (Table 2). SRI (M_3) had the highest sterility, with an average of 23.06 sterile spikelets, while conventional practice (M_1) had the lowest, at 20.61.

Higher sterility under SRI may be connected to the wider spread of tillering phases, which can lead to uneven flowering times and inconsistent pollination. In contrast, continuous flooding under conventional practices tends to promote more uniform tiller development and synchronized flowering, resulting in fewer sterile spikelets.

1000-Grain Weight

The 1000-grain weight did not show a statistically significant response to the different irrigation practices (Table 2). Even so, the heaviest grains were obtained from the conventional method (M_1), weighing 22.69 g, while the AWD treatment (M_2) produced slightly lighter grains at 22.21 g.

Grain weight is largely controlled by genetics and is known to remain relatively stable regardless of irrigation practices. Similar trends were reported by Mia et al. (2023) and Dzomeku et al. (2016), who found that grain weight is typically unaffected by water management or weed control methods.

Grain Yield

Although the differences were not statistically significant, grain yield did vary numerically across the water management treatments (Figure 4). The highest yield (5.86 t ha^{-1}) was recorded under SRI (M_3), while the lowest yield (5.47 t ha^{-1}) came from AWD (M_2). The higher yield in SRI plots may be attributed to a greater number of both total and effective tillers. The intermittent wetting and drying cycle improves soil aeration and energizes microbial activity, which enhances root growth and nutrient absorption—factors that collectively contribute to higher productivity. Similar trends were reported by Mamuna et al. (2023), who also observed superior yields under SRI compared with AWD and continuous flooding.

Straw Yield

Straw yield did not differ significantly among the water management practices (Figure 4). Nonetheless, SRI (M_3) produced the highest straw yield at 7.74 t ha^{-1}, closely followed by AWD (M_2) at 7.19 t ha^{-1}. The lowest straw yield (7.04 t ha^{-1}) was found under the conventional method (M_1). The slightly higher straw production under SRI may be linked to stronger root systems and healthier vegetative growth fostered by improved soil aeration and periodic drying, which support greater biomass accumulation.

