Research Article:

PRECISION NITROGEN MANAGEMENT FOR RICE IN MID-HILLS OF NEPAL: PRODUCTIVITY, PROFITABILITY AND NITROGEN USE EFFICIENCY

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ABSTRACT

Nepalese farmers often apply generalized nitrogen (N) recommendations that overlook field-specific conditions, leading to excessive N use, higher costs, and reduced efficiency. This study evaluated the effectiveness of precision N management tools on rice yield, economic returns, and nitrogen use efficiency in the mid-hills of Nepal. A field trial was conducted during the 2024 monsoon season in the mid-hills of Nepal using a Randomized Complete Block Design with seven treatments and three replications. The treatment included Control (N_0 – 0 kg N ha^{-1}), Farmers' Fertilizer Practice (FFP- 138 kg N ha^{-1}), National Recommendation (NR- 100 kg N ha^{-1}), Leaf Color Chart (LCC- 61.33 kg N ha^{-1}), Soil Plant Analysis Development (SPAD- 33.33 kg N ha^{-1}) meter, Normalized Difference Vegetation Index (NDVI) based Green Seeker (58.33 kg N ha^{-1}), and Nutrient Expert (NE- 113.5 kg N ha^{-1}) model. Grain yield, economic performance, partial factor productivity of Nitrogen (PFPN), and Agronomic Nitrogen use efficiency (ANUE) were measured and analyzed using Analysis of Variance and DMRT at a 5% significance level. All the nitrogen-fertilized treatments significantly outperformed the control. The NE treatment produced the highest grain yield (6.79 Mt ha^{-1}), statistically at par with NR (6.65 Mt ha-^{1}). The NE treatment provided the highest gross returns (NRs 260,481.4 ha^{-1}), net return (NRs 115,531.27 ha^{-1}), and benefit-cost ratio (1.63). However, the SPAD meter-based treatment, which applied the least amount of nitrogen (33.33 kg ha^{-1}), achieved the highest PFPN (137.57 kg grain kg^{-1} N) and ANUE (49.50 kg yield increase kg^{-1} N), significantly surpassing all other treatments, including the FFP, which recorded the lowest efficiency. The findings demonstrated that real-time, site-specific precision nitrogen management tools, particularly NE and sensor-based approaches like SPAD meter, enhance productivity, profitability, and nitrogen use efficiency. Further multi-season and multi-location studies are recommended to validate and refine these precision management tools for wider adoption across diverse agro-ecological regions of Nepal.

Keywords: Agronomic efficiency, economic analysis, fertilizer optimization, partial factor productivity, site-specific nutrient management

INTRODUCTION

Rice (*Oryza sativa* L.) is the most widely cultivated cereal in Nepal and a fundamental component of the national diet, occupying the largest share of the cultivated area among cereal crops and contributing significantly to agricultural output (Gadal et al., 2019). In Nepal, it is grown on 14.4 million ha nationwide, producing roughly 54.9 million tons, with an average productivity of 3.49 Mt ha^{-1} and contributing approximately 12.81% of the total AGDP of the country (MoALD, 2023). In the Lalitpur district, it is cultivated on 16,234 ha, generating 64,669 Mt of harvest, with a productivity of 3.98 Mt ha^{-1}, thereby contributing to food security and improving rural livelihoods. Due to the improper use of nitrogenous fertilizer, rice yield is lower than its potential, though it has high economic and nutritional importance (Ghosh et al., 2013; Billa et al., 2021). Nitrogen is the essential constituent of enzymes, chlorophyll, nucleic acids, storage proteins, and cell walls, and plays a major role in physiological and biochemical processes for the growth and development of plants. But its efficiency is low, with only about 30-40% of applied N being utilized by the crop, and the remaining is lost through processes like leaching, denitrification, and volatilization. These losses decrease the ability of the crop to take up N, posing significant challenges to achieving optimal rice yields (Li et al., 2018;Vista & Timilsina., 2022).In addition, many farmers use more Nitrogen fertilizer than required because they believe that the standard recommendation does not fit their local conditions, so they often apply fertilizer inefficiently and ineffectively (Timsina et al., 2010; Bhatta et al., 2022). As a result, there is a greater yield gap, due to excessive and untimely fertilizer application, ultimately increasing the cost of production, nutrient losses, and environmental pollution without achieving the target yield (Esfahani et al., 2008).

