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Optimizing nitrogen use efficiency and grain quality in basmati rice through Integrated weed management: Insights into nutrient partitioning and Crop–weed competition

ROMAN NISSAR*, MANZOOR AGANAI¹, MEHRAJ UD DIN SOFI, ASHAQ HUSSAIN² and F. A. BAHAR³

Division of Agronomy, Faculty of Agriculture, Wadura, ¹Extension and Research Station- Sallar, ²MRCFC- Khudwani, ³DARS-Rangreth, Sher-e-Kashmir University of Agricultural Sciences and Technology, Kashmir

**Corresponding author's email id: romanissa876@gmail.com*

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ABSTRACT: Optimizing nitrogen (N) use efficiency in rice requires effective management of crop–weed competition. A field experiment was conducted during the Kharif season of 2018 in SKUAST-Kashmir to evaluate the interactive effects of nitrogen levels (0, 45, and 90 kg N ha⁻¹) and weed management practices on weed dynamics, nutrient partitioning, resource-use efficiency, yield, and grain quality of basmati rice (Shalimar Sugandh 1). Weed interference significantly reduced grain yield (3.89 t ha⁻¹), crop nutrient uptake, and resource-use efficiency, accounting for 11.78% nutrient loss to weeds. In contrast, application of penoxsulam @ 22.5 g ha⁻¹ effectively reduced weed biomass (16.74 g m⁻²), improved weed control efficiency (72.08%), and enhanced grain yield (6.46 t ha⁻¹), comparable to weed-free conditions. Nitrogen application increased grain yield up to 6.49 t ha⁻¹, with an agronomic efficiency of 17.55 kg grain kg⁻¹ N at 90 kg N ha⁻¹. Improved weed control significantly enhanced crop nutrient advantage and reduced nutrient losses, indicating a strong shift in resource capture towards the crop. Grain quality parameters remained largely stable across treatments, although gel consistency improved under higher nitrogen and effective weed control, suggesting enhanced starch deposition. The results highlight that maximizing nitrogen use efficiency and sustaining grain quality in basmati rice requires integrated nutrient and weed management, particularly early post-emergence herbicide application to minimize competitive losses.

Keywords: Agronomic efficiency, Gel consistency, Nutrient partitioning, Penoxsulam, Rice, Weed control efficiency

Rice is a staple crop globally, but its productivity and grain quality are heavily constrained by biological stresses and inefficient nutrient utilization. Nitrogen (N) is the most critical driver of vegetative growth, grain yield, and endosperm protein/starch development. However, the application of nitrogen fertilizers initiates a highly competitive ecological dynamic; applied nutrients do not solely benefit the crop but concurrently stimulate the emergence, proliferation, and vigor of weed flora. Crop–weed competition for essential nutrients, particularly nitrogen, is a major constraint to rice productivity, often leading to significant yield losses ranging from 25 to 47% under severe infestation (Dolie *et al.*, 2025). The competitive ability of weeds during early crop growth stages results in substantial nutrient removal and reduced availability to the crop, thereby affecting growth and yield formation (Ulguim *et al.*, 2020). Recent studies have highlighted that integrated nitrogen and weed management strategies play a crucial role in regulating nutrient partitioning

and improving crop nutrient advantage in rice-based systems (Yadav *et al.*, 2025).

Weeds often exhibit faster initial growth rates and more aggressive root systems than transplanted rice, allowing them to absorb soil nutrients more rapidly. If left unchecked, this competition drastically reduces Nitrogen Use Efficiency (NUE) and translates into severe yield penalties. Furthermore, severe nutrient drain during the grain-filling stage can negatively impact the biochemical quality of the rice, such as gel consistency, which dictates the softness of the cooked grain.