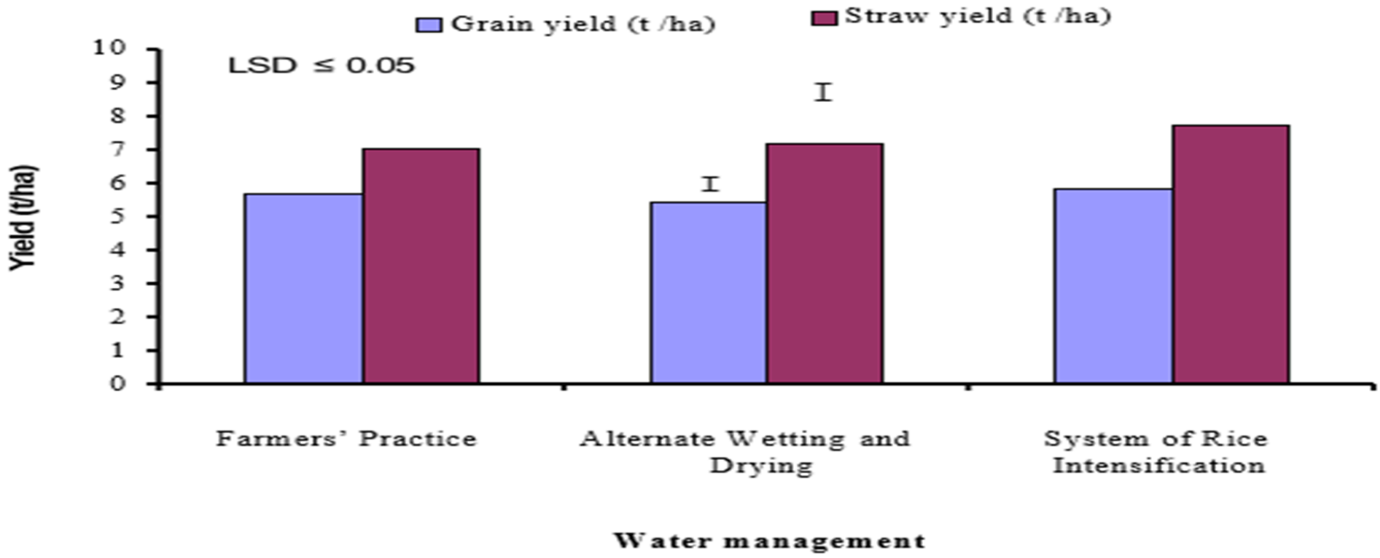

Figure 4. Grain and straw yields (t ha^{-1}) of boro rice under different water-management practices.

Harvest Index (%)

The harvest index varied noticeably across the water-management treatments (Table 2). The farmers' practice (M_1) produced the highest harvest index at 44.51%, which did not differ statistically from the AWD method (M_2), registering 43.07%. In contrast, the SRI approach (M_3) resulted in the lowest harvest index, measuring 42.91%.

Table 2: Effect of methods of water management on the performance of *Boro* rice

Methods of water management	Plant height (cm)	Length of panicle (cm)	Grains panicle^{-1} (no.)	Sterile spikelets panicle^{-1} (no.)	1000-grain weight (g)	Harvest index (%)
Farmers' practice (M_1)	95.31	24.39a*	139.8a	20.61b	22.69	44.51a
AWD (M_2)	95.52	23.42b	133.70b	21.28b	22.21	43.07a
SRI (M_3)	94.16	23.57b	133.70b	23.06a	22.64	42.91a
CV (%)	2.04	1.42	2.66	10.53	6.23	5.32
Level of significance	NS	**	**	*	NS	*

*In a column, values having same letters or without letters do not differ significantly whereas values with dissimilar letters differ significantly as per DMRT.**= Significant at 1% level of probability, *= Significant at 5% level of probability, NS = Not significant

Effect of Weeding

Plant Height

No significant differences in plant height were observed across the various weed management treatments (Table 3). Numerically, the tallest plants (95.54 cm) were recorded under W_2, where the post-emergence herbicide Pyrazosulfuron-ethyl 10WP (Manage 10WP) was applied, followed by a single hand weeding at 30 DAT. The shortest plants (93.59 cm) were observed in the unweeded control (W_0). These results agree with the findings of Sadik et al. (2025) and Tasmin et al. (2019), indicating that plant height is largely controlled by genetic factors and is minimally affected by external interventions like weeding.

Total Number of Tillers per Hill

Weed management had a significant impact on the total number of tillers per hill (Figure 5). The highest number of tillers (19.47) was found in W_4, where pre-emergence herbicide Pendimethalin 33 EC (Panida) was applied, followed by one hand weeding at 30 DAT. The lowest count (14.18) occurred in the unweeded control (W_0). This suggests that effective weed management reduces competition for light, water, and nutrients, thereby promoting tiller production. In contrast, weeds in untreated plots compete with rice plants, limiting vegetative growth and tiller development. Similar patterns have been observed by Afroz et al. (2019) and Tasmin et al. (2019), who reported that integrated weed management significantly increases tiller numbers compared to untreated plots.

Number of Effective Tillers per Hill

Significant differences were also observed in the number of effective tillers per hill among weed management treatments (Figure 5). W_4 recorded the highest number of effective tillers (15.64), while the lowest (10.98) was found in W_0. The improved performance under W_4 is likely due to better weed suppression during the early and mid-tillering stages, which allows rice plants greater access to sunlight and nutrients, promoting productive tiller formation. Untreated plots, by contrast, experience heavy weed competition, reducing effective tiller numbers. These findings are consistent with Salam et al. (2022) and Tasmin et al. (2019), who demonstrated that combining herbicide application with manual weeding effectively controls weeds and enhances tillering and yield in Boro rice.