To address such issues, there is a need for the dissemination of site-specific nutrient management (SSNM) techniques such as the Leaf Color Chart (LCC), green seeker, SPAD meter, and Nutrient Expert (NE) model. The use of these tools and techniques offers a strategic solution to address these challenges by synchronizing Nitrogen supply with real-time crop demand using SSNM approaches. Studies have shown that LCC and SPAD meter-based management can reduce N use by up to 32% while increasing yield by around 5%. Green Seeker-based N application improves agronomic N use efficiency by 5-12 kg grain per kg N applied, increasing grain yield (Bijay-Singh et al., 2015). The NE model tool also enhances fertilizer use efficiency, reduces the yield gap, and increases profitability (Amgain et al., 2021; Phulara et al., 2023). Improved Nitrogen use efficiency ultimately enhances resource use efficiency, lowers input costs, and increases economic returns, making precision Nitrogen management a better alternative to sustainable intensification of rice production in mid-hill agroecology. Therefore, this study aims to evaluate the effectiveness of different precision Nitrogen management tools in improving rice yield, nitrogen use efficiency, and economic return in the mid-hills of Nepal. This study is grounded in the premise that real-time, SSNM can improve crop yield and profitability compared to conventional farmer practices and blanket fertilizer recommendations. By evaluating both agronomic and economic performance, it aims to provide field-based evidence to promote the broader adoption of precision Nitrogen management technologies.

RESEARCH METHODS

Experimental site, weather, and soil

The field trial was carried out during the 2024 monsoon season at the Agronomy farm research block of Nepal Agricultural Research Council, Khumaltar, Lalitpur, Nepal. The site was located at 27°39′ N latitude, 185°10′ E longitude with an elevation of 1360 masl, which represents the mid-hill agroecology and subtropical climatic zone of Nepal. During the research period, June to October 2024, the monthly mean temperature was observed to be 26 °C in June and 22.25 °C in October. Likewise, the highest monthly rainfall occurred in July (556.3 mm), and the lowest in October (7.2 mm), and the total rainfall of 1639.2 mm was recorded during the research period. For soil testing, composite soil samples were collected from each plot to a depth of 20 cm using a tube auger before crop establishment. The samples were carefully mixed, ground, sieved, and processed for laboratory analysis. The initial fertility status of the soil was tested in the Central Agriculture Lab, Hariharbhawan, Lalitpur. The soil of the experimental field was silty loam with acidic pH (5.92) and low organic matter content (2.30%). The nitrogen content was medium (0.12%), available phosphorus was high (277.0 kg ha^{-1}), while available potassium was low (83.33 kg ha^{-1}).

Field experiment

Research design

The experiment was conducted in a Randomized Complete Block Design (RCBD) with seven treatments and three replications. The total experimental area was 280.8 m^2, with a spacing of 0.4 m between the plots and 1.5 m between replications. Each experimental plot was 3m×3m (9 m^2). A seed rate of 40 kg ha^{-1} was applied, and transplanting was performed using two seedlings per hill. The rice genotype NR11105-B-B-27 was used for the study, maintaining a spacing of 20 cm × 20 cm between both rows and plants. Over the past three years, the field had a previous cropping history of rice-wheat, rice-maize, rice-lentil.

Fertilizer management practices

In each treatment, P_2O_5 and K_2O were uniformly applied at 30 kg ha^{-1} each through Di-ammonium Phosphate (DAP) and Muriate of Potash (MOP) during final land preparation before transplanting. Seven fertilizer treatments were evaluated: control (Nitrogen (N_0), 0 kg N ha^{-1}); National Recommendation (NR) with 100 kg N ha^{-1} was applied in two equal splits (basal and 30 DAT) following MoALD (2023) guidelines; Nutrient Expert (NE) with 113.5 kg N ha^{-1} applied in three equal splits (basal, 20 and 70 Days After Transplanting (DAT) treatment based on the NE-rice model developed for India as valid in Nepal (Timsina et al., 2022; Amgain et al., 2021); Farmers' Fertilizer Practice (FFP) with 138 kg N ha^{-1} applied in two equal splits (basal and 20 DAT) as recommended by the NE-rice model; Leaf Color Chart (LCC) treatment, where 10 topmost fully opened leaves were assessed at 10-day intervals from 20-25 DAT to flowering and 28 kg N ha^{-1} was applied when >6 leaves recorded LCC reading ≤ 4 (IRRI CREMNET LCC), receiving 33.33 kg N ha^{-1} basal plus 28 kg N ha^{-1} at 25 DAT (total 61.33 kg N ha^{-1}); SPAD-based treatment, where readings from 10 plants were taken every 10 days from 20-25 DAT to flowering and 25 kg N ha^{-1} was applied when SPAD <36 (Baral et al., 2021), with 33.33 kg N ha^{-1} basal applied but no topdressing required; and Green Seeker (NDVI) treatment, where readings were taken every 10 days from 20-25 DAT to flowering at 60-120 cm above canopy and 25 kg N ha^{-1} was applied when NDVI <0.8 (Billa et al., 2021), receiving 33.33 kg N ha^{-1} basal plus 25 kg N ha^{-1} at 25 DAT (total 58.33 kg N ha^{-1}).

