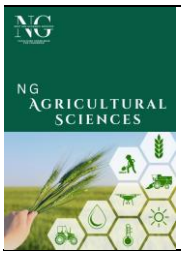

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Integrating Azolla with Reduced Nitrogen Fertilizer Improves Weed Suppression, Productivity and Profitability of Lowland Rice Systems

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ABSTRACT

Sustainable rice production in sub-Saharan Africa is increasingly threatened by declining soil fertility, high nitrogen fertilizer costs, and severe weed infestation, which together limit productivity and farmer profitability. While mineral nitrogen fertilizer remains essential for yield improvement, its inefficient use increases production costs and environmental risks. Biological alternatives such as *Azolla pinnata* offer potential for supplementing nitrogen while simultaneously suppressing weeds; however, quantitative field evidence on its capacity to reduce nitrogen requirements while improving agronomic and economic performance in East African irrigated rice systems remains limited. This study aimed to evaluate whether Azolla integration can reduce nitrogen fertilizer requirements while improving weed suppression, grain yield, and economic returns in lowland irrigated rice systems. A randomized complete block design with eight treatments and four replications was conducted over two cropping seasons. Results showed that Azolla application significantly reduced weed density by up to 84% compared to the unfertilized control. The combined application of Azolla with 40 kg N ha^{-1} produced the highest grain yield (3.7 t ha^{-1}), representing a 68% increase over the control, while also achieving the highest net economic benefit (981.5 USD ha^{-1}) and benefit–cost ratio (2.36). Higher nitrogen rates without Azolla did not produce additional economic advantages, highlighting the importance of integrated nutrient management. The study demonstrates that Azolla integration with moderate nitrogen rates improves nitrogen use efficiency, weed control, yield stability, and farm profitability. Adoption of Azolla with 40–80 kg N ha^{-1} is therefore recommended as a climate-smart and cost-effective nutrient management strategy for sustainable intensification of irrigated rice systems. This study was conducted over two seasons at a single irrigation scheme; therefore, further multi-location and long-term studies are needed to confirm the stability of these findings under diverse agroecological conditions.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a primary staple food for more than half of the global population and plays a crucial role in food and nutrition security in sub-Saharan Africa (Hashim et al., 2024; Valavanidis, 2026). In Tanzania, rice production in irrigated lowland ecosystems has increased in recent years due to growing population pressure and changing dietary preferences. Major irrigation schemes such as Kitere,

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Kilombero, and Mbarali contribute significantly to national production (Marzouk et al., 2024). However, the productivity of these systems remains below potential due to several biophysical and management constraints. Among the most important challenges are declining soil fertility, inefficient nitrogen (N) management, increasing weed pressure, and high labor costs associated with manual weed control. These constraints not only reduce yield and profitability but also threaten the long-term sustainability of smallholder rice production systems (Magubika et al., 2025; Mboyerwa et al., 2021)

Nitrogen fertilizer remains the most limiting nutrient in lowland rice production, yet its use efficiency is often low due to losses through volatilization, leaching, and denitrification. Consequently, farmers tend to apply higher fertilizer rates to compensate for these losses, increasing production costs and environmental risks (Liu et al., 2025; Zhu et al., 2025). At the same time, weed infestation remains one of the most serious biological constraints in irrigated rice systems, often causing substantial yield losses if not effectively managed. Conventional weed management through hand weeding is labor-intensive and costly, while reliance on herbicides raises concerns related to environmental safety and affordability for smallholder farmers (Islam et al., 2024a; Raza et al., 2025). These challenges highlight the urgent need for integrated nutrient and weed management strategies that can simultaneously improve nitrogen use efficiency, suppress weeds, and reduce production costs in a sustainable manner (Mboyerwa et al., 2022).

Nature-based solutions such as Azolla, a free-floating aquatic fern with a symbiotic relationship with the nitrogen-fixing cyanobacterium Anabaena azollae, have received increasing attention as a sustainable option for rice intensification (Marzouk et al., 2023). Azolla can fix substantial amounts of atmospheric nitrogen and rapidly produce biomass that contributes to soil fertility improvement and nutrient cycling (Pandey et al., 2025). In addition to its fertilization role, Azolla forms a dense mat on the water surface that can suppress weed emergence by limiting light penetration, thereby reducing weed competition during critical crop growth stages. Previous studies have also shown that Azolla can improve soil organic matter, enhance nutrient availability, reduce water evaporation, and contribute to climate-smart agricultural practices (Xu et al., 2024; Yang et al., 2025).