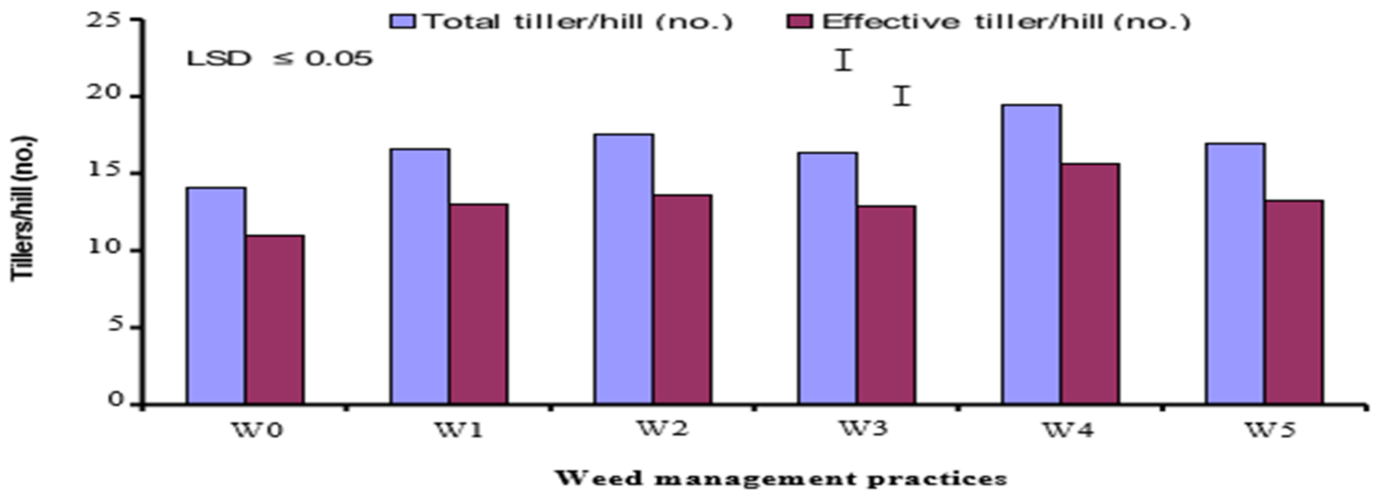

Figure 5. Effect of weed management practices on the number of tillers per hill.

Effect of Weeding on Growth and Yield Attributes of Boro Rice

Panicle Length

Panicle length was significantly affected by the different weed management practices (Table 3). The longest panicles (24.66 cm) were observed in W_4, where pre-emergence herbicide Pendimethalin 33 EC (Panida) was applied followed by a single hand weeding at 30 DAT. This was statistically similar to W_3, which involved Pendimethalin application alone. The shortest panicles (22.99 cm) occurred in W_5, where Pendimethalin was combined with the post-emergence herbicide Pyrazosulfuron-ethyl 10WP. The increased panicle length in W_4 is likely due to more effective weed suppression during key growth stages, allowing plants better access to water and nutrients, which promotes spikelet development and panicle elongation. These findings are in line with Farzana et al. (2021), who noted that timely weed control during the reproductive phase enhances panicle growth.

Number of Grains per Panicle

The number of grains per panicle was significantly influenced by weed management practices (Table 3). W_4 recorded the highest grain count per panicle (150.90), followed closely by W_3, while the unweeded control (W_0) had the lowest value (119.90). The higher grain numbers in W_4 can be attributed to healthier plant growth and reduced competition from weeds, which improved nutrient and water availability and facilitated assimilate translocation to developing panicles. In contrast, W_0 suffered from competition, limiting nutrient uptake and grain filling. These results are consistent with Siddika et al. (2024) and Islam et al. (2024), who found that proper weed management increases grains per panicle in rice.