Table 1. Treatment details

S.N.	Abbreviations	Treatment details
T1	N_o	Control
T2	FFP	138 kg N ha^{-1} in two equal splits
T3	NR	100 kg N ha^{-1} in three equal splits
T4	LCC	33.33 kg N ha^{-1} basal + 28 kg N ha^{-1}, based on LCC at critical value ≤ 4
T5	SPAD	33.33 kg N ha^{-1} basal + 25 kg N ha^{-1}, based on SPAD critical value ≤ 36
T6	NDVI	33.33 kg N ha^{-1} basal + 25 kg N ha^{-1}, based on green seeker (NDVI) critical value ≤ 0.8
T7	NE	113.5 kg N ha^{-1} in three equal splits

Remarks: N_0- Control, FFP- Farmers Fertilizer Practices, NR- National Recommendation, LCC- Leaf Color Chart, SPAD- Soil Plant Analysis Development, NDVI- Normalized Difference Vegetation Index, NE- Nutrient Expert

Observations recorded and statistical analysis

Grain yield for each treatment was recorded from the net plot area and adjusted to approximately 14% moisture content. The yield was then converted to MT ha^{-1} using the following formulae:

$$\text{Grain yield (Mt ha}^{-1}\text{) adjusted at 14\% moisture} = \frac{(100 - \text{MC}) \times \text{grain yield per net plot} \times 10000\ (\text{m}^2)}{(100 - 14) \times \textit{net plot area}\ (\text{m}^2) \times 1000}$$

The total farming costs were estimated based on local prices of inputs, including labor, fertilizers, seeds, pesticides, and other materials. Gross income was determined by summing the market value of the harvested grain and straw per hectare. Net revenue and benefit-cost ratio were estimated as follows:

Net revenue = Gross revenue (NRs. ha^{-1}) – total farming expenses (NRs. ha^{-1})

$$\text{B: C ratio} = \frac{\text{Gross revenue (NRs. ha}^{-1}\text{)}}{\text{Total farming cost (NRs. ha}^{-1}\text{)}}$$

Nitrogen Use Efficiency (NUE) related parameters were computed based on the grain yield and N fertilizer application. Partial Factor Productivity Nitrogen (PFPN) and Agronomic Nitrogen Use Efficiency (ANUE) were calculated using:

$$\text{PFPN} = \frac{\text{Grain yield in N fertilized plot (kg ha}^{-1}\text{)}}{\text{rate of N applied (kg ha}^{-1}\text{)}}$$

$$\text{ANUE} = \frac{\text{Grain yield from N treated plot} - \text{Grain yield from control plot (kg ha}^{-1}\text{)}}{\text{Amount of N fertilizer used (kg ha}^{-1}\text{)}}$$

Data were analyzed using RStudio version 4.4.2. Treatment effects were assessed through analysis of variance (ANOVA), and mean comparisons were conducted through Duncan's Multiple Range Test (DMRT) at 5% significance level.

RESULTS AND DISCUSSION

Grain yield

The grain yield varied significantly among the different nitrogen management treatments ($p \leq 0.05$), with an average mean grain yield of 6.02 Mt ha^{-1}. T7 recorded the highest grain yield (6.79 Mt ha^{-1}), closely followed by NR (6.65 Mt ha^{-1}), which were statistically at par with FFP, LCC, SPAD, and NDVI (Fig. 1). In contrast, the control treatment recorded the lowest grain yield (4.13 Mt ha^{-1}). Several elements influence grain yield, such as fertile tillers, panicle count, proportion of filled grains, and thousand-grain weight. Subsequently, these components are affected by the crop's growth, development, and nutrient uptake. The increment in yield could be credited to the timely use of N fertilizer that aligned with the crop's nutrient requirement, leading to efficient utilization with minimal loss (Ladha et al., 2005).

