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Precision Nitrogen Management in Spring Rice (*Oryza sativa* L.) using Decision Support Tools in Chitwan, Nepal

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ABSTRACT

The blanket prescription of nitrogen (N) fertilizer often results in irrational fertilization. To address this issue and align the application of nitrogen fertilizers with the crop-specific demand, it is imperative to save nitrogen resources, maximize the uptake and net income, and subside environmental pollution. In this context, a field experiment was carried out in Kumroj, Chitwan, Nepal during 2022 to assess the growth, yield, and profitability of rice production by comparing different precision nitrogen management practices. The study was carried out in a randomized complete block design with seven treatments and three replications. The treatments included decision support tools for nitrogen management such as the Green Seeker (GS), the Soil plant analysis development Development (SPAD) meter, and the Leaf Color Chart (LCC) combined with basal application of nitrogen at 30 kg ha^{-1} and the Urea briquette Deep Placement (UDP), the Polymer Coated Urea (PCU), and the Recommended Dose of Fertilizers (RDF, 120 kg N ha^{-1}). The growth, yield, yield attributes, and financial data were taken. Precision nitrogen management techniques significantly enhanced rice growth and yield parameters. GS–guided application required the highest nitrogen demand (155 kg ha^{-1}), while SPAD (80 kg ha^{-1}) and UDP (78 kg ha^{-1}) resulted in lower usage. PCU and UDP enhanced plant height, leaf area index, and above–ground dry matter. Higher grain yield (6.64 t ha^{-1}) was attained with LCC, SPAD (6.44 t ha^{-1}), and UDP (6.41 t ha^{-1}) treatments. GS application exhibited the highest straw yield (11.17 t ha^{-1}), while LCC demonstrated the highest benefit–cost ratio (1.96). This study concluded that SPAD and UDP demonstrated the potential to save nitrogen resources, while LCC and UDP were found profitable.

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Introduction

Nitrogen (N) stands as the foremost essential nutrient in rice production across the globe. Tailoring N–fertilizer application based on demand and thorough in-situ examination can significantly enhance rice production (Bo et al., 2020). This approach not only boosts yield by enhancing grain filling quality, increasing tiller numbers, and improving plant vitality, but also maintains and regulates the physiological processes of rice (The et al., 2021). The fixed rate and predetermined timing of nitrogen application might need to be revised to align effectively with the actual nitrogen requirements of the crop (Colaco & Bramley, 2018). Excessive nitrogen application can lead to extreme plant height, susceptibility to pest infestations, lodging, inadequate canopy light, reduced fertility rates, and delayed maturation (Ali et al., 2017). Furthermore, it can elevate nitrogen losses through various processes (Li et al., 2017), ultimately leading to a lower recovery efficiency of N of about 30% (Baral et al., 2020). The recovery efficiency of N of significant cereal crops betrays a relatively low rate of around 33%, as reported by Chaudhary et al. (2019). Applying precision and decision–supportive tools for nitrogen management becomes imperative to solve these challenges. Precision nitrogen management employs a range of tools and technologies to collect data on spatial and temporal variations within a field, which is then utilized to align inputs following the distinct conditions of each specific location within the field (Godwin et al., 2003; Diacono et al., 2013). According to Chaudhary et al. (2019), the foundation of precision nitrogen management lies in adhering to the ‘4 R’s Principle, which involves administering fertilizers at the right rate, at the right time, by the right way of application, and by utilizing the right fertilizer source. The various precision nitrogen management tools used in rice cultivation include the LCC (Alam et al., 2013), SSNM (Chaudhary et al., 2019), SPAD meter (Xiong et al., 2015), Green seeker as crop canopy sensor (Ali et al., 2015), crop simulation models (Chaudhary et al., 2019), coated fertilizers, and controlled–release N–fertilizers (Gaihre et al., 2015). These tools contribute to nitrogen management strategies by synchronizing cereal crops' nitrogen demands with nitrogen supply from applied fertilizers. Urea prill coating using a diverse range of materials, including sulfur, synthetic polymers, and neem–coated materials, has emerged as a strategy to counter the challenges (Azeem et al., 2017) and has demonstrated the potential to enhance crop yields, nutritional content, and overall agro–ecological conditions, as evidenced by Abdullah et al. (2022). The use of controlled–release N–fertilizers by placing in a deeper level of soil enhances the production of rice, enhances NUE, and mitigates nitrogen losses (Bandaogo et al., 2015; Zheng et al., 2017; Yao et al., 2018). Manual deep placement of Urea Briquettes (UB) has been shown to enhance yields by (15.0–20.0%) and improve the agronomic effectiveness of NUE by (50.0–70.0)% (Bulbule et al., 1996). This technique has also substantially increased rice grain yields from (11.0–86.0%) (Deep et al., 2020). The GS employs the evaluation of the Normalized Difference Vegetation Index (NDVI), which relies on the reflection of light in the red and near–infrared regions. NDVI, a vegetation index derived from empirical observations and intricately linked to the leaf area index, is a predictive indicator for biomass and yield (Raun et al., 2002). It leads to a noteworthy enhancement of 6.0–22.0 % in nitrogen recovery efficiency and an increase of 5.0–12.0 kg grain per kg of applied nitrogen in agronomic efficiency (Singh et al., 2015). Chlorophyll meters offer a rapid assessment of leaf nitrogen (N) status by clamping onto leaf tissue based on chlorophyll content (Balasubramanian et al., 1999). Maintaining nitrogen fertilizer applications above a certain threshold is crucial to prevent yield losses, and this threshold may vary across different rice cultivation fields (Balasubramanian et al., 1999). The SPAD meter can signal potential nitrogen deficiency before affecting crop yield (Peng et al., 1996). The critical SPAD values, ranging from 35 to 37, have been established for semi–dwarf indica varieties of rice (Singh, 2008). Two main methods have been adopted for nitrogen assessment: (a) when the recorded SPAD value falls below a predetermined critical threshold (Maiti et al., 2004) and (b) when the sufficiency index drops below 0.90 for rice (Hussain et al., 2000). By adopting nitrogen management based on SPAD meter readings, a better Nitrogen Use Efficiency (NUE) has been achieved which is significantly higher compared to conventional methods (Singh et al., 2015)