Despite these potential benefits, the integration of Azolla with reduced nitrogen fertilizer rates as a combined strategy for improving agronomic efficiency and weed management remains insufficiently studied under African conditions, particularly in Tanzania (Marzouk et al., 2023; Yang et al., 2021). Most previous studies have focused primarily on the nitrogen contribution of Azolla or its effects on rice yield, with limited attention given to its simultaneous role in reducing mineral nitrogen requirements while improving weed suppression and overall agronomic performance. Furthermore, there is limited empirical evidence quantifying how Azolla integration can optimize nitrogen inputs while maintaining productivity under farmer-managed irrigation schemes. This represents an important knowledge gap that limits the development of practical recommendations for sustainable rice intensification in the region (Chaudhary et al., 2025; Korsa et al., 2024).

Addressing this gap is particularly important for smallholder farmers in irrigation schemes such as Kitere, where declining soil fertility, rising fertilizer costs, and labor shortages continue to constrain productivity. Identifying integrated management options that reduce dependence on mineral fertilizers while improving weed control and crop performance could significantly improve the sustainability and resilience of these systems. Integrating Azolla with reduced nitrogen fertilizer may provide such an opportunity by offering a low-cost and environmentally friendly approach to optimize nutrient management and improve agronomic efficiency (Seleiman et al., 2022) .

Therefore, this study aimed to evaluate the effects of integrating Azolla with reduced nitrogen fertilizer rates on weed suppression, nitrogen use efficiency, and agronomic performance of irrigated lowland rice in Kitere Irrigation Scheme, Tanzania. By simultaneously examining nutrient management and weed dynamics, this study provides new evidence on the potential of Azolla as a multifunctional component of sustainable rice production systems. The findings are expected to contribute to the development of integrated soil fertility and weed management strategies, support climate-smart agriculture initiatives, and provide practical recommendations for improving productivity while reducing environmental impacts in smallholder rice systems.

2. MATERIALS AND METHODS

2.1 Study area

The experiment was conducted at the Kitere Irrigation Scheme (KIS) located in Mtwara Region, Tanzania (10°20′28″ S, 39°41′33″ E) during two consecutive rice growing seasons from September

2023 to July 2024. The area is characterized by a tropical climate with a mean annual temperature of approximately 26 °C and annual rainfall ranging from 820 to 1245 mm. The soils of the study site are classified as Vertisols, characterized by deep cracking clay with moderate fertility status. Pre-experiment soil analysis indicated slightly alkaline soil conditions (pH 7.6), low soil organic carbon (0.22–0.85%), medium total nitrogen (0.22%), and moderate available phosphorus (8.9 mg kg^{-1}).

2.2 Experimental design and treatments

The experiment was laid out in a randomized complete block design (RCBD) with four replications. Eight treatments consisting of Azolla integration and different nitrogen fertilizer rates were evaluated. Each experimental plot measured 3 m × 2 m (6 m^2) with a net plot area of 2.52 m^2 used for data collection. Plots were separated by bunds measuring 30 cm in width and 30 cm in height to prevent water and nutrient movement between treatments. Each plot was provided with independent water inlet and drainage channels to ensure proper water management.

T1 – Absolute control (no Azolla and no nitrogen fertilizer)
T2 – Azolla alone
T3 – 40 kg N ha^{-1}
T4 – 40 kg N ha^{-1} + Azolla
T5 – 80 kg N ha^{-1}
T6 – 80 kg N ha^{-1} + Azolla
T7 – 120 kg N ha^{-1}
T8 – 120 kg N ha^{-1} + Azolla

2.3 Crop establishment and field management

The rice variety SARO 5 (TXD 306) was used in the experiment. Seedlings were raised in a nursery and transplanted at 21–25 days after sowing. Two seedlings were transplanted per hill at a spacing of 20 cm × 20 cm to ensure uniform plant population and optimal crop growth. Each plot consisted of approximately 140 hills arranged in 10 rows with 14 hills per row. Standard agronomic practices including irrigation management and pest control were uniformly applied across all treatments following local recommendations.

2.4 Azolla and fertilizer management

Fresh Azolla (*Azolla pinnata*) biomass was applied at a rate of 10 t ha^{-1} and allowed to multiply in situ for 10 days before incorporation into the soil seven days before transplanting. Additional fresh Azolla biomass of 1 t ha^{-1} was applied at 3 days before transplanting and again at 14 days after transplanting to maintain surface coverage and enhance nitrogen contribution.

Nitrogen fertilizer was applied in the form of urea (46% N) according to treatment levels. Nitrogen was applied in three splits: 20% as basal at transplanting, 40% at 20 days after transplanting (DAT), and 40% at 40 DAT to improve nitrogen use efficiency. Phosphorus fertilizer was applied as triple superphosphate (TSP) at a uniform rate of 20 kg P ha^{-1} at transplanting in all plots except the absolute control. Potassium fertilizer was applied as muriate of potash at rate of 20kg kg K at transplanting in all plots except the absolute control.