NE performed better results, giving the highest grain yield among other treatments. This matched the findings from Acharya et al. (2022), who stated that SSNM improves N use by matching crop needs with soil supply. This phenomenon boosted grain filling and increased yield. The NR treatment had also shown good results; it might be due to the recommendation of fertilizer that is developed considering specific domains, regional weather, and crop growth patterns. The findings from Kamruzzaman et al. (2014) supported this, showing that national recommendations are also suitable for increasing N efficiency than general fertilization methods. The LCC and SPAD meter, applying much lower nitrogen doses, showed moderate yield among the treatments, indicating the potential of real-time N management to reduce fertilizer use without affecting the yield. These findings supported the work by Fayaz et al. (2022) and Esfahani et al. (2008), who reported that LCC and SPAD guided top dressing enables real-time N adjustment according to the crop physiological condition, avoiding under- or over-application. The NDVI-based treatment achieved an intermediate yield among the treatments. This might be due to the requirement of further calibration for local conditions such as canopy density and sunlight variability. Kumar et al. (2020) noted that NDVI thresholds were highly site and growth stage-specific, which could explain their relatively lower efficiency in this case compared to NE or NR treatments. The control treatment showed the lowest grain production, showing an N deficiency. Lack of N during the peak growth stages reduced photosynthesis, limited biomass growth, and affected grain development.

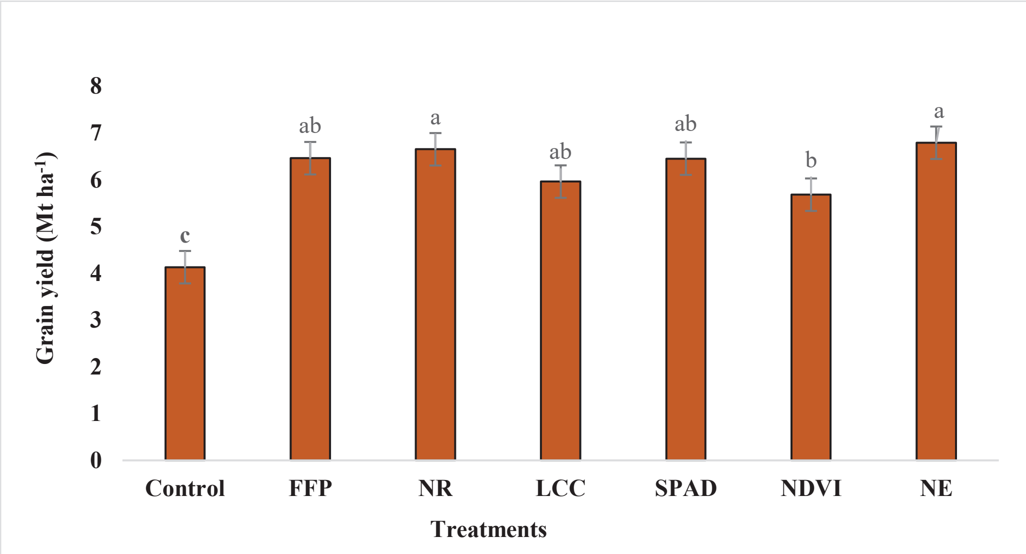

Fig. 1. Effect of various nitrogen management strategies on grain yield of rice in Khumaltar, Lalitpur

(N_0- Control, FFP- Farmers Fertilizer Practices, NR- National Recommendation, LCC- Leaf Color Chart, SPAD- Soil Plant Analysis Development, NDVI- Normalized Difference vegetation Index, NE- Nutrient Expert. Within columns, means followed by common superscript letters are not statistically different ($p<0.05$) according to the LSD test)

Economic performance

Economic evaluation of different nitrogen management strategies showed significant variation in gross revenue, net revenue, and the B: C ratio (Table 2). The cost of cultivation ranged from NRs 140,084.7 ha^{-1} in the control to NRs. 146,123.7 ha^{-1} in the FFP treatment, with a grand mean of NRs 143,048.46 ha^{-1}. Gross revenue was the highest under the Nutrient Expert treatment (NRs 260,281.4 ha^{-1}), followed by the National Recommendation (NRs 256,527.7 ha^{-1}), and SPAD-based N management (NRs 249,443.2 ha^{-1}), while the control had the lowest gross revenue (NRs 163,298.3). Net revenue followed a similar trend, with NE and NR showing the highest net returns (NRs 115,531.27 ha^{-1} and 112,225.51 ha^{-1}, respectively), while NDVI and the control recorded the lowest net revenues (NRs 79,593.08 ha^{-1} and 23,213.6 ha^{-1}, respectively).