The underlying concept of the LCC is rooted in the strong correlation between leaf chlorophyll and nitrogen content throughout various stages of growth. The LCC shows a range of yellowish green to dark green, with values from 1.0–6.0, displaying a spectrum of green shades corresponding to the wavelength properties of rice leaves. Shukla et al. (2004) identified an essential LCC value (4.0) for inbred rice cultivars. Maiti et al. (2004) determined a critical LCC value of (4.0) for transplanted rice in the northeastern region of India. They demonstrated the potential to save (20.0–42.0) kg N per hectare, resulting in a notable increase of (59.0–68.0%) in NUE compared to the blanket recommendation. Similarly, Marahatta (2017) concluded that the LCC–guided nitrogen application led to a yield increase of 0.31 metric tons per hectare compared to farmers' conventional practices.

The current rice production of Nepal is 5130665 mt with a productivity of 3.47 mt ha^{-1} (MoALD, 2022). This production is not enough to meet the increasing demand of rice (Thapa & Bhusal, 2020). Thus, it is imperative to enhance rice productivity to reach the achievable yield (>8.0 t ha$^{–1}$) within the constraints of limited land (Devkota, 2017). The current government's fertilizer recommendations are generalized based on national irrigation patterns rather than tailored to specific soil properties, climates, and crop management needs. It is crucial to conduct a comparative assessment of various nutrient management techniques, such as LCC and SPAD meters. Optical sensor–based methods, and nutrient expert recommendations vary across diverse geographical locations within the country (Baishya et al., 2022). As Baral et al. (2021) highlighted, implementing GS demands a higher level of technical proficiency, potentially necessitating farmer training to facilitate broader adoption. Regarding practical application, UDP and PCU might not require extensive technical expertise but entail significant labor input. On the other hand, LCC stands out as user–friendly and cost–effective. Thus, this research underscores the benefits of diverse nitrogen management strategies and application techniques, which can prove advantageous for rice cultivators in enhancing NUE without compromising yields.

Materials and methods

Experimental Site

The experiment was conducted in the Small Farmers Cooperative Organization field in Kumroj, Chitwan, Nepal, from February to June 2022. The site features a humid subtropical climate at 228 meters above mean sea level. Its coordinates are 27°04' north latitude and 84°02' east longitude.