2.5 Data collection

Weed assessment: Weed density was determined at 14 days after transplanting by counting all weed species within each plot. Weed suppression percentage was calculated relative to the control treatment following the method described by (Choudhary et al., 2025; Küçük & Bozdoğan, 2026; Nagargade et al., 2024).

$$Weed\ suppression\ (\%) = \frac{Wdc - Wdt}{Wdc} X\ 100$$

- Wdc = Weed density in control
- Wdt =Weed density in treatment

This assessment was used to evaluate the effectiveness of Azolla in suppressing weed emergence through surface coverage and light interception.

Grain yield determination: Rice grain yield was determined from the net plot area by harvesting all plants within the sampling area at physiological maturity. Harvested plants were bundled, labeled, and threshed separately. Grain weight was measured using a digital balance and adjusted to a standard moisture content of 14%. Grain yield was then converted to tons per hectare. The final yield values were averaged across the two cropping seasons to account for seasonal variability.

Economic analysis: Economic analysis was conducted to evaluate the profitability of Azolla and nitrogen integration treatments following the partial budget analysis approach. The economic indicators calculated were total production cost, Gross revenue, Net economic benefit (NEB), Benefit–cost ratio (BCR), Economic efficiency (EE) and Profit margin (%). These indicators were used to assess the economic feasibility and sustainability of the tested nutrient management strategies.

2.6 Statistical analysis

All data were subjected to analysis of variance (ANOVA) using GenStat statistical software (Version 20). Treatment means were compared using the least significant difference (LSD) test at the 5% probability level. Where appropriate, Tukey and Bonferroni post-hoc tests were used to assess seasonal treatment differences, while Duncan's Multiple Range Test (DMRT) was applied for comparison of economic indicators. Statistical significance was declared at $p \leq 0.05$.

3. RESULTS

3.1 Weed density response to Azolla and nitrogen treatments

Weed density differed significantly among treatments ($p < 0.05$), indicating the influence of Azolla integration and nitrogen fertilizer rates on weed emergence (Table 1). The absolute control (T1) recorded the highest weed density (7,917 plants ha^{-1}), while treatments incorporating Azolla showed substantially lower weed populations.

Table 1. Weed density and weed suppression under Azolla and nitrogen treatments

Treatment	Weed Density (plants ha^{-1})	Weed Density Suppression (%)
T1	7917	–
T2	1250	84.2
T3	3333	57.9
T4	2500	68.5
T5	12917	-63.1
T6	3750	52.7
T7	5417	31.6
T8	2500	68.5

Azolla alone (T2) resulted in the lowest weed density (1,250 plants ha^{-1}), corresponding to 84.2% weed suppression compared to the control. Treatments combining Azolla with nitrogen fertilizer also showed reduced weed density, with T4 (40 kg N ha^{-1} + Azolla) and T8 (120 kg N ha^{-1} + Azolla) each recording 2,500 plants ha^{-1} (68.5% suppression), while T6 (80 kg N ha^{-1} + Azolla) recorded 3,750 plants ha^{-1} (52.7% suppression).

Nitrogen-only treatments showed variable weed density levels. Treatment T3 (40 kg N ha^{-1}) recorded 3,333 plants ha^{-1} (57.9% suppression), whereas T7 (120 kg N ha^{-1}) recorded 5,417 plants ha^{-1} (31.6% suppression). The highest weed density (12,917 plants ha^{-1}) was observed under T5 (80 kg N ha^{-1}), indicating increased weed growth compared to the control.

3.2 Effects of Azolla integration and nitrogen rates on rice growth, biomass and yield performance

Rice growth and productivity parameters responded differently to Azolla and nitrogen treatments across seasons (Table 2). Plant height at early growth (14 DAT) did not differ significantly among treatments ($p = 0.670$), indicating uniform crop establishment. However, significant differences were observed at 31 DAT ($p < 0.001$), where integrated Azolla–nitrogen treatments generally produced taller plants compared to the control. The tallest plants were observed under T8 (59.06 cm), while the control recorded the lowest height (47.01 cm). At maturity (85 DAT), plant height did not differ significantly among treatments ($p = 0.957$), suggesting that early growth advantages did not translate into large differences at physiological maturity.

Productive tiller numbers were significantly influenced by treatments during Season 1 ($p < 0.001$), with integrated treatments (T4, T6 and T8) producing substantially higher tiller densities (273–327 tillers m^{-2}) compared to the control (147 tillers m^{-2}). However, no significant differences were observed in Season 2 ($p = 0.437$), indicating seasonal environmental influence on tillering response (Figure 1).

Total biomass followed a similar trend. In Season 1, biomass differed significantly ($p < 0.001$), ranging from 17.9 t ha^{-1} in the control to 43.2 t ha^{-1} in T8. Integrated treatments consistently produced greater biomass than sole nitrogen or Azolla treatments. In contrast, biomass differences were not significant in Season 2 (Figure 2).