The B: C ratio was found the highest for NE (1.79), followed by NR (1.77), while the lowest was found for the control (1.62). The NE, NR, FFP, and sensor-based treatments were at par, showing that rice farmers could maintain high profitability even with reduced N doses when guided by decision-support and real-time diagnostic tools. The higher N rate under FFP did not convert into significantly greater economic returns, showing diminishing response at excessive N levels. In contrast, LCC, SPAD, and NDVI showed moderate profitability at lower input costs, highlighting their potential to improve NUE while maintaining economic sustainability. Similar trends have been reported in other relevant studies. Lamsal et al. (2023) found that LCC-based N management enhanced yield and profitability while reducing fertilizer use compared to conventional practices. Click or tap here to enter text. Parihar et al. (2020)reported that site-specific nutrient management (SSNM) and NE-guided fertilizer application optimized NUE and improved profitability in the rice cropping system. Similar findings by Shrestha et al. (2018) show that NE-based N management increases profitability in rice cropping systems by optimizing input-output ratios.

Table 2. Effect of various nitrogen use strategies on the economic performance of rice in Khumaltar, Lalitpur, 2024

Treatments	Cost of cultivation (NRs ha^{-1})	Gross revenue (NRs ha^{-1})	Net revenue (NRs ha^{-1})	B: C ratio
Control	140084.7	163298.3^{c}	23213.6^{c}	1.26^{c}
FFP	146123.7	248114.3^{ab}	101990.65^{ab}	1.69^{ab}
NR	144302.1	256527.7^{a}	112225.51^{a}	1.77^{ab}
LCC	142452.8	232962.4^{ab}	90509.51^{ab}	1.63^{ab}
SPAD	141116.2	249443.2^{ab}	108326.93^{ab}	1.76^{ab}
NDVI	142309.6	221902.7^{b}	79593.08^{b}	1.56^{b}
NE	144950.1	260481.4^{a}	115531.27^{a}	1.79^{a}
Grand mean	143048.46	233247.1	90198.65	1.63
LSD (=0.05)		31176.48	31176.48	0.22
SEm (±)		10117.94	10117.94	0.07
F-test		***	***	***
CV, %		7.51	19.42	7.55

Note: FFP- Farmers Fertilizer Practices, NR- National Recommendation, LCC- Leaf Color Chart, SPAD- Soil Plant Analysis Development, NDVI- Normalized Difference vegetation Index, NE- Nutrient Expert. Within columns, means followed by common superscript letters are not statistically different (p<0.05) according to the LSD test. LSD= Least Significant Difference, CV= Coefficient of Variation, NS= non-significant, SEm= Standard Error of Mean, '***' denotes significance at 0.001 level.

The results of the study showed that judicious and site-specific, real-time N management could maintain economic performance equivalent to conventional high-input practices while reducing fertilizer requirements. This has significant implications for resource-scarce farmers in Nepal, where excessive N use is common, and fertilizer prices are rising. The economic performance observed in this study aligned with previous research showing the benefits of precision and site-specific nutrient management in rice systems. Studies in Nepal have shown that such approaches significantly increase yield while reducing fertilizer inputs, thereby improving overall economic efficiency (Marahatta et al., 2025). LCC-based nitrogen management is the economically efficient practice for both inbred and hybrid rice varieties, enhancing productivity and profitability through nitrogen conservation and improved utilization efficiency(Subedi & Panta, 2018; Subedi et al., 2019).

Nitrogen use efficiency

The PFPN and ANUE were significantly different among different nitrogen management practices ($p < 0.05$). SPAD showed the highest PFPN and ANUE (137.57 and 49.50, respectively), followed by NDVI (56.29) and LCC (17), respectively. The lowest PFP and ANUE were found in FFP (23.55 and 8.48), respectively. In this study, NUE referred to the quantity of grain yield obtained for each unit of N fertilizer applied. This included the available N for the plant during the growth period, which consisted of the starting levels of inorganic N in the soil, N supplied through fertilizers, and N released from the decomposition of organic matter (Singh et al., 2024). NUE was higher when the yield response to N was substantial. Consequently, NUE was generally higher at low N application rates and tended to decrease as the amount of applied N increased (Fixen et al., 2015).