Number of Sterile Spikelets per Panicle

Weed management also significantly affected spikelet sterility (Table 3). The highest number of sterile spikelets (25.11) was recorded in W_0, where intense competition from weeds reduced the availability of nutrients, water, and light, negatively impacting physiological processes and assimilate translocation. This agrees with Hoque et al. (2011), who reported higher spikelet sterility in unweeded plots. The lowest sterility (20.00) occurred in W_1, where Pyrazosulfuron-ethyl 10WP was applied alone. Early post-emergence herbicide application effectively suppressed weeds during critical reproductive stages, improving pollination and grain filling.

1000-Grain Weight

No significant differences were found in 1000-grain weight across the weed management treatments (Table 3). Numerically, the heaviest grains (22.86 g) were recorded in W_2, where Pyrazosulfuron-ethyl 10WP was applied followed by hand weeding at 30 DAT, while the lowest weight (22.02 g) occurred in W_4. This stability aligns with the understanding that grain weight is largely genetically determined and relatively insensitive to weed management. Similar observations have been reported by Mia et al. (2023) and Dzomeku et al. (2016).

Grain Yield

Grain yield was significantly influenced by weed management practices (Figure 6). The highest yield (6.49 t ha⁻¹) was achieved in W_5, where Pendimethalin was combined with Pyrazosulfuron-ethyl 10WP, which was statistically similar to W_2 (6.17 t ha⁻¹). The lowest yield (4.11 t ha⁻¹) was observed in the unweeded control (W_0). Higher yields in W_5 and W_2 are likely due to effective and sustained weed suppression, which enhanced plant vigor, tillering, and panicle formation. In contrast, uncontrolled weed growth in W_0 limited nutrient uptake and photosynthetic efficiency. These results support the findings of Chowdhury et al. (1995), who reported that weed-free conditions maximize rice yields by minimizing competition for essential resources.

Straw Yield

Straw yield did not differ significantly among the treatments (Figure 6). Numerically, the highest straw yield (7.58 t ha⁻¹) was recorded in W_5, followed by W_2 (7.57 t ha⁻¹) and W_1 (7.41 t ha⁻¹), while the lowest (7.00 t ha⁻¹) occurred in W_3. Slightly higher straw yields in W_5 and W_2 are likely due to better weed suppression, which allowed more vigorous vegetative growth and biomass accumulation. Weed-free conditions promote nutrient assimilation and vegetative development, contributing to increased straw production.

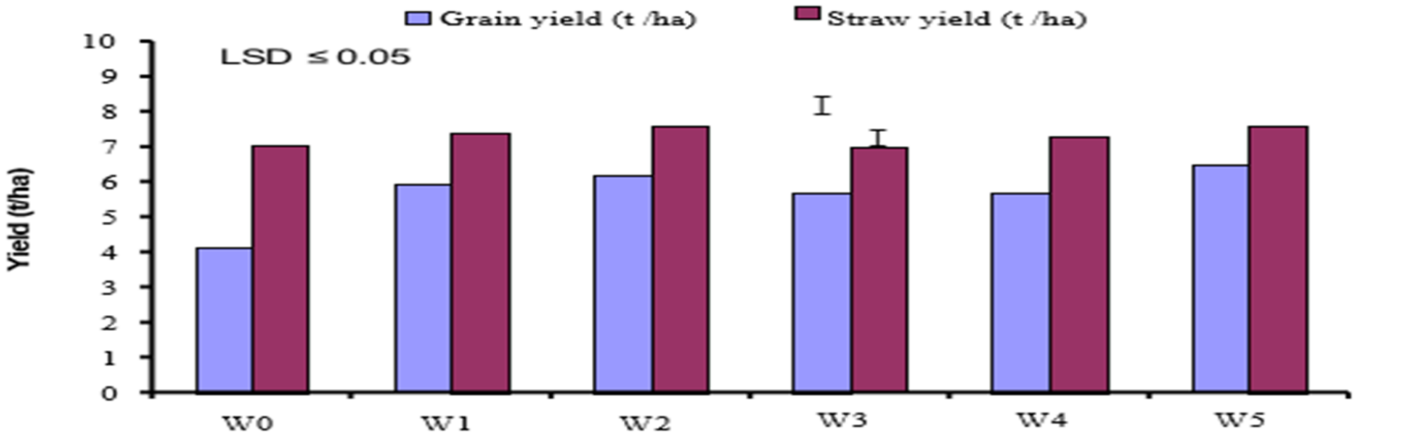

Figure 6: Harvest Index.

