Research Article

Effect of Weed Management Strategies on the Growth, Yield, and Biochemical Quality of *Boro* Rice (BRRI dhan 102)

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Abstract | Weed infestation is a major constraint in achieving the potential yield of *boro* rice in Bangladesh. Field experiments were conducted during the December 2023 to May 2024 *boro* season to evaluate the efficacy of different weed management strategies on the performance of BRRI dhan 102. Six treatments were implemented: T_0 (Control), T_1 (Hand weeding twice), T_2 (Pre-emergence: Pyrazosulfuron-ethyl 10% WP), T_3 (Early post-emergence: Bensulfuron methyl 4% + Acetachlor 14% WP), T_4 (post-emergence: 2,4-D Amine 72% SL), and T_5 (Integrated: One hand weeding + Pyrazosulfuron-ethyl). The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Results demonstrated that weed management practices significantly ($p<0.05$) influenced all measured parameters. The integrated treatment (T_5) and two weeding (T_1) consistently performed superiorly. T_1 produced the highest grain yield (9.22 t/ha), straw yield (8.36 t/ha), harvest index (52.54%), and panicle length (28.86 cm), alongside the lowest weed biomass (333.07 kg/ha) and weed density (5.60 no/m^2). Notably, T_1 also resulted in the highest protein (1.69 mg/ml) and antioxidant (8.70 mg/ml) content in grains. Among herbicidal treatments, the integrated approach (T_5) was most effective, demonstrating results statistically on par with T_1 for many agronomic traits and significantly better than herbicide-only applications (T_2, T_3, T_4). The control (T_0) exhibited the poorest performance across all parameters. This study concludes that while two-time hand weeding is most effective but costly, the integration of a pre-emergence herbicide with a single hand weeding is a highly efficient strategy for optimizing the productivity and quality of BRRI dhan 102.

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Introduction

Rice (*Oryza sativa* L.) is the staple food for over 163 million people of Bangladesh and is pivotal to the nation's agricultural economy and food security (Shelley *et al*., 2016). The *boro* season, characterized by irrigated cultivation during the dry winter months (November to May), contributes more than 55% of the country's total rice production, making it the most crucial cropping season for ensuring national food security (Mainuddin *et al*., 2021; BBS, 2023). However, achieving high yields is persistently challenged by intense weed competition, which can cause significant yield losses ranging from 30% to 50%, and in severe cases, even complete crop failure if not managed properly (Siddika *et al*., 2024; Mahajan *et al*., 2014). In Bangladesh, rice cultivation occupies about 78.42% of the total cultivated land. Among the three rice-growing seasons, *boro* rice covers the largest area, accounting for approximately 41.37% of the total rice-growing area (BBS, 2021). Agriculture contributes around 13.47% to the country's gross domestic product (GDP) (BBS, 2021). According to the Food and Agriculture Organization, Bangladesh produced about 37.8 million tonnes of rice in 2021 (FAO, 2022).

Rice cultivation in Bangladesh flourishes because of the country's mostly low-lying landscape, warm and humid climate, and plentiful monsoon rainfall (Imran *et al*., 2025). Rice is grown throughout the year in three major seasons *aus* (summer), *aman* (monsoon), and *boro* (winter) which together form the backbone of the nation's rice production system (Jesia *et al*., 2025). The complex and dynamic weed flora in *boro* rice ecosystems, comprising both grassy weeds like *Echinochloa crus-galli* and *Leptochloa chinensis*, and broadleaf weeds such as *Monochoria vaginalis* and *Ludwigia octovalvis*, competes aggressively with the crop for essential resources light, nutrients, and water particularly during the critical early growth stages (Juraimi *et al*., 2013; Nazir *et al*., 2022). Traditional manual weeding, while highly effective, is becoming increasingly labor-intensive, costly, and often impractical due to rising wage rates and a shrinking agricultural labor force, especially during peak seasons (Rahman and Al-Amin, 2016; Kiron and Islam, 2023).