The sensor-based SPAD meter resulted in higher PFPN and ANUE compared with the conventional approaches. This finding showed that real-time, in-season nitrogen management could enhance NUE by matching N supply with crop demand rather than relying on conventional and fixed rate recommendations (Hasanain et al., 2025). The higher PFPN and ANUE observed under SPAD meter and NDVI, and LCC treatments suggested a more efficient conversion of applied N into grain yield per unit N. NUE declined as applied N increased beyond the crop's incremental response threshold. So, adopting an optimized N rate based on crop status enabled the maintenance of yield while reducing N inputs, thereby improving efficiency metrics (Mitra et al., 2023). FFP showed the lowest efficiency; this low efficiency may result from excessive application of N fertilizer during the early crop cycle, without considering the N fertilizer already present in the soil or the crop's growth stages. Alam et al. (2023) noted that traditional farming often led to uneven N use, resulting in lower fertilizer efficiency.

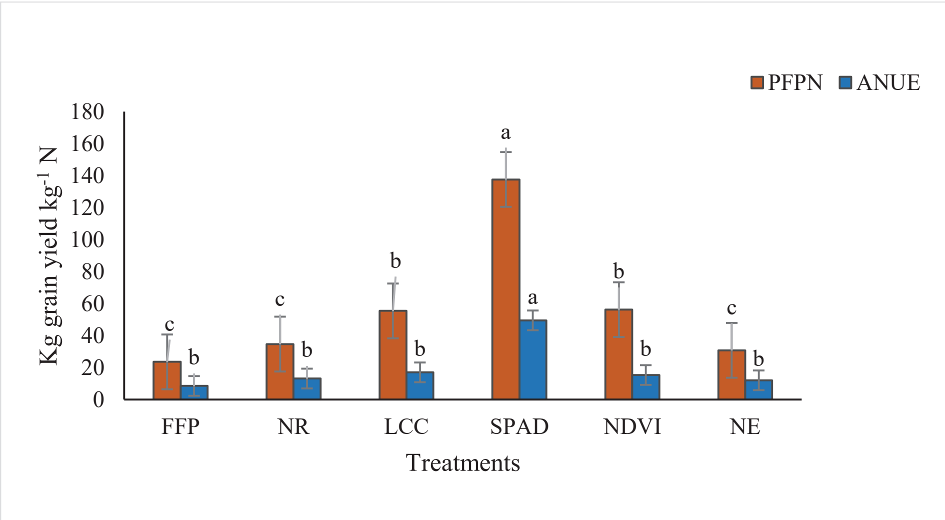

Fig. 2. Effect of various nitrogen application strategies on partial factor productivity (PFP) and agronomic nitrogen use efficiency (ANUE) of rice in Khumaltar, Lalitpur, 2024

(Note: FFP- Farmers Fertilizer Practices, NR- National Recommendation, LCC- Leaf Color Chart, SPAD- Soil Plant Analysis Development, NDVI- Normalized Difference Vegetation Index, NE- Nutrient Expert. Within columns, means followed by common superscript letters are not statistically different ($p<0.05$).

CONCLUSION

The research evaluated the performance of precision N management tools on the productivity, economics, and NUE of rice in the mid-hills of Nepal. All the N applied treatments significantly outperformed the treatment with no nitrogen (N_0), highlighting the critical role of N in rice cultivation. NE and NR treatments achieved the highest yield and economic returns, while sensor/chart-based tools such as SPAD, LCC, and NDVI made comparable performance with reduced N inputs. These findings demonstrated that the real-time, site-specific N management could enhance yield and profitability, improve NUE, and minimize input requirements, offering a viable alternative to conventional fertilizer practices. This study also highlighted the need for future research to validate precision N management tools across multiple seasons and locations under diverse agroecological conditions in Nepal to develop general recommendations for farmers.

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AUTHOR CONTRIBUTIONS

SP: Methodology, Data curation, Software, Visualization, Validation, Formal analysis, Writing – original draft; **LPA:** Supervision, Conceptualization, Validation, Writing – review & editing, Visualization, Resources; **AG:** Supervision, Validation, Writing – review & editing, Visualization; **SK:** Supervision, Conceptualization, Resources.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICAL APPROVAL AND PERMITS

Not applicable.

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