Climatic Conditions during Experimentation

The meteorological data for the 2022 cropping season, shown in Figure 1, was obtained from NASA Power. For the period of five months from February to June, the average maximum and minimum temperatures were 33°C and 22°C. Similarly, the total rainfall during the experiment was 450.9 mm, with the highest rainfall of 291 mm, whereas the average relative humidity was 94.94%.

Physio–Chemical Properties of Soil

The composite soil samples (W pattern) were taken from 0–15.0 cm layers of the experimental field with the help of a soil auger. The sample was first air–dried, ground, and then sieved through two separate sieves: a (2.0) mm sieve for pH analysis, total nitrogen, available phosphorus, and potash, and a 0.5 mm sieve for organic matter as mentioned by Gikonyo et al. (2022). . The details of the soil properties from the field are presented in Table 1.

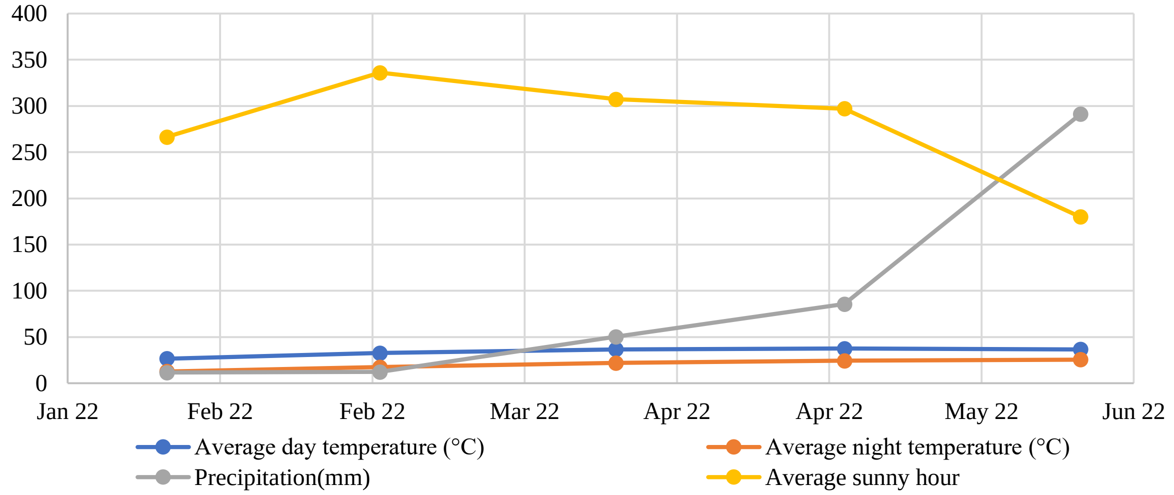

Figure 1. Meteorological data of the experimental site between February and June 2022.

Table 1. Soil analysis results.

Factors	Average Value	Fertility	Method
Soil texture	Loamy		Hydrometric Bouyoucos (1927)
Organic matter (%)	1.57	Low	Walkley and Black (1934)
Total N (%)	0.08	Low	Kjeldahl Bremner and Mulvaney (1982)
Available P_2O_5 (Kg ha^{-1})	120.4	High	Modified Olsen (1954)
Exchangeable K_2O (Kg ha^{-1})	145.2	Medium	Ammonium Acetate Jackson (1967)
pH	7.3	Neutral	Potentiometric Jackson (1973)

Table 2. Treatment details used in the experimental study.

Treatments	Symbol used
30 kg ha^{-1} N basal + 25 kg ha^{-1}N when GS<0.80	GS
30 kg ha^{-1} N basal + 25 kg ha^{-1}N when SPAD <36	SPAD
30 kg ha^{-1} N basal + 25 kg ha^{-1}N when LCC ≤4	LCC
120 kg ha^{-1}N basal PCU	PCU
78 kg ha^{-1}N basal UDP	UDP
RDF 120 kg ha^{-1} N. Split at 40 kg ha^{-1}N basal application + 40 kg ha^{-1} N top dressing at maximum tillering and panicle initiation	RDF
Control (0 kg ha^{-1} Nitrogen)	Control

Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}), Urea deep placement; SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker; DAT, days after transplanting.

Experimental Details

The experiment was conducted in RCBD, comprising seven treatments and three replications. The plot was 2.4 m x 1.6 m, with a 30 cm x 20 cm plant spacing. Rice was transplanted in 8 rows. The transplanting was done on the 19th of March 2022, and harvesting was carried out on the 25th and 26th of June 2022.