Grain yield showed significant treatment effects ($p < 0.001$). The control produced the lowest yield (2.2 t ha^{-1}), while Azolla alone improved yield to 2.8 t ha^{-1}. The highest yield was obtained in T4 (40 kg N ha^{-1} + Azolla) with 3.7 t ha^{-1}, followed by T6 (3.5 t ha^{-1}) (Figure 3). Higher nitrogen rates did not produce substantial additional yield benefits, indicating improved nitrogen use efficiency under integrated management.

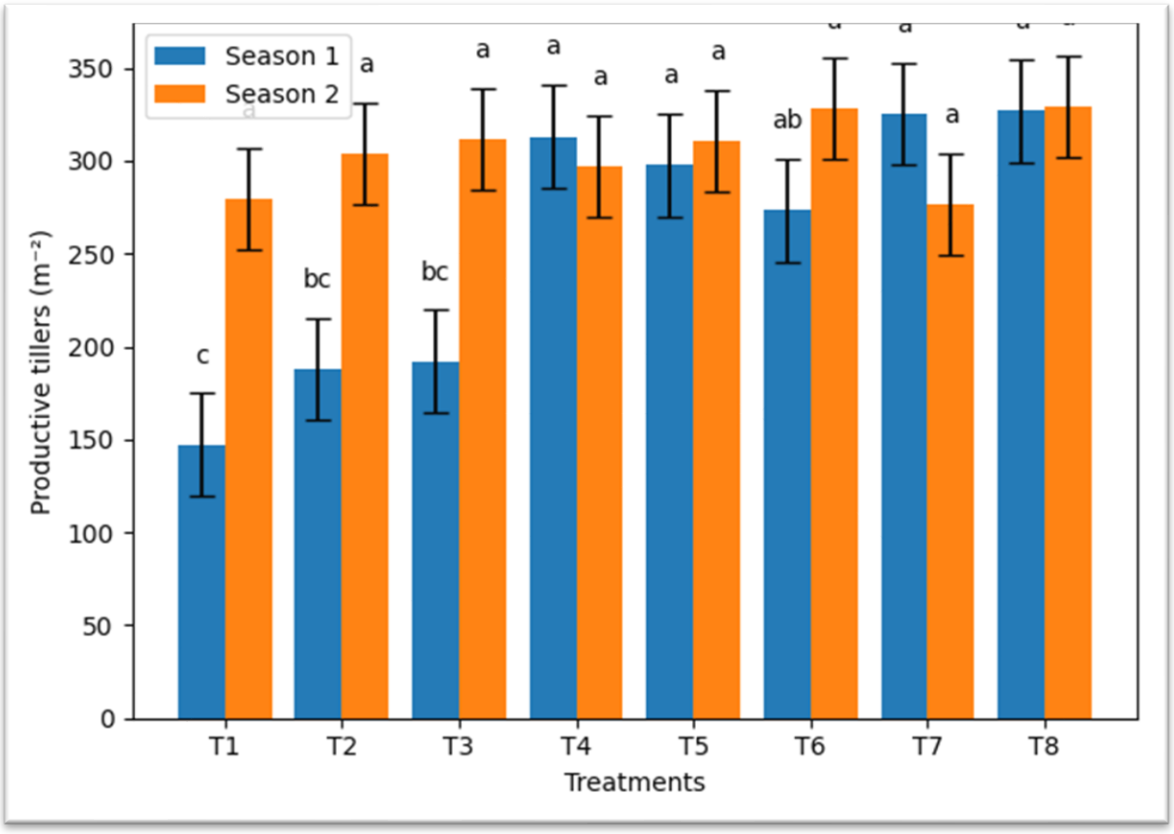

Figure 1. Productive tillers of rice as affected by integrated Azolla–nitrogen management. Bars represent mean ± SED