Effect of Weed Management on Harvest Index

Harvest index (HI) was significantly influenced by the different weed management treatments (Table 3). The highest HI (46.17%) was recorded in W_5, where pre-emergence herbicide Pendimethalin 33 EC was combined with early post-emergence herbicide Pyrazosulfuron-ethyl 10WP (Panida + Manage). This was statistically comparable to W_2 (44.83%), W_3 (44.72%), and W_1 (44.62%), which involved Pyrazosulfuron-ethyl 10WP with one hand weeding, Pendimethalin 33 EC alone, and Pyrazosulfuron-ethyl 10WP alone, respectively.

The lowest HI (36.96%) was observed in the unweeded control (W_0). The higher harvest indices in W_1, W_2, W_3, and W_5 are likely due to effective weed suppression, which reduced competition for essential resources such as nutrients, water, and light. This allowed the plants to direct more assimilates toward grain formation rather than vegetative growth, increasing the proportion of grain yield relative to total aboveground biomass. Conversely, W_0 experienced intense competition from weeds, which limited grain development and resulted in a lower harvest index.

These results suggest that integrated herbicide-based weed management strategies can significantly improve both grain yield and harvest index in Boro rice.

Table 3: Effect of weed management practices on the performance of *Boro* rice

Weed management Practices	Plant height (cm)	Length of panicle (cm)	Grains panicle^{-1} (no.)	Sterile spikelets panicle^{-1} (no.)	1000-grain weight (g)	Harvest index (%)
W_0	93.59	23.23cd*	119.90f	25.11a	22.59	36.96c
W_1	95.49	23.52c	132.62d	20.00b	22.27	44.62ab
W_2	95.54	23.96b	137.73c	20.67b	22.86	44.83ab
W_3	94.92	24.39a	144.61b	21.44b	22.43	44.72ab
W_4	95.20	24.66a	150.90a	20.67b	22.02	43.66b
W_5	95.24	22.99d	128.83b	22.00b	22.92	46.17a
CV (%)	2.04	1.42	2.66	10.53	6.23	5.32
Level of significance	NS	**	**	**	NS	**

Interaction Effect of Water Management and Weed Control on Growth, Yield, and Yield Attributes of Boro Rice

Plant Height

Plant height was not significantly affected by the combined influence of water and weed management (Table 4). Numerically, the tallest plants (96.40 cm) were recorded under M_2W_5 (AWD × Pendimethalin 33 EC + Pyrazosulfuron-ethyl 10WP), while the shortest (92.93 cm) occurred in M_2W_0 (AWD × no weeding). These observations are consistent with previous studies (Pramanik et al., 2015; Ghosh et al., 2016), which reported that plant height is largely genetically controlled and less responsive to external management practices.

Total and Effective Tillers per Hill

The total number of tillers per hill was significantly influenced by the interaction between water and weed management. The maximum number of tillers (21.40) was found under M_3W_4 (SRI × Pendimethalin 33 EC + hand weeding), whereas the minimum (13.53) occurred in M_1W_0 (Farmers' practice × no weeding). The SRI method, with wider spacing, younger seedlings, and intermittent irrigation, likely promoted better root growth and nutrient uptake. Coupled with timely weed control, this enhanced tiller production.