To fully understand and manage crop–weed dynamics, it is essential to utilize quantitative agro-ecological parameters. Metrics such as Weed Control Efficiency (WCE), Agronomic Efficiency of Nitrogen (AEN), Crop Nutrient Advantage (CNA), and Nutrient Loss Due to Weeds (NLW) provide a mechanistic understanding of how resources are

partitioned in the field. Therefore, this study was designed to quantify the interactive effects of varying nitrogen levels and modern herbicidal management on weed suppression, crop yield, resource-use indices, and biochemical grain quality in the Shalimar Sugandh 1 rice variety.

MATERIALS AND METHODS

Experimental Site and Treatment Details

A field experiment was conducted during the *Kharif* season of 2018 using a Randomized Complete Block Design (RCBD) with three replications. The Kashmir basmati rice 'Shalimar Sugandh 1', was transplanted at a spacing of 15 cm × 15 cm within a gross plot size of 10.35 m² and a net harvested area of 8.00 m². The soil of the experimental site was silty clay loam with a neutral pH of 6.78, electrical conductivity of 0.15 dSm⁻¹ at 25°C, organic carbon of 0.87%, available nitrogen of 215 kg ha⁻¹, available phosphorus of 15.0 kg ha⁻¹, and available potassium of 205 kg ha⁻¹. The experiment evaluated 15 treatment combinations encompassing three nitrogen levels and five weed management practices. The nitrogen levels included a control of 0 kg N ha⁻¹ (N₀), 45 kg N ha⁻¹ (N₁), and 90 kg N ha⁻¹ (N₂). The weed management practices consisted of applying Florpyrauxifen-benzyl at 31.25 ml ha⁻¹ at 10 Days After Transplanting (DAT) (W₁), Penoxsulam at 22.5 g ha⁻¹ at 10 DAT (W₂), and a combination of Pyrazosulfuron-ethyl at 60 g ha⁻¹ plus Pretilachlor at 300 g ha⁻¹ at 3 DAT (W₃). Additionally, the study included a weed-free treatment maintained via hand weeding at weekly intervals up to 45 DAT (W₄), and a weedy check (W₅). The findings are based on a single-season study and require multi-year validation.

Data Collection

Weed dry matter was recorded at 25 and 45 Days After Transplanting (DAT). Crop grain and straw yields were recorded at harvest. Nitrogen, phosphorus, and potassium (NPK) concentrations in both crop and weeds were analyzed using standard laboratory procedures. Physical and biochemical grain quality parameters, specifically Gel Consistency (measured by the length of the gel in

mm), were evaluated post-harvest using standard biochemical protocols. The data obtained in respect of various observations were statistically analyzed on OP Stat Software Programme (Anonymous, 2012) by method described by Gomez and Gomez (1984). Weed parameters were transformed and then analyzed. The significance of 'F' and 't' was tested at 5% level of significance. The critical difference value was computed when 'F' test was significant.

Calculation of Agro-Ecological Indices

To evaluate resource efficiency and competition, the following parameters were calculated:

Weed Control Efficiency (WCE):

$$\text{WCE (\%)} = \frac{\text{WDM}_c - \text{WDM}_t}{\text{WDM}_c} \times 100$$

(Where WDM_c is weed dry matter in the weedy check and WDM_t is weed dry matter in the respective treatment).

Agronomic Efficiency of Nitrogen (AEN)

$$\text{AEN} = \frac{Y_n - Y_0}{N_r}$$

(Where Y_n is yield in N-fertilized plot, Y_0 is yield in 0 kg N control, and N_r is the rate of applied N in kg ha⁻¹).

Crop Nutrient Advantage (CNA) and Nutrient Loss Due to Weeds (NLW)

$$\text{CNA} = \frac{N_c}{N_w}$$

$$\text{NLW (\%)} = \frac{N_w}{N_c + N_w} \times 100$$

(Where N_c and N_w are the total N uptake by crop and weeds, respectively).

RESULTS AND DISCUSSION

Weed Dynamics and Weed Control Efficiency (WCE)

Weed proliferation was highly responsive to soil fertility; weed dry matter at 45 DAT increased

linearly with N application, peaking at 31.68 g m⁻² under 90 kg N ha⁻¹.