Consequently, herbicides have become an integral and dominant component of modern rice cultivation for their efficiency, timeliness, and cost-effectiveness (Asha *et al*., 2025; Kumawat *et al*., 2018). Although herbicides can be highly effective, relying on them alone raises several serious concerns. These include the risk of phytotoxic effects that may hinder crop growth and development (Langaro *et al*., 2016; Ma *et al*., 2021), adverse impacts on the environment and aquatic ecosystems (Yu *et al*., 2017), and the rapid emergence of herbicide-resistant weed biotypes, which ultimately threatens the long-term sustainability of this weed management approach (Norsworthy *et al*., 2013; Löbmann, 2021). Furthermore, different herbicides applied at various growth stages (pre, early post, and post-emergence) can have divergent effects on crop physiology and ultimate yield components (Islam *et al*., 2024; Mia *et al*., 2024).

Therefore, Integrated Weed Management (IWM) which strategically combines cultural, mechanical, and chemical control methods is widely promoted as a sustainable and cost-effective approach (Islam *et al*., 2025; Rao, 2011; Mia and Salam, 2024). The primary goal of IWM is to achieve effective and long-lasting weed control while reducing adverse effects on crops, the environment, and human health (Hossain *et al*., 2024). By capitalizing on the strengths of individual practices, IWM enhances overall efficiency; for example, the use of a pre-emergence herbicide can suppress early weed emergence, thereby lower weed density and biomass and easing the burden on subsequent manual or post-emergence control measures (Salam *et al*., 2022; Tasmin *et al*., 2019). This study was designed to evaluate the impact of various herbicide-based weed management strategies, including an integrated approach, on the growth, yield, and biochemical quality of the high-yielding *boro* variety BRRI dhan 102, to provide farmers with a practical and sustainable recommendation.

Materials and Methods

Experimental site and design

The field experiment was conducted at the research farm of the Department of Agriculture, Noakhali Science and Technology University, during the *boro* season of 2023-2024. The site is located in the Young Meghna Estuarine Floodplain (AEZ-18). The soil was sandy loam with a pH of 8.0, low organic matter (1.15%), and low total nitrogen (0.06%). The experiment was arranged in a Randomized Complete Block Design (RCBD) with three replications. Six weed management treatments were assigned to individual plots of 10 m^2 (4 m × 2.5 m) size.

Experimental treatments

The experiment was conducted with these treatments T_0: Control (No weeding), T_1: Hand Weeding (2 hand weeding at 20 and 40 Days After Transplanting), T_2: Pre-emergence herbicide (Pyrazosulfuron-ethyl 10% WP @ 30 g/ha at 3 DAT), T_3: Early post-emergence herbicide (Bensulfuron methyl 4% + Acetachlor 14% WP @ 750 g/ha at 15 DAT), T_4: Post-emergence herbicide (2,4-D Amine 72% SL @ 1.5 kg/ha at 30 DAT), T_5: Integrated (Pyrazosulfuron-ethyl 10% WP @ 30 g/ha at 3 DAT + One hand weeding at 35 DAT).

Fertilizer application

The experimental field was fertilized with urea, triple superphosphate (TSP), muriate of potash (MOP), gypsum, and zinc sulphate to ensure adequate supply of nitrogen, phosphorus, potassium, sulfur, and zinc. Zinc sulphate (10 kg ha^{-1}), gypsum (60 kg ha^{-1}), MOP (80 kg ha^{-1}), and TSP (120 kg ha^{-1}) were applied as basal doses at the time of transplanting. Urea was applied at a rate of 260 kg ha^{-1} in three equal split applications as top dressing at 15, 30, and 45 days after transplanting (DAT).

Crop cultivation

The high-yielding variety BRRI dhan 102 was used. Forty days old seedlings were transplanted on January 10, 2024, with a spacing of 25 cm × 15 cm. Fertilizers were applied as per recommended doses.