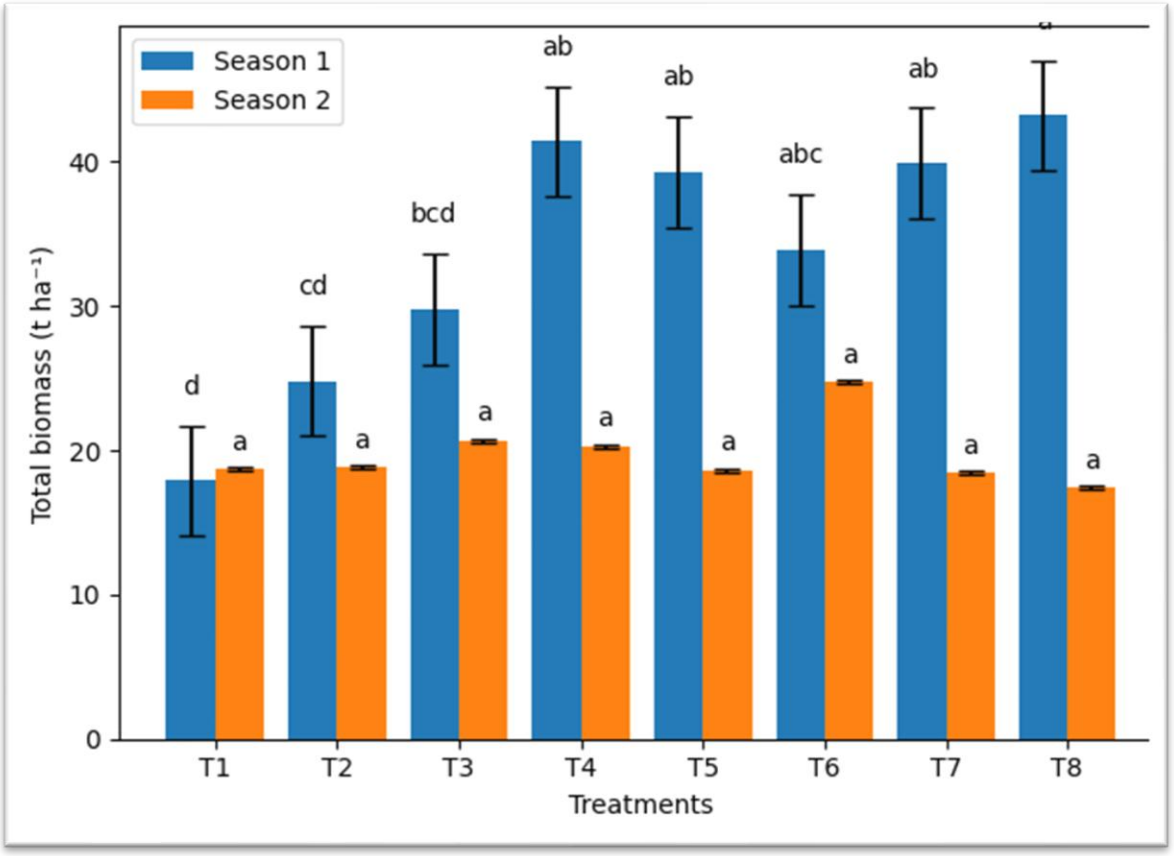

Figure 1. Total biomass production under Azolla and nitrogen integration. Bars represent mean ± SED