Among the management practices, Penoxsulam (W₂) proved to be the most highly effective chemical intervention. It significantly restricted weed dry matter to 16.74 g m⁻² at 45 DAT and achieved a Weed Control Efficiency (WCE) of 72.08% (Table 1). This vastly outperformed Florpyrauxifen-benzyl (W₁, WCE: 46.04%) and Pyrazosulfuron + Pretilachlor (W₃, WCE: 59.17%).

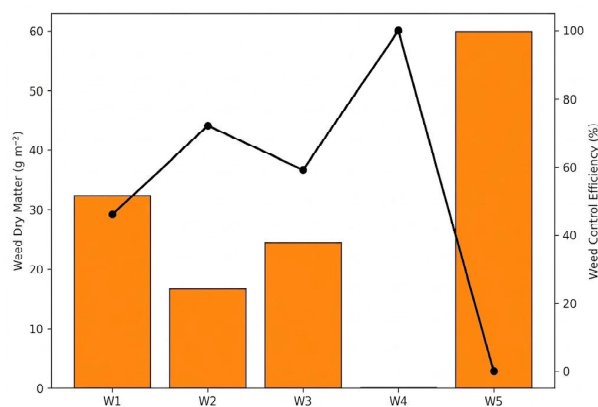


Fig. 1: Effect of different weed management practices (W₁–W₅) on weed dry matter (orange bars, left axis) and weed control efficiency (black line, right axis) at 45 days after transplanting

Crop Yield and Agronomic Efficiency of Nitrogen (AEN)

Grain yield was significantly enhanced by nitrogen

application, increasing from 4.91 t ha⁻¹ (0 kg N) to 6.49 t ha⁻¹ (90 kg N). The calculation of AEN revealed that the crop efficiently utilized the applied fertilizer, producing 17.55 kg of additional grain per kg of N applied at the 90 kg N ha⁻¹ rate.

Weed management dictated the realization of this yield potential. The weed-free treatment (W₄) produced the highest grain yield (6.75 t ha⁻¹), closely followed by the Penoxsulam treatment (W₂, 6.46 t ha⁻¹). Conversely, the weedy check (W₅) suffered a massive yield penalty, producing only 3.89 t ha⁻¹.

Nutrient Partitioning and Ecological Competition Indices

Nutrient drain by weeds fundamentally altered the ecological balance of the field (Table 2). Under the weedy check (W₅), weeds depleted 8.16 kg N ha⁻¹. This resulted in a very low Crop Nutrient Advantage (CNA) of 7.49 and meant that 11.78% of all mobilized nitrogen was entirely lost to weeds (NLW).

Effective chemical weed management via Penoxsulam (W₂) drastically suppressed weed nutrient uptake to just 2.00 kg N ha⁻¹. This shifted the competitive balance entirely, resulting in an exceptional CNA of 53.69 and restricting nitrogen loss to weeds to a negligible 1.83%.

Table 1: Effect of weed management practices on Weed Dry Matter and Control Efficiency (at 45 DAT)

Weed Management Practice	Weed Dry Matter (g m ⁻²)	Weed Index (%)	Weed Control Efficiency (WCE %)
W ₁ : Florpyrauxifen-benzyl	32.35	19.26	46.04
W ₂ : Penoxsulam	16.74	4.21	72.08
W ₃ : Pyrazosulfuron + Pretilachlor	24.48	11.68	59.17
W ₄ : Weed Free	0.00	0.00	100.00
W ₅ : Weedy Check	59.96	42.83	0.00

Table 2: Effect of weed management practices on Crop-Weed Nitrogen Competition Indices

Weed Management Practice	Crop Total N Uptake (N _c) (kg ha ⁻¹)	Weed Total N Uptake (N _w) (kg ha ⁻¹)	Crop Nutrient Advantage(CNA)	Nutrient Loss to Weeds (NLW %)
W ₁ : Florpyrauxifen-benzyl	91.38	4.02	22.73	4.21
W ₂ : Penoxsulam	107.38	2.00	53.69	1.83
W ₃ : Pyrazosulfuron + Pretilachlor	98.62	3.24	30.43	3.18
W ₄ : Weed Free	113.54	0.00	∞	0.00
W ₅ : Weedy Check	61.11	8.16	7.49	11.78

(Note: N_c calculated as Grain N + Straw N from original data).