Crop Management Practices

The 21 days old rice seedlings were transplanted in the field. The field was ploughed properly, about ten days prior to transplanting. The recommended fertilizer dose (RDF) for rice is 120–60–60 kg N, P_2O_5, and K_2O ha^{-1} (MoALD, 2022). This recommended dose was supplied in the form of Urea, single superphosphate (SSP), and Muriate of Potash (MoP). The basal application of phosphorus and potash was done completely during transplanting. Nitrogen fertilizers were applied @30 kg ha^{-1} in basal dose, and the remaining were applied as per the recommendations from the LCC, SPAD, and GS. However, for PCU and UDP, a single application of 120 kg ha^{-1} N and 78 kg ha^{-1} N, respectively, were applied as basal. Weeding was done manually at 30 and 45 Days After Transplanting (DAT). Irrigation and drainage were performed when necessary.

Observations and Measurements

Leaf Color Chart Observations

Readings were taken from 10 independently selected healthy rice plants, from the topmost fully open leaf in each plot after 30 days of transplantation at 10 days intervals. It was taken in the morning between (8.00–10.00) a.m. and kept under the body's shade to prevent the influence of sunlight, which may reflect the LCC color. The leaf was adjusted vertically so that the LCC crossed horizontally. The greenness of the leaves was compared with the six stripes of LCC, and whenever the average readings were below or equal to threshold 4, nitrogen was top–dressed at a rate of 25 kg ha^{-1}.

SPAD observations

SPAD readings were also taken after 30 days of transplanting rice at 10 days intervals between (8.00–10.00) a.m. The average SPAD readings of 10 plants were recorded from fully expanded uppermost leaves of disease–free plants. The upper, wide center part of the leaf was placed on the SPAD meter, and a reading was displayed, directly correlating with the crop's nitrogen status. Whenever the SPAD readings were less than 36, then 25 kg ha^{-1} of nitrogen was top–dressed.

Green seeker observations

GS readings were also taken after 30 days of transplanting rice at 10 days intervals between (8.00-10.00 a.m.) The readings were taken from the whole central portion of the plot. The device was monitored above the crop, maintaining a 30 cm distance from the crop, and the average reading was displayed on GS, which directly correlated with the crop's nitrogen status. Billa et al. (2020) found an ideal critical GS value of 0.80 for higher yield of rice. Whenever the GS readings were less than 0.80, 25 kg ha^{-1} of nitrogen was top–dressed according to the treatment.

Biometrical observations

Phenological stages, such as tillering, panicle initiation, and physiological maturity, were recorded from the fourth row. The completion of each stage was determined when approximately 50% of the plants in the selected row reached that particular development stage. This day was then treated as the completion of that stage and expressed as days after transplanting (DAT).

Plant height (cm)

Plant height is defined as the distance between the ground and the tip of the highest leaf in seedlings or juvenile plants. It was measured from 10 randomly selected plants from the non–destructive sampling rows. Data were taken at 15 days intervals, starting one month after transplantation and continuing until the maturity stage of the crop.

Leaf area index (LAI)

In each plot, second row was used to measure the leaf area (cm2) of the functioning leaves that were obtained from plant samples). After 30 days of transplanting, measurement was done at 15 days interval using an automated leaf area meter to the physiological maturity stage. The following formula was used to determine the plant's leaf area index (Raj et al., 2021).

LAI = Leaf Area Crop Geometry

Number of tillers per square meter (No)

Tillers from the fourth row, measuring (1.6) m in length, of each plot, were counted at 15 days intervals, starting from 30 days to the physiological maturity stage. The number of tillers per square meter was obtained through calculation.

Dry matter accumulation (g)

The dry matter accumulation was studied from the plants that were chosen for measurement of leaf area by uprooting. The dry matter was obtained by drying the leaves and tillers in a hot air oven at 70°C for one week until a constant weight was achieved. The above–ground dry matter was measured at 15 days intervals, starting from 30 DAT to the physiological maturity stage.

Yield Components

Thousand–grain weight (g)

One thousand seeds were totaled from the yield of the net plot and weighed, along with the moisture percentage. The thousand–grain weight was expressed at a 12% moisture level.