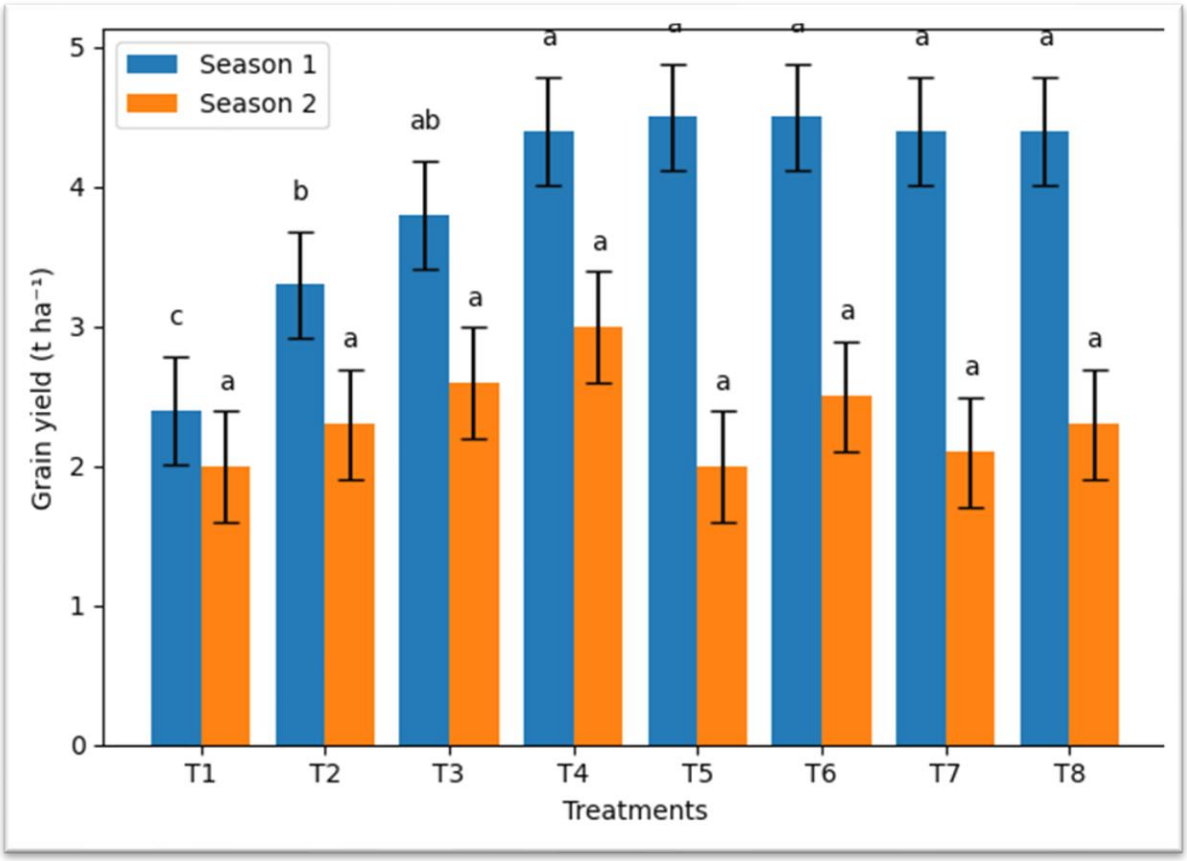

Figure 2. Grain yield response of rice to Azolla and nitrogen integration across two seasons. Bars represent mean ± SED. Different letters indicate significant differences at $p \leq 0.05$.

Table 2. Effects of Azolla and nitrogen integration on rice growth, yield components, biomass accumulation and grain yield across two cropping seasons

Treatment	Plant height (cm) 14 DAT S1	Plant height (cm) 31 DAT S1	Plant height (cm) 85 DAT S2	Productive tillers (m^{-2}) S1	Productive tillers (m^{-2}) S2	Total biomass (t ha^{-1}) S1	Total biomass (t ha^{-1}) S2	Grain yield (t ha^{-1}) S1	Grain yield (t ha^{-1}) S2
T1	33.27^{a}	47.01^{c}	92.8^{a}	147.2^{c}	279.5^{a}	17.9^{d}	18.7^{a}	2.4^{c}	2.0^{a}
T2	33.07^{a}	48.84^{bc}	92.4^{a}	187.8^{bc}	303.6^{a}	24.8^{cd}	18.8^{a}	3.3^{b}	2.3^{a}
T3	33.12^{a}	51.88^{abc}	93.6^{a}	191.9^{bc}	311.6^{a}	29.8^{bcd}	20.7^{a}	3.8^{ab}	2.6^{a}
T4	31.70^{a}	55.35^{ab}	97.4^{a}	312.9^{a}	297.3^{a}	41.4^{ab}	20.3^{a}	4.4^{a}	3.0^{a}
T5	31.16^{a}	52.62^{abc}	93.4^{a}	297.5^{a}	310.7^{a}	39.3^{ab}	18.6^{a}	4.5^{a}	2.0^{a}
T6	34.18^{a}	54.85^{ab}	96.1^{a}	273.1^{ab}	327.7^{a}	33.9^{abc}	24.7^{a}	4.5^{a}	2.5^{a}
T7	34.21^{a}	55.29^{ab}	91.5^{a}	325.3^{a}	276.8^{a}	39.9^{ab}	18.4^{a}	4.4^{a}	2.1^{a}
T8	33.41^{a}	59.06^{a}	92.6^{a}	326.9^{a}	329.5^{a}	43.2^{a}	17.4^{a}	4.4^{a}	2.3^{a}
Parameter	**14 DAT**	**31 DAT**	**85 DAT**	**Tillers S1**	**Tillers S2**	**Biomass S1**	**Biomass S2**	**Yield S1**	**Yield S2**
SED	1.827	2.237	5.37	27.66	27.27	3.829	0.129	0.384	0.397
LSD ($p \leq 0.05$)	3.799	4.651	11.17	57.53	56.72	7.963	2.361	0.799	0.826
p–value	0.670	<0.001	0.957	<0.001	0.437	<0.001	Ns	<0.001	0.235

Note: L.S. D= least of significance differences; S.E. D= Standard error of differences of means; different suffix laters indicates statistically significant difference along the column.

3.3 Economic performance of Azolla–nitrogen integration

Economic analysis showed clear differences among treatments in terms of production costs, revenue, and profitability indicators (Table 3). The control treatment (T1) recorded the lowest net economic benefit (380.5 USD ha^{-1}) and benefit–cost ratio (1.61). Application of Azolla alone (T2) improved net benefit to 651.5 USD ha^{-1} and BCR to 2.02. The highest net economic benefit (981.5 USD ha^{-1}) and benefit–cost ratio (2.36) was obtained from T4 (40 kg N ha^{-1} + Azolla). Treatment T6 also recorded high economic returns with a net benefit of 887.1 USD ha^{-1} and BCR of 2.18. results indicated that there is a positive relationship between Benefit–Cost Ratio (BCR) and Economic Efficiency (EE) across treatments over two season (Figure 4).