Sampling, harvesting, threshing, cleaning, and processing

Harvesting was determined when 90 % of the grains exhibited a golden yellow color. To collect Data, there was a selection of ten hills (Without boundary hills) in each unit plot randomly, the seedlings of which were uprooted before harvesting. A (1m × 1m) harvest plot was also selected from the center of each unit plot after sampling. After individual wrapping and marking, the harvested crop from each unit area was transported to the threshing floor. Crop was removed and threshed on a pedal thrasher. The grains were then sun-dried to 14% moisture and cleaned. The straws were also sun-dried. Finally, grain and straw in each plot were recorded and converted to t/ha.

Data collection

Data on growth, yield, yield components, and weed parameters were recorded following standard procedures. Protein and antioxidant content in grains were analyzed using a spectrophotometer via the Bradford and DPPH methods, respectively.

Table 1: *Effect of weed management practices on growth parameters of BRRI dhan 102*

Treatment	Plant height (cm)	No. of tillers	Effective tillers	LAI (cm^2)	Chlorophyll (μmol m^{-2})
T_0	84.04a	8.74 a	7.01 a	4.10a	42.42 b
T_1	100.97d	17.04d	12.86 d	6.12c	53.60 a
T_2	94.54 c	14.48bcd	10.61 bc	4.78ab	50.08 ab
T_3	90.93 b	13.16bc	9.70 b	4.45a	47.67 ab
T_4	87.20a	11.98b	8.76 ab	4.32 a	45.05 ab
T_5	97.29c	15.81cd	11.77 cd	5.43bc	51.38 a
CV (%)	1.85	6.44	7.15	5.37	3.82
LSD (0.05)	2.17	1.83	1.27	0.61	5.66
Significance	*	*	*	*	*

Means within a column followed by the same letter are not significantly different at p<0.05 by LSD test. * = Significant at p<0.01.

Statistical analysis

All collected data were subjected to Analysis of Variance (ANOVA) using Statistix 10 software. The significance of mean differences between treatments was assessed using the Least Significant Difference (LSD) test at a 5% probability level (Gomez and Gomez, 1984). Furthermore, correlation analysis between all parameters was conducted, and a path analysis was performed to determine the direct and indirect effects of key yield components on final grain yield using RStudio (R Core Team, 2022).

Results and Discussion

Growth parameters

Weed management practices exerted a highly significant ($p<0.01$) influence on plant growth (Table 1). At maturity, the tallest plants (100.97 cm) were recorded in T_1, which was statistically on par with T_5 (97.29 cm). The control (T_0) resulted in the shortest plants (84.04 cm). A similar trend was observed for the number of tillers and Leaf Area Index (LAI). T_1 produced the highest number of effective tillers (12.86) and LAI at 8 WAT (6.12 cm^2), followed closely by T_5. The superior growth in T_1 and T_5 is attributed to effective weed control, which reduced competition

Table 2: *Effect of weed management practices on yield components of BRRI dhan 102.*

Treatment	Panicle Wt. (g)	Panicle Length (cm)	Fertile Grains/ Panicle	Sterile Grains/ Panicle	1000- Grain Wt. (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest Index (%)
T_0	2.13 a	19.15 e	128.57 e	20.63 a	18.43 e	3.75 e	4.07 d	47.92 b
T_1	3.91 e	28.86 a	155.77 a	9.72 d	25.17 a	9.22 a	8.36 a	52.54 a
T_2	3.07 c	24.95 bc	147.67 bc	14.33 bc	22.03 bc	6.61 bc	6.45 abc	50.60 ab
T_3	2.70 bc	22.58 cd	142.89 c	15.33 b	20.67 cd	5.81 cd	5.95 bcd	49.39 ab
T_4	2.49 ab	21.12 de	136.00 d	17.13 ab	19.02 de	4.95 de	5.27 cd	48.55 ab
T_5	3.49 d	26.07 ab	149.66 ab	10.53 cd	23.18 b	7.78 ab	7.35 ab	51.46 ab
CV (%)	3.92	7.57	1.49	7.30	5.16	9.35	4.91	2.48
LSD (0.05)	0.25	2.17	4.27	2.59	1.29	1.02	1.28	2.91
Significance	*	*	*	*	*	*	*	*