Table 3: Effect of nitrogen levels and weed management practices on NPK concentration (%) and uptake (kg ha⁻¹) of grain and straw of Basmati rice

Treatment	Grain						Straw					
	NPK concentration (%)			NPK uptake (kg ha ⁻¹)			NPK concentration (%)			NPK uptake (kg ha ⁻¹)		
	N	P	K	N	P	K	N	P	K	N	P	K
Nitrogen levels												
N ₁	1.009	0.206	0.198	50.07	10.28	9.84	0.450	0.059	1.219	30.33	3.96	82.33
N ₂	1.033	0.208	0.216	59.33	11.99	12.43	0.465	0.061	1.242	34.17	4.45	91.24
N ₃	1.077	0.209	0.224	70.14	13.71	14.62	0.480	0.062	1.307	39.18	5.10	106.62
SEm ±	0.0081	0.0006	0.0017	1.14	0.24	0.23	0.0031	0.0003	0.0025	0.69	0.08	1.57
CD (p≤0.05)	0.0236	0.0017	0.0049	3.30	0.69	0.66	0.0091	0.0008	0.0071	1.99	0.23	4.54
Weed management practices												
W ₁	1.037	0.200	0.205	56.53	10.96	11.29	0.477	0.061	1.273	34.85	4.45	93.62
W ₂	1.071	0.218	0.220	69.32	14.08	14.28	0.497	0.063	1.286	38.06	4.85	99.15
W ₃	1.046	0.215	0.211	62.53	12.89	12.69	0.478	0.062	1.279	36.09	4.73	97.38
W ₄	1.082	0.219	0.228	73.07	14.75	15.40	0.507	0.064	1.296	40.47	5.14	104.28
W ₅	0.962	0.186	0.198	37.78	7.28	7.81	0.367	0.053	1.145	23.33	3.35	72.56
SEm ±	0.0105	0.0007	0.0022	1.47	0.31	0.29	0.0040	0.0003	0.0032	0.89	0.10	2.02
CD (p≤0.05)	0.0304	0.0022	0.0063	4.26	0.89	0.85	0.0117	0.0009	0.0092	2.58	0.30	5.86
N × W	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 4: Effect of nitrogen levels and weed management practices on NPK concentration (%) and uptake (kg ha⁻¹) by weeds

Treatment	NPK concentration (%)			NPK uptake (kg ha ⁻¹)		
	N	P	K	N	P	K
Nitrogen levels						
N ₁	1.39 (0.97)	1.061 (0.127)	1.37 (0.93)	1.80 (2.57)	1.163 (0.376)	1.81 (2.69)
N ₂	1.41 (1.02)	1.066 (0.138)	1.39 (1.00)	2.02 (3.55)	1.220 (0.527)	2.02 (3.61)
N ₃	1.42 (1.07)	1.069 (0.145)	1.42 (1.06)	2.19 (4.33)	1.258 (0.625)	2.19 (4.32)
SEm ±	0.01	0.004	0.017	0.03	0.01	0.04
CD (p≤0.05)	NS	NS	NS	0.08	0.04	0.11
Weed management practices						
W ₁	1.49 (1.24)	1.093 (0.19)	1.51 (1.27)	2.23 (4.02)	1.28 (0.64)	2.25 (4.12)
W ₂	1.48 (1.19)	1.060 (0.12)	1.41 (0.99)	1.72 (2.00)	1.10 (0.21)	1.63 (1.74)
W ₃	1.52 (1.31)	1.066 (0.14)	1.50 (1.26)	2.05 (3.24)	1.16 (0.34)	2.02 (3.13)
W ₄	1.00 (0.00)	1.000 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
W ₅	1.54 (1.36)	1.107 (0.23)	1.57 (1.46)	3.02 (8.16)	1.53 (1.36)	3.11 (8.70)
SEm ±	0.01	0.005	0.02	0.03	0.02	0.05
CD (p≤0.05)	0.04	0.013	0.06	0.10	0.05	0.14
N × W	NS	NS	NS	NS	NS	NS