Table 3. Economic analysis of Azolla–nitrogen integration (mean of Seasons 1 and 2)

Treatment	Total Cost (USD ha^{-1})	Yield Revenue (USD ha^{-1})	NEB (USD ha^{-1})	BCR	EE (%)	Profit Margin (%)
T1	617.4d	998c	380.5c	1.612c	31.64b	38.1
T2	627.1d	1279b	651.5b	2.021ab	63.57a	50.9
T3	684.0c	1492ab	808.1ab	2.158ab	66.62a	54.2
T4	700.4bc	1682a	981.5a	2.364a	79.11a	58.4
T5	739.4a	1490ab	750.3ab	1.924bc	64.20a	50.4
T6	720.9ab	1608a	887.1ab	2.176ab	72.25a	55.2
T7	735.9a	1483ab	747.5ab	1.954b	62.85a	50.4
T8	737.5a	1533ab	795.4ab	2.013ab	63.86a	51.9

Note: Different letters indicate statistically significant differences along the column (LSD, $P < 0.05$).

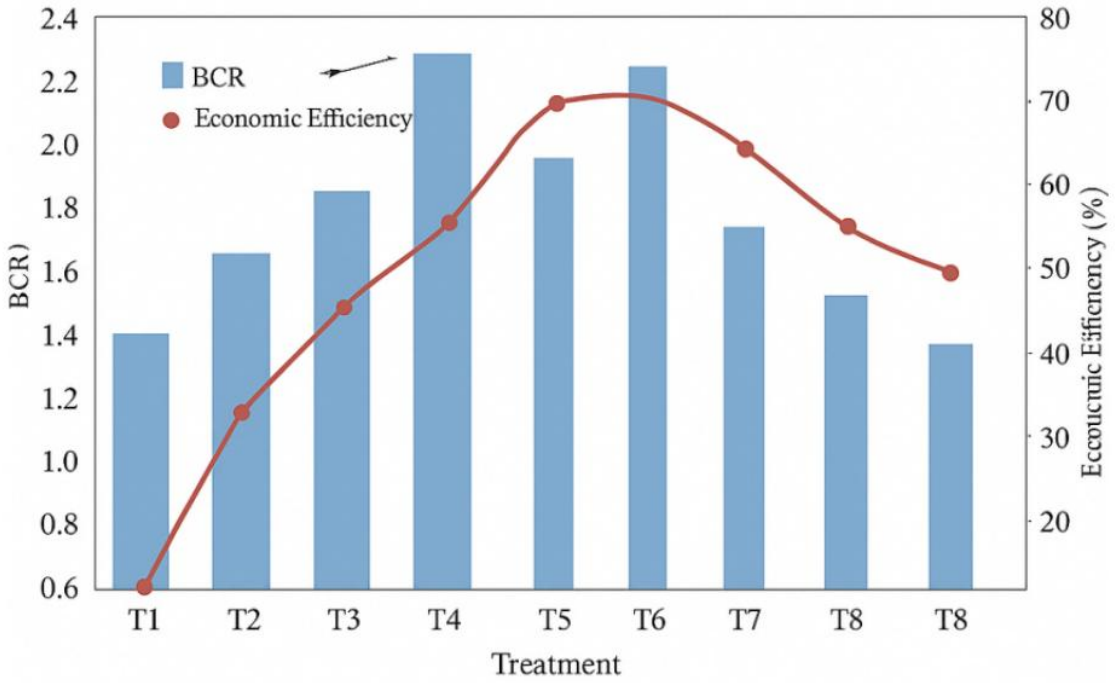

Figure 3. Relationship of Benefit–Cost Ratio (BCR) and Economic Efficiency (EE) across Azolla–Nitrogen treatments (mean of Seasons 1 and 2)

4. DISCUSSION

4.1 Azolla as a biological weed management tool

This study demonstrates that integrating Azolla with reduced nitrogen fertilizer provides a practical strategy for improving weed control. The strong reduction in weed density observed in Azolla treatments confirms its role as an effective ecological weed management strategy (Shin et al., 2021). The floating Azolla mat likely suppressed weeds primarily through shading of the water surface, which limits

light penetration required for weed germination, and through competition for nutrients during early crop establishment (Xu et al., 2024).

Further, the increase in weed density observed under higher nitrogen rates without Azolla suggests that excessive nitrogen may favor weed growth more than crop growth when no biological suppression mechanism is present (Burgos et al., 2006). Similar responses have been reported in flooded rice systems where high nitrogen availability increases the competitiveness of dominant weed species (Vu et al., 2023). These findings therefore highlighted that nitrogen management alone cannot effectively control weeds unless combined with ecological approaches such as biological surface cover. From a management perspective, the results suggest that Azolla can function as a living mulch, reducing the need for repeated manual weeding and potentially lowering labor demand, which remains a major production constraint in smallholder rice systems.