*Means within a column followed by the same letter are not significantly different at p<0.05 by LSD test. * = Significant at p<0.01.*

for light, nutrients, and water, allowing for better resource utilization and vegetative development (Adhikari *et al*., 2018; Rahman *et al*., 2025; Kolo *et al*., 2021). The superiority of hand weeding (T_1) aligns with findings from Nazir *et al*. (2022), confirming that manual removal provides the most thorough and non-phytotoxic weed control.

Yield and yield components

Weed management practices exerted a highly significant (p<0.01) influence on all yield and yield contributing parameters of BRRI dhan 102 (Table 2). Effective weed control resulted in substantial improvements across all measured components.

The treatment comprising two hand weedings (T_1) consistently produced the superior results, recording the highest panicle dry weight (3.91 g), the longest panicles (28.86 cm), the maximum number of fertile grains per panicle (155.77), and the greatest 1000-grain weight (25.17 g). This synergistic enhancement of yield attributes culminated in the significantly highest grain yield (9.22 t ha^{-1}) and straw yield (8.36 t ha^{-1}) under T_1, which also achieved the peak harvest index of 52.54%.

The integrated weed management treatment (T_5), which combined a pre-emergence herbicide with a single hand weeding, proved to be the second most effective option. It performed comparably to T1 in terms of fertile grains per panicle, grain yield, and straw yield, highlighting its strong effectiveness; this advantage likely arises because early weed suppression by the pre-emergence herbicide reduces initial weed pressure, making the later manual weeding more efficient and less labor-intensive (Mou *et al*., 2017; Rao, 2011). This strategy offers a balanced solution, mitigating the high cost and labor scarcity associated with T_1 (Rahman and Al-Amin, 2016) while minimizing the risks of sole herbicide reliance.

In contrast, the unweeded control plot (T_0) consistently registered the lowest values for all yield components and consequently the poorest grain (3.75 t ha^{-1}) and straw (4.07 t ha^{-1}) yields. Among the herbicidal treatments, the pre-emergence application (T_2) generally outperformed the early post-emergence (T_3) and post-emergence (T_4) applications.

The marked increase in yield components under effective weed management regimes (T_1 and T_5) can be attributed to a significant reduction in weed competition during the critical growth stages of panicle initiation and grain filling. This minimized competition allowed for better resource allocation, leading to improved panicle formation, enhanced grain filling efficiency, and ultimately, a higher economic yield (Jehangir *et al*., 2024; Rana and Rana, 2016).

The marked increase in yield components under T_1 and T_5 is a direct result of the reduced weed competition during panicle initiation and grain filling, allowing for better resource allocation and grain filling efficiency (Jehangir *et al*., 2024; Hossen *et al*., 2021).

Weed control efficiency

Weed management efficacy was profoundly significant (p<0.01) across all weed-related parameters (Table 3). T_1 was most effective, recording the lowest weed species count (3.90 no/m^2), weed density (5.60 no/m^2), weed dry weight (8.33 g/m^2), and total weed

Table 3: *Effect of weed management practices on weed parameters*

Treatment	Weed species (no/m²)	Weed density (no/m²)	Weed dry weight (g/m²)	Weed biomass (kg/ha)
T_0	8.64 a	12.17 a	24.61 a	984.53 a
T_1	3.90 c	5.60 c	8.33 d	333.07 d
T_2	4.83 bc	6.79 bc	14.47 bc	578.67 bc
T_3	5.46 bc	7.31 bc	17.05 b	682.13 b
T_4	6.47 b	8.83 b	21.92 a	876.67 a
T_5	4.30 c	6.22 c	11.85 cd	473.87 cd
CV (%)	8.51	13.22	7.81	7.81
LSD (0.05)	1.36	1.42	2.66	106.40
Significance	*	*	*	*