*Figures in parenthesis are original values, data subjected to $\sqrt{x+1}$ transformation

Nutrient Concentration and Uptake by Grain and Straw

Perusal of the data reveals that 90 kg N ha⁻¹ (N₃) significantly recorded higher NPK concentration of grain and straw over 45 kg N ha⁻¹ (N₂) and the control (N₁). Consequently, N uptake by grain was significantly higher under N₃ (70.14 kg ha⁻¹) compared to N₁ (50.07 kg ha⁻¹) (Table 3).

Among weed management practices, weed-free

treatment recorded significantly higher NPK content for both grain and straw over the weedy check. Regarding herbicidal treatments, application of Penoxsulam @ 22.5 g ha⁻¹ (W₂) recorded higher NPK content and significantly higher nitrogen uptake by grain (69.32 kg ha⁻¹) followed by Pyrazosulfuron-ethyl + Pretilachlor (62.53 kg ha⁻¹). The superiority exhibited by Penoxsulam in recording higher nitrogen uptake over the weedy check was 45.5%.

Nutrient Concentration and Uptake by Weeds

Different nitrogen levels remained non-significant in altering the NPK concentration in weeds. However, different nitrogen levels significantly influenced nitrogen uptake by weeds. Application of 90 kg N ha⁻¹ (N₃) significantly increased N uptake of weeds (2.19 kg ha⁻¹) over N₁ (1.80 kg ha⁻¹) (Table 4).

Among weed management practices, the weedy check significantly increased the NPK concentration and total uptake of weeds over other management practices. Conversely, among the herbicide applications, Penoxsulam (W₂) recorded the lowest NPK concentration and significantly lowest values for N uptake (1.72 kg ha⁻¹), P uptake (1.10 kg ha⁻¹), and K uptake (1.63 kg ha⁻¹) in weeds.

Grain quality response to nitrogen and weed management

Nitrogen fertilization did not significantly influence kernel dimensions, L:B ratio, or cooking quality parameters; however, a consistent numerical improvement was observed with increasing nitrogen levels. The highest values for kernel length, breadth, L:B ratio, kernel length after cooking, and elongation ratio were recorded at 90 kg N ha⁻¹, suggesting a positive but limited role of nitrogen in modulating grain morphology. This marginal response indicates that grain physical traits are relatively stable and primarily governed by genetic factors, with nitrogen-induced changes in assimilate supply being insufficient to induce significant structural variation. In contrast, weed management exerted a measurable influence on kernel length prior to cooking, while