Grain yield (kg ha^{-1})

The plants within the net plot were first harvested. The plants were threshed, grains were separated, cleaned, and weighed. The moisture content was recorded immediately with the help of a moisture meter. After that, the grain yield was computed for the yield per hectare, and the moisture percent was converted to 12% using the following formula (Shahidullah et al., 2009):

Grain yield (kg ha^{-1}) at 12% moisture = (((100 - MC) × plot yield(kg))/ ((100-12) × net plot area (m^2))) × 10000 (m^2)

where, MC= moisture content in percentage of the grains.

Straw yield (kg ha^{-1})

The straw yield was computed by subtracting the grain weight from the total biomass and was expressed at zero percent moisture content.

Harvest Index (HI)

The harvest index (HI) was computed by dividing the grain yield by the total biological yield. Both the grain yield and straw yield were brought to a moisture content of 0% and were computed using the following formula (Yang et al., 2020).

$$\text{HI}=\frac{\text{Grain yield at 0\% moisture}}{\text{Grain yield at 0\% moisture+straw yield at 0\% moisture}}$$

Financial Analysis

Cost of cultivation (NRs ha^{-1})

The cultivation costs were determined based on the expenses incurred for different inputs, labor, machineries, etc. under the existing market prices at the time of experiment.

Gross return (NRs ha^{-1})

Based on current market prices for the farmers, the grain yield (t ha^{-1}) and straw yield (t ha^{-1}) (economic yield) were converted into gross returns (NRs ha^{-1}).

Net returns (NRs ha^{-1})

To calculate net returns per hectare (NRs ha^{-1}), the gross returns were subtracted from the cultivation cost. Since it represents the actual income of producers, it is useful in determining whether the cropping system is appropriate.

Benefit–cost Ratio

The Benefit–cost (B: C) ratio was computed by dividing the gross return by the cultivation costs (Thapa et al., 2019).

$$\text{B:C Ratio}=\frac{\text{Gross Return}}{\text{Cost of Cultivation}}$$

Statistical Analysis

Data entry was done using MS Excel, and R Studio software was used for data analysis. The results were subjected to Duncan's Multiple Range Test (DMRT) for mean comparison at a 5% significance level.

Results

Total nitrogen applied for rice fertilization

The data on the amount of nitrogen applied using LCC, SPAD, GS, UDP, and PCU is presented in Table 3. The average amount of nitrogen applied in the experiment was 94 kg ha^{-1}. The amount of nitrogen used in different precision nitrogen management practices differed significantly. The highest amount of nitrogen (155 kg ha^{-1}) was used with GS, whereas SPAD consumed a significantly lower amount of nitrogen (80 kg ha^{-1}), and UDP consumed an even lower amount (78 kg ha^{-1}) of N. The treatments SPAD, LCC, and UDP were more efficient than blanket application of the RDF. Use of SPAD, LCC and UDP saved 40, 15, and 42 kg ha^{-1} N, respectively. In contrast, GS led to use of more nitrogen than RDF, an excess of 35 kg ha^{-1} N.

Biometrical observations

Plant height (cm)

Data collected at 30, 45, 60, and 75 DAT revealed significant effects of nitrogen management practices on plant height across all growth stages compared to the control (N0). The mean plant height increased throughout the crop growth period, ranging from 25.5 cm to 104.5 cm at the final harvest. At 30 DAT, plant height exhibited distinct variations, with the PCU treatment yielding the tallest plants (64.46 cm), followed by the UDP treatment (58.72 cm), and the control treatment displaying the lowest height of 49.00 cm. At 45 DAT, UDP exhibited a higher height (88.13 cm), statistically similar to LCC (82.53 cm), with the lowest (65.66 cm) in control.

Table 3. Total nitrogen (kg ha^{-1}) applied in rice influenced by precision management at Kumroj, Chitwan, 2022.

Treatments	Nitrogen Added	Loss/Excess
GS	155^{a}	35
SPAD	80^{d}	–40
LCC	105^{c}	–15
PCU	120^{b}	0
UDP	78^{e}	–42
RDF	120^{b}	0
Control(N_0)	0^{f}	–120
ANOVA (p values)	0.000***	
CV	1.77	
SEm (±)	9.63	
Grand mean	94	–26

Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}); SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker. Treatment means followed by a common letter(s) are not significantly different from each other based on DMRT at the 5% level of significance; DAT, days after transplanting; DMRT, Duncan's Multiple Range Test; CV, coefficient of variation; SEm, standard error of the mean.