*Means within a column followed by the same letter are not significantly different at $p<0.05$ by LSD test. * = Significant at $p<0.01$.*

biomass (333.07 kg/ha). The integrated treatment (T_5) was the next most effective, performing significantly better than the sole herbicide applications (T_2, T_3, T_4). The uncontrolled plot (T_0) had the highest weed infestation. The superior performance of T_1 and T_5 highlights the advantage of physical removal and the synergistic effect of combining chemical and mechanical control, which targets weeds at multiple growth stages and reduces the chance of escape (Rao *et al*., 2015; Norsworthy *et al*., 2013).

Table 4: *Effect of weed management practice*

Treatment	Protein (mg/ml)	Antioxidant (mg/ml)
T_0	1.06 c	5.69 b
T_1	1.69 a	8.70 a
T_2	1.37 abc	7.43 ab
T_3	1.27 bc	6.98 ab
T_4	1.14 bc	6.04 b
T_5	1.47 ab	7.84 ab
CV (%)	7.65	7.30
LSD (0.05)	0.25	1.59
Significance	*	*

Means within a column followed by the same letter are not significantly different at $p<0.05$ by LSD test. * = Significant at $p<0.01$.

Grain quality parameters

Weed management also significantly improved the biochemical quality of the rice grains (Table 4). The highest protein content (1.69 mg/ml) and antioxidant activity (8.70 mg/ml) were found in T_1, followed by T_5. The improvement in grain protein content and antioxidant activity under effective weed management suggests that reduced weed competition allowed the crop to utilize nutrients and photosynthates more efficiently. Consequently, treatments like T_1 and T_5 created a more favorable growth environment, leading not only to higher yield but also to better grain nutritional quality. Reduced weed competition likely lessened abiotic stress on the rice plants, allowing for better nutrient uptake and assimilation, which translates into improved grain quality (Singh *et al*., 2020). The results suggest that effective weed management is not only crucial for yield but also for enhancing the nutritional value of the harvest.

Statistical modeling of yield components and trait relationships

To move beyond treatment means and understand the fundamental relationships driving yield, a correlation analysis and path analysis were conducted. The correlation heatmap (Figure 1) provides a holistic view of the interrelationships among all measured parameters, revealing that effective weed management fosters a synergistic improvement across the entire crop system. A strong, positive correlation cluster is evident among desirable agronomic traits including plant height, tiller number, leaf area index, chlorophyll content, panicle traits, and ultimately grain and straw yield indicating that treatments which enhance vegetative growth simultaneously optimize yield components by reducing resource competition with weeds (Juraimi *et al*., 2013; Kolo *et al*., 2021). Furthermore, the positive associations between these yield parameters and enhanced grain protein and antioxidant content suggest that the conditions favoring high productivity, such as reduced abiotic stress and improved nutrient assimilation, also promote the accumulation of nutritional compounds in the grain (Singh *et al*., 2020; Salma *et al*., 2017). Conversely, all these beneficial traits exhibit strong negative correlations with weed density and biomass, visually confirming that weed infestation is the fundamental constraint limiting the expression of the crop's full genetic potential.

The path analysis (Figure 2) elucidates the precise mechanistic pathway through which weed control influences final grain yield, identifying that its effect is fully mediated by two key yield components. The model demonstrates that the number of fertile grains per panicle and the thousand-grain weight have identical, very strong direct positive effects on yield (path coefficients = 0.91, $p < 0.001$), with no significant