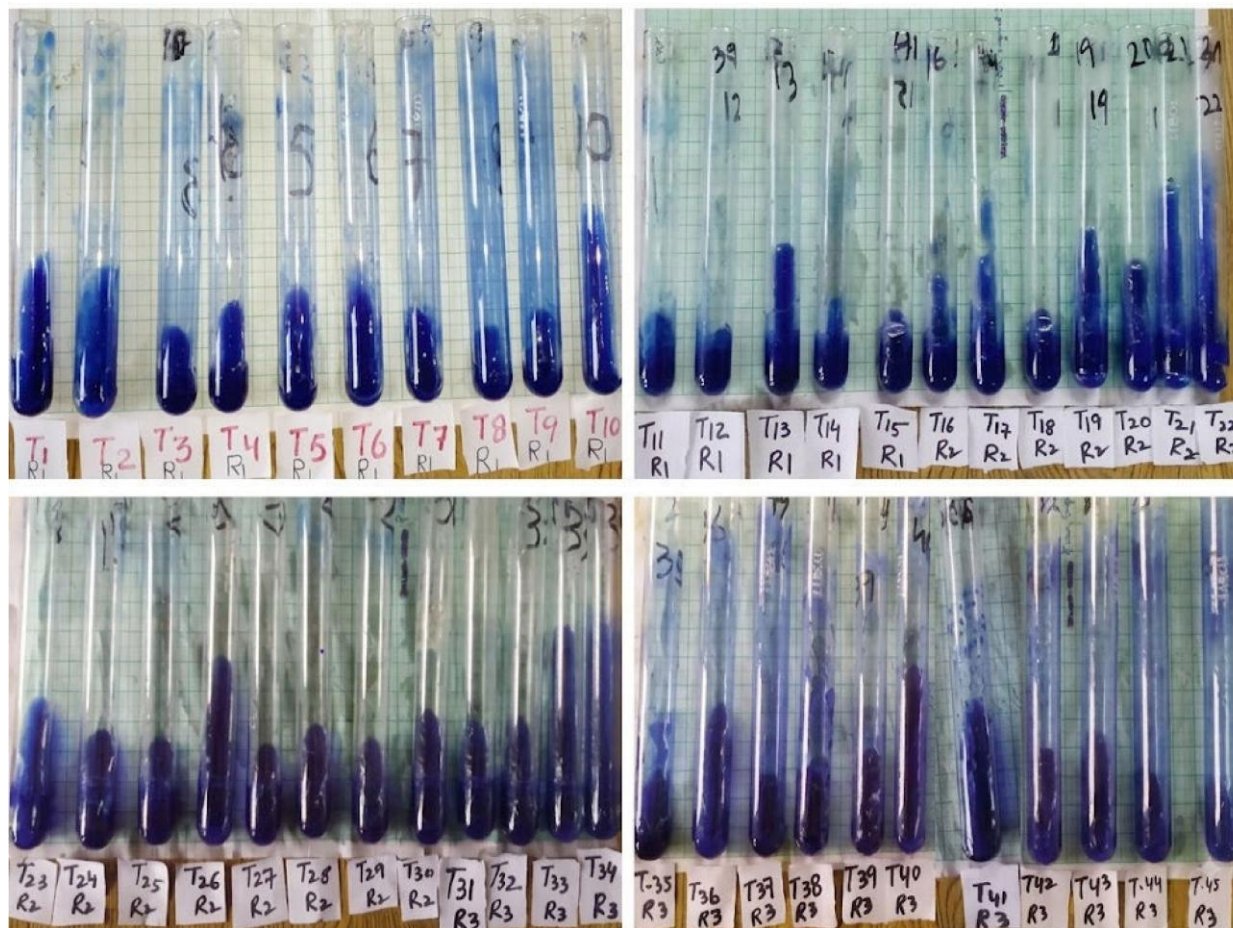


Plate 1: Gel consistency

other grain quality traits remained statistically unaffected. The weed-free treatment recorded the highest kernel length, indicating that alleviation of crop–weed competition during critical growth stages enhances assimilate availability for grain development. Among herbicidal treatments, penoxsulam application resulted in comparatively higher kernel length, reflecting improved early-season weed suppression and enhanced source–sink relationships.

Despite these trends, kernel breadth, L:B ratio, kernel elongation, and cooking quality parameters exhibited limited sensitivity to both nitrogen and weed management. This suggests that these attributes are conservative traits with low environmental plasticity. However, slight numerical improvements under effective weed control indicate that reduced competition may facilitate better grain filling and starch deposition.

Gel consistency, in contrast, responded significantly to both nitrogen and weed management. Increasing nitrogen levels enhanced gel length, indicating improved starch quality and softer cooking characteristics. Similarly, effective weed control increased gel length, likely due to improved nutrient uptake and uninterrupted assimilate translocation during grain filling. These findings suggest that while physical grain traits remain relatively stable, biochemical quality parameters are more responsive to improved resource availability and reduced competitive stress.