Effective tillers per hill also varied significantly. The highest count (17.87) was observed in M_3W_4, while the lowest (10.27) occurred in M_1W_3 (Farmers' practice × Pendimethalin alone). This indicates that the combination of effective weed suppression and optimal water management supports productive tiller survival and panicle formation.

Panicle Length

Panicle length was significantly affected by the interaction of water and weed management (Table 4). The longest panicles (25.20 cm) were recorded in M_1W_3 (Farmers' practice × Pendimethalin alone), and the shortest (21.73 cm) occurred under M_2W_5 (AWD × Pendimethalin + Pyrazosulfuron-ethyl). Some combinations, such as AWD with pre- and post-emergence herbicides and SRI with pre-emergence herbicide plus hand weeding, produced intermediate panicle lengths (24.63–24.90 cm) that were statistically similar. These results suggest that integrating suitable water and weed management practices can optimize panicle elongation.

Number of Grains per Panicle

The number of grains per panicle was significantly influenced by treatment interactions. The highest grain count (157.32) was observed in M_2W_4 (AWD × Pendimethalin + hand weeding), followed by M_3W_4 (SRI × Pendimethalin + hand weeding) with 149.70 grains per panicle. Effective water and weed management reduced competition, promoting vigorous growth and enhanced assimilate translocation to the developing panicles. The lowest grain count (113.30) occurred in M_2W_5, likely due to suboptimal growth conditions caused by weed competition.

Number of Sterile Spikelets per Panicle

Sterile spikelets also showed significant variation among interaction treatments. Maximum sterility (26.67) was recorded in M_3W_1 (SRI × Pyrazosulfuron-ethyl alone), while the minimum (14.00) occurred in M_1W_1 (Farmers' practice × Pyrazosulfuron-ethyl alone). These results indicate that proper weed control reduces competition and improves nutrient allocation, enhancing spikelet fertility.

1000-Grain Weight

The interaction of water and weed management did not significantly affect 1000-grain weight. Numerically, the heaviest grains (23.23 g) were recorded in M_1W_4 (Farmers' practice × Pendimethalin + hand weeding), while the lightest (19.83 g) occurred in M_2W_4. This indicates that grain weight is mainly determined by genetic factors and is less sensitive to environmental management practices.

Grain Yield

Grain yield was significantly influenced by the interaction of treatments. The highest yield (6.61 t ha^{-1}) was observed under M_3W_5 (SRI × Pendimethalin + Pyrazosulfuron-ethyl), which was statistically similar to M_3W_2 (SRI × Pyrazosulfuron-ethyl + hand weeding). The lowest yield (3.87 t ha^{-1}) occurred under M_1W_0 (Farmers' practice × no weeding), likely due to intense weed competition and reduced effective tillers. These results underscore the importance of integrating optimal water management with effective weed control to maximize Boro rice yield.

Straw Yield

Straw yield differed significantly among interaction treatments. The highest yield (8.41 t ha^{-1}) was recorded in M_3W_1, while the lowest (6.10 t ha^{-1}) occurred in M_1W_0. Greater biomass accumulation under effective water and weed management likely contributed to increased straw production.

Harvest Index (HI)

The interaction between water and weed management did not significantly affect harvest index. Numerically, the highest HI (46.61%) was observed in M_2W_5, and the lowest (35.60%) in M_3W_0 (SRI × no weeding). These results suggest that combining proper water and weed management improves assimilate partitioning toward grain, resulting in higher harvest indices.