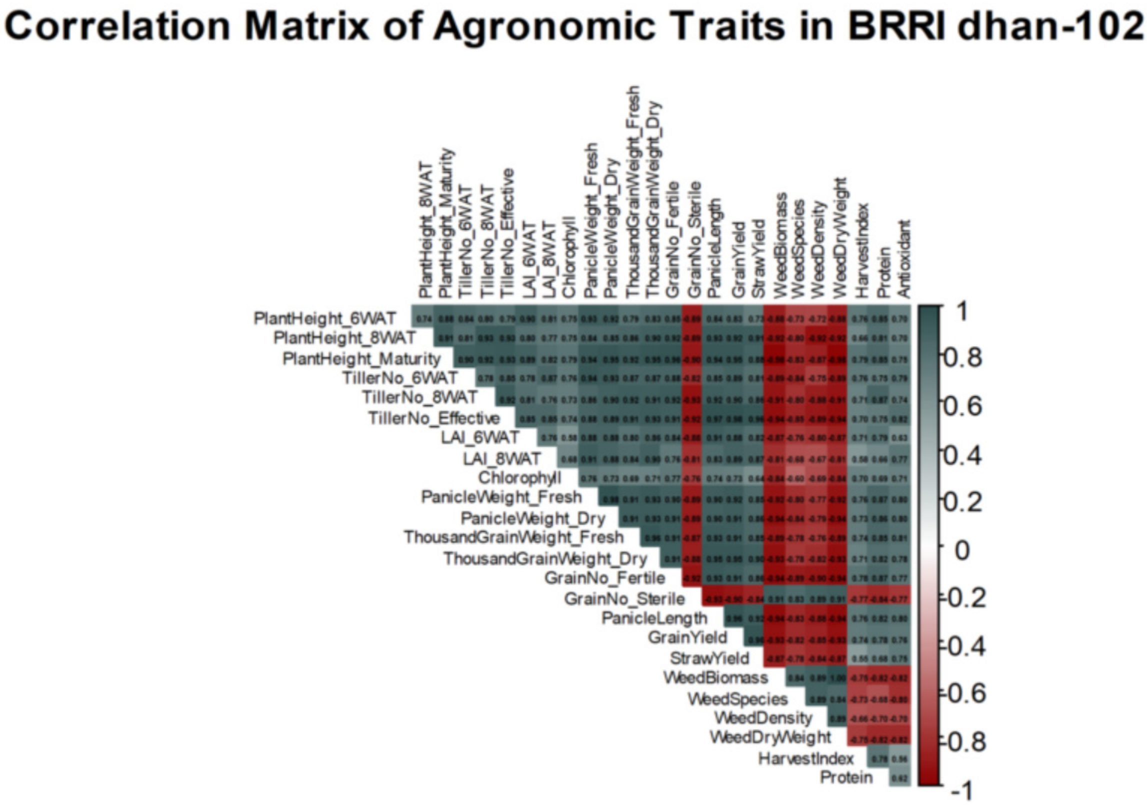

Figure 1: *Correlation matrix showing relationships between measured agronomic, yield, and weed parameters. Blue indicates positive correlations and red indicates negative correlations. Color intensity and size of the circle are proportional to the correlation coefficients.*