The present study clearly demonstrates that nitrogen use efficiency in rice is strongly regulated by crop–weed competition, which governs the partitioning of nutrients between crop and weeds. Although nitrogen application enhanced yield and nutrient uptake, its effectiveness was substantially constrained under conditions of inadequate weed control, indicating that nutrient availability alone is insufficient without effective regulation of biotic competition.

The increased nutrient removal by weeds under weedy conditions reflects their superior competitive

ability, particularly during early growth stages when resource demand is high and crop establishment is vulnerable. This competitive dominance results in reduced nutrient acquisition by the crop, impaired canopy development, and lower assimilate production. Consequently, yield reduction under weedy conditions is primarily a function of resource pre-emption by weeds rather than nutrient deficiency per se. Enhanced nitrogen availability further intensifies this competition by stimulating vigorous weed growth, leading to greater nutrient depletion and reduced crop advantage (Ulguim *et al.*, 2020; Yadav *et al.*, 2025).

The significant improvement in crop nutrient uptake and the reduction in nutrient losses under effective weed management indicates a decisive shift in nutrient partitioning towards the crop. This reinforces the role of weed control in regulating resource capture and improving nutrient use efficiency, as also reported by Nazir *et al.* (2022). Among the weed management practices, early post-emergence application of penoxsulam at 10 DAT proved particularly effective in suppressing weed growth during the critical period of crop–weed competition, thereby enhancing nutrient availability, promoting better crop growth, and ultimately improving yield formation. These findings are in close agreement with those of Gowda *et al.* (2009), Kumar *et al.* (2010) and Talla and Jena (2014), who also demonstrated that effective early weed management minimizes crop–weed competition, enhances nutrient uptake by the crop, and ultimately improves crop productivity.

The observed improvements in crop nutrient advantage further highlight the importance of early-season weed suppression in maximizing resource-use efficiency. By minimizing competition during the vegetative phase, the crop is able to establish a stronger canopy, intercept more radiation, and sustain higher rates of photosynthesis, which collectively contribute to improved biomass accumulation and yield.

In contrast, physical grain quality traits such as kernel dimensions and L:B ratio exhibited limited

responsiveness to nitrogen and weed management, suggesting that these characteristics are predominantly under genetic control with low environmental plasticity. However, the improvement in gel consistency under higher nitrogen levels and effective weed control indicates that biochemical grain quality attributes are more sensitive to changes in nutrient availability and assimilate supply. Enhanced nitrogen uptake likely promotes protein synthesis and alters starch composition, resulting in improved cooking quality.

Furthermore, nitrogen use efficiency in rice is not solely determined by total nitrogen uptake but also by its allocation to economically important plant components, particularly the panicle. Efficient partitioning of nitrogen enhances grain filling and productivity, underscoring the importance of synchronizing nitrogen availability with crop demand and minimizing competitive losses (Liu *et al.*, 2026).

Overall, the findings emphasize that efficient nitrogen utilization in rice is not merely a function of fertilizer application but is critically dependent on minimizing biotic competition. Integrated nitrogen and weed management strategies are therefore essential to optimize nutrient partitioning, enhance resource-use efficiency, and sustain both productivity and grain quality.

CONCLUSION

The study demonstrates that nitrogen fertilization alone is insufficient to achieve optimal productivity and resource-use efficiency in rice unless accompanied by effective weed management. Uncontrolled weeds significantly reduce nutrient availability to the crop, leading to substantial yield losses and inefficient fertilizer utilization.

Application of 90 kg N ha⁻¹ in combination with early post-emergence weed control, particularly through penoxsulam, significantly improved crop nutrient uptake, reduced nutrient losses, and enhanced yield. While physical grain quality traits remained relatively stable, improvements in gel consistency under better resource availability highlight the

sensitivity of biochemical quality parameters to agronomic management.

These findings underscore the importance of integrating nutrient and weed management strategies to enhance nitrogen use efficiency, sustain productivity, and maintain grain quality in basmati rice systems.

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