Table 4: Effect of interaction of methods of water management and weed management practices on the yield of *boro* rice

Methods of water management × Weeding	Plant height (cm)	Total tillers hill^{-1} (no.)	Effective tillers hill^{-1} (no.)	Length of panicle (cm)	Grains panicle^{-1} (no.)	Sterile spikelets panicle^{-1} (no.)	1000-grain weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
M_1W_0	93.83	13.53h	10.33g	24.63abc	124.33hi	25abc	22.33	3.87e	6.10f	38.80
M_1W_1	95.83	14.73fg	11.53ef	23.43e	127.00gh	14f	22.30	5.80abc	7.08cde	44.93
M_1W_2	95.87	15.87ef	12.33de	24.27bc	141.12de	19de	23.00	6.09abc	7.60ad	44.35
M_1W_3	95.87	13.73gh	10.27g	25.20a	152.73ab	19.67de	22.40	5.77abc	7.123cde	44.70
M_1W_4	95.23	16.73cde	12.60de	24.43bc	145.70cd	21cde	23.23	6.54a	7.51ae	46.46
M_1W_5	95.23	15.73ef	11.60ef	24.37bc	148.07bc	25abc	22.90	6.27ab	6.83def	47.83
M_2W_0	92.93	15.40f	11.87e	22.47f	119.33ij	28.33a	22.77	4.18de	7.30be	36.49
M_2W_1	96.07	15.13f	12.07de	23.50de	132.30fg	19.33de	22.37	5.77abc	6.75 def	46.06
M_2W_2	95.83	16.67de	13.00d	23.53de	133.33fg	21cde	22.80	5.94abc	7.21be	45.06
M_2W_3	95.97	17.80cd	14.33c	24.37bc	146.30bcd	21.33cde	22.53	5.26bcd	6.54ef	44.46
M_2W_4	95.93	20.27b	16.47b	24.90ab	157.32a	18.00e	19.83	5.09cd	7.13cde	41.72
M_2W_5	96.40	17.93c	14.13c	21.73g	113.30j	19.67de	22.97	6.60a	8.20ab	46.61
M_3W_0	94.00	13.60gh	10.73fg	22.60f	116.10j	22.00cde	22.66	4.29de	7.77ad	35.60
M_3W_1	94.57	20.20b	15.67b	23.63de	138.30ef	26.67ab	22.13	6.32ab	8.41a	42.88
M_3W_2	94.93	20.23b	15.53b	24.07cd	138.72ef	22.00cde	22.76	6.49a	7.90abc	45.08
M_3W_3	92.93	17.80cd	14.27c	23.60de	134.70ef	23.33bcd	22.37	6.02abc	7.36be	45.02
M_3W_4	94.43	21.40a	17.87a	24.63abc	149.70abc	23.00bcd	23.00	5.43abc	7.26be	42.79
M_3W_5	94.10	17.47cd	14.20c	22.87f	125.00hi	21.33cde	22.90	6.61a	7.73ad	46.08
CV (%)	2.04	3.85	4.33	1.42	2.66	10.53	6.23	10.50	7.23	5.32
Level of significance	NS	* *	**	**	**	**	NS	*	**	NS

Values in the same column that share the same letter or have no letters are not significantly different, whereas values with different letters are considered significantly different according to DMRT. ** indicates significance at the 1% probability level, * indicates significance at the 5% probability level, and NS indicates not significant.

Conclusion and Recommendation

The findings of this study revealed that the System of Rice Intensification (SRI) consistently promoted superior growth performance and higher grain yields in Boro rice compared to conventional farmers' practices and alternate wetting and drying (AWD) irrigation methods. Effective weed management also played a critical role in enhancing grain production, emphasizing the need to minimize weed competition throughout the crop cycle.

Among the weed control measures evaluated, the integrated use of the pre-emergence herbicide Pendimethalin 33 EC combined with the early post-emergence herbicide Pyrazosulfuron-ethyl 10WP was the most effective. This combination efficiently suppressed weed growth, facilitated better nutrient uptake, supported panicle development, and ensured improved grain filling, resulting in higher yield.

Based on these results, it is recommended that Boro rice cultivation adopt SRI water management along with integrated herbicide application (Pendimethalin 33 EC pre-emergence and Pyrazosulfuron-ethyl 10WP post-emergence) to achieve optimal weed control and maximize productivity. However, additional trials across diverse agro-ecological regions are suggested to validate the consistency, adaptability, and broader applicability of this approach.

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