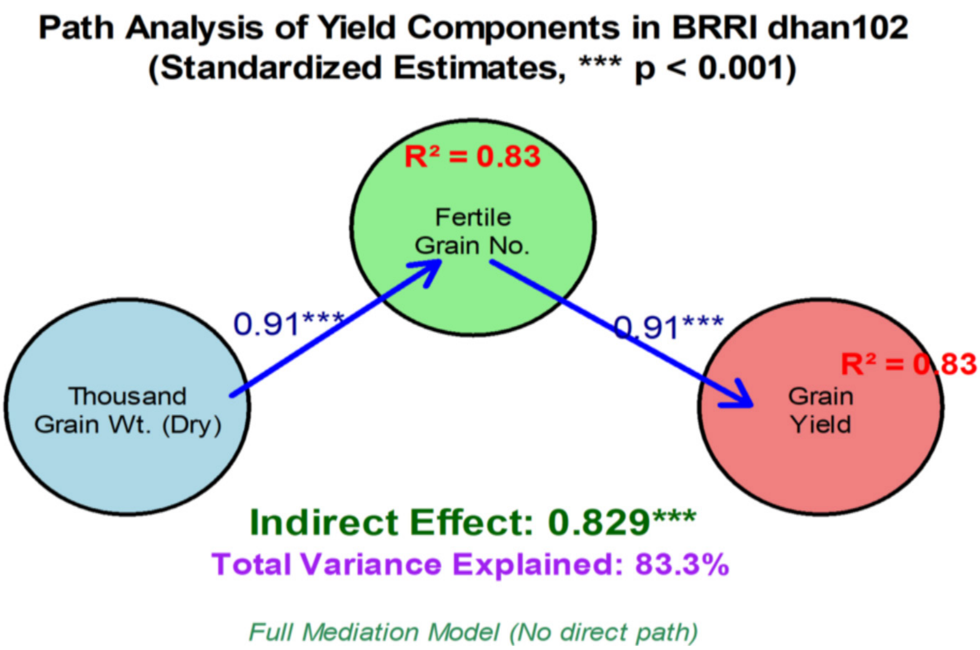

Figure 2: *Path analysis model showing the direct effects of yield components on grain yield. Standardized path coefficients are shown; *** denotes $p < 0.001$. The model demonstrates full mediation, with no direct effect of weed management on yield outside of these components.*

direct path from weed management itself. The path analysis clearly shows that weed control improves grain yield indirectly, mainly by increasing the number of fertile grains per panicle and enhancing thousand-grain weight, rather than acting directly on yield. This indicates that effective weed management supports yield formation by creating favorable conditions for better grain filling and panicle productivity. (Jehangir *et al*., 2024; Rana and Rana, 2018). This full mediation model, which explains 83% of the total variance in yield (R^2 = 0.83), statistically confirms that the highest-yielding treatments (T_1 and T_5) achieved their success by most effectively mitigating weed competition during the critical developmental stages of panicle formation and grain maturation, thereby maximizing these essential components.

Conclusions and Recommendations

This study concludes that weed management practices significantly influence the growth, yield, and quality of BRRI dhan 102. While two hand weddings were the most effective method, they are often economically and logistically challenging for farmers. The integrated weed management approach, which combines a pre-emergence application of Pyrazosulfuron-ethyl 10% WP with one hand weeding at 35 DAT, proved to be highly effective and sustainable. It provided excellent weed control, maximized yield and yield components, enhanced grain quality, and is likely to be more economically viable than multiple hand weeding. Therefore, for the profitable and sustainable cultivation of BRRI dhan 102, farmers are recommended to adopt this integrated weed management strategy.

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Novelty Statement

Using the recently developed *boro* rice variety BRRI dhan 102, this study offers the first comprehensive assessment of integrated weed management techniques under irrigated dry-season conditions. In contrast to single weed control techniques, it uniquely shows that the combination of a pre-emergence herbicide and hand weeding greatly improves growth, yield, and grain quality. By connecting weed control techniques with BRRI Dhan 102's productivity and quality characteristics, the study expands on existing knowledge. The results provide a workable, economical weed control solution that promotes sustainable rice production and Bangladesh's national food security.

Author's Contribution

Kawsar Hossen: Conceptualization, methodology, data curation, writing - original draft, supervision, project administration
Khandaker Bushra Rahman: data curation, writing - original draft
Md. Ismail Hossain: methodology, data curation
Mst. Sharmin Jahan Tithi: data curation, Formal analysis
Mahin Islam Talha: data curation, Conceptualization
Md. Liton Mia: Formal analysis, writing - review & editing
Sumaiya Akter: visualization, validation
Mohammed Nuruzzaman: Conceptualization, methodology, investigation, supervision
Md. Riyajuddin Karim: data curation, visualization
Tahmina Ferdous: data curation, Formal analysis, Funding Acquisition.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflicts of interest:
The authors declare no conflict of interest.

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