Table 4. Amount and time of nitrogen application in rice influenced by precision nitrogen management at Kumroj, Chitwan, 2022.

Treatments	Time of application	Replication	GS	SPAD	LCC	PCU	UDP	RDF	Control (N_0)
N added (kg ha^{-1})	Basal	R1	30	30	30	120	78	40	0
		R2	30	30	30	120	78	40	0
		R3	30	30	30	120	78	40	0
	30 DAT	R1	25	25	25	0	0	40	0
		R2	25	25	25	0	0	40	0
		R3	25	0	25	0	0	40	0
	40 DAT	R1	25	0	0	0	0	0	0
		R2	25	0	25	0	0	0	0
		R3	25	25	25	0	0	0	0
	50 DAT	R1	25	25	25	0	0	0	0
		R2	25	25	0	0	0	0	0
		R3	25	25	25	0	0	0	0
	60 DAT	R1	25	0	25	0	0	40	0
		R2	25	0	25	0	0	40	0
		R3	25	0	0	0	0	40	0
	70 DAT	R1	25	0	0	0	0	0	0
		R2	25	0	0	0	0	0	0
		R3	25	0	0	0	0	0	0
N mean			155	80	105	120	78	120	0
N saved compared to RDF (120 kg ha^{-1})			–35	40	15	0	42	0	120

Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}), Urea deep placement. SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker. Treatment means followed by a common letter(s) are not significantly different from each other based on DMRT at the 5% level of significance; DAT, days after transplanting.

Table 5. Plant height of rice and leaf area index as influenced by precision nitrogen management at Kumroj, Chitwan, 2022.

Treatments	Plant height (cm)				Leaf area index (LAI)			
	30 DAT	45 DAT	60 DAT	75 DAT	30 DAT	45 DAT	60 DAT	75 DAT
GS	55.20^{bc}	79.26^{bc}	95.50^{abc}	108.20^{bc}	5.77^{bc}	11.33^{a}	14.69^{b}	16.66^{ab}
SPAD	54.96^{bc}	73.46^{c}	88.70^{c}	119.46^{ab}	4.63^{bc}	10.77^{a}	14.11^{b}	19.36^{a}
LCC	58.26^{b}	82.53^{ab}	98.10^{ab}	108.53^{bc}	3.94^{c}	11.80^{a}	14.00^{b}	14.36^{abc}
PCU	64.46^{a}	76.20^{c}	91.13^{bc}	105.73^{c}	8.00^{a}	13.55^{a}	21.66^{a}	13.08^{bcd}
UDP	58.72^{ab}	88.13^{a}	102.23^{a}	122.23^{a}	6.38^{ab}	12.61^{a}	18.16^{ab}	10.30^{cd}
RDF	54.93^{bc}	75.40^{c}	93.00^{bc}	109.40^{bc}	4.75^{bc}	7.77^{b}	14.69^{b}	10.19^{cd}
Control(N_0)	49.00^{c}	65.66^{d}	76.06^{d}	93.36^{d}	3.50^{c}	4.50^{c}	8.91^{c}	7.88^{d}
ANOVA (p)	0.003**	0.000***	0.000***	0.005**	0.007**	0.000***	0.002**	0.007**
CV	5.79	4.15	4.35	6.26	22.23	14.17	16.84	23.28
SEm (±)	1.88	1.85	2.31	3.96	0.67	0.84	1.47	1.76
Grand mean	56.50	77.23	92.10	109.56	5.28	10.33	15.17	13.12

Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}), Urea deep placement. SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker. Treatment means followed by a common letter(s) are not significantly different from each other based on DMRT at the 5% level of significance; DAT, days after transplanting; DMRT, Duncan's Multiple Range Test; CV, coefficient of variation; SEm, standard error of the mean.

Heights for GS (79.26 cm), PCU (76.20 cm), RDF (75.40 cm), and SPAD (73.46 cm) were intermediate and statistically similar. At 60 DAT, UDP displayed a higher height (102.23 cm), on par with LCC (98.10 cm) and GS (95.50 cm); the lowest (76.06 cm) was in control. At 75 DAT, UDP showed a higher height (122.23 cm), statistically at par with SPAD (119.46 cm), and the lowest (93.36 cm) was in control. This manifested an influence of nitrogen management on early plant growth, as indicated by the significant differences in plant height across treatments at this stage.