4.2 Effects of Azolla integration and nitrogen rates on rice growth, biomass and yield performance

The results demonstrate that integration of Azolla with mineral nitrogen fertilizer improved rice growth, yield components, biomass production and grain yield compared to sole nitrogen application and the control. The absence of significant differences in plant height at early growth (14 DAT) suggests that nutrient demand at this stage was still low and largely supported by basal soil fertility. However, significant differences observed at 31 DAT indicate that combined Azolla–nitrogen treatments enhanced vegetative growth during the active tillering stage when nitrogen demand is highest. This improvement may be attributed to the dual role of Azolla as a biological nitrogen fixer and as a source of organic matter that improves nutrient availability and soil biological activity (Marzouk et al., 2024).

Moreover, higher number of productive tillers observed under integrated treatments during Season 1 further confirms the importance of balanced nutrient supply in promoting tiller formation. Azolla likely improved nitrogen synchronization with crop demand through gradual mineralization, which enhanced nitrogen use efficiency compared to sole fertilizer application. The lack of significant differences in Season 2 suggests that environmental factors such as temperature, water management, or seasonal variability may have reduced treatment expression, a phenomenon commonly reported in field-based nutrient management studies (Yang et al., 2021).

Similarly, the higher biomass accumulation under integrated treatments reflects improved photosynthetic capacity and better nutrient uptake resulting from improved soil conditions. The synergistic effect observed between Azolla and nitrogen fertilizer supports previous findings that integrated nutrient management enhances crop vigor through improved soil structure, microbial activity, and nutrient cycling (Islam et al., 2024b).

Grain yield responses further confirmed the benefits of integration, with the highest yields recorded under moderate nitrogen combined with Azolla rather than the highest nitrogen rates alone. This suggests that Azolla improved nitrogen recovery efficiency and reduced nutrient losses. The comparable yields obtained at higher nitrogen rates indicate diminishing returns of excessive fertilizer application without biological supplementation (Adnyana et al., 2025; Marzouk et al., 2023).

4.3 Economic benefits of integrated Azolla–nitrogen management

Economic analysis clearly shows that integrating Azolla with moderate nitrogen produced the highest economic returns, mainly due to improved yields combined with lower fertilizer requirements. The higher benefit–cost ratios observed in integrated treatments confirm that reducing nitrogen inputs while maintaining productivity is more economically efficient than relying on high fertilizer rates (Chanapanchai et al., 2025).

The relatively lower profitability observed under high nitrogen treatments highlights the economic risks associated with excessive fertilizer use, particularly under conditions of rising input prices. In contrast, Azolla provides a low-cost nutrient source that improves input efficiency and profitability simultaneously (Paramesha et al., 2025). These findings suggest that Azolla integration could be particularly beneficial for smallholder farmers who face fertilizer affordability constraints. By reducing dependence on external inputs while maintaining yields, Azolla contributes to more resilient and cost-effective rice production systems.

4.4 Implications for sustainable rice intensification

The results indicate that Azolla integration supports multiple objectives of sustainable rice production, including reduced fertilizer dependence, improved weed management, and enhanced economic returns. The study particularly demonstrates that the combination of Azolla with moderate nitrogen rates represents the most efficient

balance between productivity and input use efficiency (Marzouk et al., 2023). Despite these benefits, adoption of Azolla remains limited in many African rice systems due to constraints such as limited awareness, lack of inoculum supply, and insufficient technical knowledge. The present findings therefore provide locally relevant evidence supporting the inclusion of Azolla in integrated nutrient management recommendations for irrigated rice systems in Tanzania and similar agroecological environments (Chanapanchai et al., 2025).

5. CONCLUSIONS

Integrating Azolla pinnata with reduced nitrogen fertilizer rates offers a practical and sustainable approach for enhancing rice productivity, suppressing weeds, and improving economic returns in lowland irrigated systems. The study confirms that Azolla can partially replace mineral nitrogen while maintaining high grain yield and reducing production costs, making it suitable for smallholder farming. This integration also represents a climate-smart agricultural strategy, as it promotes efficient nutrient use, reduces dependency on synthetic fertilizers, and supports environmentally sustainable rice production under changing climate conditions. Future research should focus on evaluating the long-term effects of Azolla integration on soil fertility, nitrogen cycling, and greenhouse gas emissions across different rice-growing environments, as well as optimizing application methods for wider adoption in sustainable rice intensification programs. Integrating Azolla with moderate nitrogen rates (particularly 40–80 kg N ha^{-1}) is recommended to optimize yield, reduce weed pressure, and improve fertilizer efficiency. Early establishment of Azolla after transplanting should be encouraged to maximize weed suppression benefits. Farmers may consider Azolla as a supplementary nutrient source rather than a complete replacement for mineral fertilizers. Further studies should evaluate long-term effects of Azolla integration on soil fertility, nitrogen dynamics, and soil biological properties.

Author contributions: D.K.K. implemented the methodology, carried out the laboratory analysis and wrote the introduction and Results sections, M.J.S., S.H.M. and E.K.N. supervised the research work and provided guidance throughout the study. All authors read and approved the final version of the manuscript.

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