Leaf Area Index

The results indicated a substantial influence of the applied treatments on the leaf area index (LAI). At 30 DAT, the PCU treatment resulted in the highest LAI (8.00), statistically higher than the UDP's (6.38). Similarly, at 45 DAT, PCU showed a significantly higher leaf area index (13.55) compared to RDF (7.70) and control (4.50) and was statistically on par with UDP (12.61), followed by LCC, GS, and SPAD treatment groups. By 60 DAT, PCU retained the highest leaf area index, followed by UDP (18.16). GS, RDF, SPAD, and LCC exhibited significantly lower leaf area index than PCU but were statistically similar. Lastly, at 75 DAT, SPAD displayed the highest leaf area index (19.36), statistically significant with GS and LCC's LAI. These findings suggest that the PCU treatment can notably enhance the leaf area index during early growth stages, while treatments like SPAD might be more effective later.

Above–ground dry matter (kg ha^{-1})

Precision nitrogen applications significantly influenced dry matter production across various growth stages. At 30 and 45 DAT, UDP treatment showed the highest above–ground dry matter (158.21 and 432.04 kg ha^{-1}, respectively). RDF's above–ground dry matter was statistically on par with UDP's at 45 DAT with 379.43 kg ha^{-1}. At 60 DAT, GS resulted in the most remarkable above–ground dry matter (777.55 kg ha^{-1}), statistically similar to that of LCC, UDP, and RDF. At 75 DAT, SPAD recorded the highest above–ground dry matter (985.35 kg ha^{-1}), showing no significant difference from LCC (947.67 kg ha^{-1}) and GS (940.15 kg ha^{-1}). These results suggested that precision nitrogen management impacts dry matter production, with varying effects observed across growth stages.

Number of tillers per square meter (no)

The impact of precision nitrogen management on rice tiller numbers is evident across growth stages. Precision nitrogen management significantly influenced rice tiller numbers, with PCU and UDP–treated plots performing well throughout various stages. At 30 DAT, the PCU treatment showed the highest tiller number (466.66), significantly differing from the control plots (230.55). At 45 DAT, the effects of LCC, PCU, and UDP were observed to be statistically similar, showing higher tiller numbers than the control. At 60 and 75 DAT, PCU and UDP resulted in statistically similar tiller numbers, whereas PCU showed significant differences compared to SPAD, GS, RDF, LCC, and control plots.

Yield and yield parameters

Panicle Length (cm)

The mean panicle length in response to various precision nitrogen management treatments was found to be highly significant among the treatments used. The UDP treatment resulted in the most extended panicle length at 24.50 cm, followed by GS (22.46 cm) and LCC (22.16 cm). The PCU and RDF treatments had a panicle length of 21.90 cm, statistically on par with the panicle length observed in SPAD's treatment. The lowest panicle length value was recorded in the control (N0) treatment at 18.70 cm, which was significantly different from all other treatments.

Thousand–grain weight (g)

The precision nitrogen management treatments influenced the thousand–grain weight (TGW) significantly. In the experimental study, the SPAD treatment was found to have the highest grain weight at 24.61 g and was significantly different (higher) from all other treatments. It was followed by the LCC treatment (23.12 g), which was statistically similar to the GS treatment.

Days to heading (days)

Days to panicle emergence significantly varied among different precision nitrogen management treatments. The UDP treatment had the highest value for days to heading (64.33 days) and was significantly different from all other treatments, followed by the LCC treatment at 63.00 days, which was not statistically at par with the GS and RDF treatments. The control (N0) treatment had the lowest value at 58.66 days, indicating the earliest heading in the crops.

Table 6. Dry shoot biomass and tiller number of rice as influenced by precision nitrogen management at Kumroj, Chitwan, 2022.

Treatments	Above–ground dry matter (kg ha^{-1})				Tiller number per square meter (no)			
	30 DAT	45DAT	60DAT	75DAT	30 DAT	45 DAT	60 DAT	75DAT
GS	97.71^{bc}	232.71^{cd}	777.55^{a}	940.15^{ab}	369.44^{ab}	288.88^{bc}	291.66^{b}	286.11^{b}
SPAD	96.54^{bc}	270.58^{c}	582.54^{bc}	985.35^{a}	305.55^{bc}	341.66^{ab}	313.889^{b}	288.88^{b}
LCC	88.71^{bc}	273.08^{c}	758.91^{a}	947.67^{ab}	291.66^{bc}	402.77^{ab}	294.44^{b}	275.00^{b}
PCU	114.87^{b}	313.26^{bc}	539.81^{c}	843.16^{bc}	466.66^{a}	416.66^{a}	336.66^{a}	330.55^{a}
UDP	158.21^{a}	432.04^{a}	737.76^{a}	801.59^{c}	347.22^{abc}	327.77^{abc}	336.11^{ab}	308.33^{ab}
RDF	99.87^{bc}	379.43^{ab}	725.54^{ab}	842.85^{bc}	308.33^{bc}	361.11^{ab}	294.44^{b}	275.00^{b}
Control (N_0)	68.61^{c}	153.07^{d}	473.72^{c}	632.69^{d}	230.55^{c}	211.11^{c}	197.22^{c}	186.11^{c}
ANOVA(p)	0.011^{*}	0.000^{***}	0.002^{**}	0.000^{***}	0.022^{*}	0.026^{*}	0.000^{**}	0.000^{***}
CV	21.63	15.78	12.29	8.32	19.81	18.85	8.97	7.22
SEm (±)	12.93	26.74	46.60	41.16	37.89	36.54	15.50	11.62
Grand mean	103.50	293.45	656.55	856.21	331.3492	335.71	299.20	278.57

Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}), Urea deep placement. SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker. Treatment means followed by a common letter(s) are not significantly different from each other based on DMRT at the 5% level of significance; DAT, days after transplanting; DMRT, Duncan's Multiple Range Test; CV, coefficient of variation; SEm, standard error of the mean.

Table 7. Grain yield, straw yield, and yield attributes of rice as influenced by precision nitrogen management at Kumroj, Chitwan, 2022.

Treatments	Panicle length (cm)	Days to heading	Thousands grain weight (gm)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index
GS	22.46^{b}	64.33^{a}	22.48^{abc}	5.82^{b}	11.17^{a}	0.34^{b}
SPAD	19.93^{cd}	61.00^{bc}	24.61^{a}	6.44^{a}	9.70^{ab}	0.40^{a}
LCC	22.16^{b}	63.00^{ab}	23.12^{ab}	6.64^{a}	10.76^{ab}	0.38^{ab}
PCU	21.90^{bc}	61.33^{bc}	22.09^{bc}	5.81^{b}	9.48^{b}	0.38^{ab}
UDP	24.50^{a}	61.66^{ab}	21.06^{bc}	6.41^{a}	9.61^{ab}	0.40^{a}
RDF	21.90^{bc}	61.66^{ab}	20.68^{c}	6.27^{ab}	9.95^{ab}	0.39^{ab}
Control(N_0)	18.70^{d}	58.66^{c}	17.94^{d}	3.32^{c}	6.22^{c}	0.34^{b}
ANOVA (p)	0.001^{**}	0.016*	0.000^{***}	0.000^{***}	0.000^{***}	0.08
CV	5.27	2.40	5.33	5.19	8.62	7.01
SEm (±)	0.65	0.85	0.66	0.17	0.27	0.008
Grand mean	21.65	61.66	21.71	5.81	9.56	0.37

Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}), SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker. Treatment means followed by a common letter(s) are not significantly different from each other based on DMRT at the 5% level of significance; DAT, days after transplanting; DMRT, Duncan's Multiple Range Test; CV, coefficient of variation; SEm, standard error of the mean.

Grain yield (kg ha^{-1})

Precision nitrogen management treatments significantly enhanced the grain yield of rice. The superior grain yield (6.64 t ha^{-1}) was observed for the LCC treatment, which was statistically commensurate with the SPAD (6.44 t ha^{-1}) and UDP (6.41 t ha^{-1}) treatments. Meanwhile, the control (N0) treatment had the lowest value at 3.32 t ha^{-1} and was significantly less than all other treatments.

Straw yield (kg ha^{-1})

Precision nitrogen management in rice field crops significantly influenced the total straw yield. Among the treatments, the GS treatment had the highest straw yield at 11.17 t ha^{-1} and was reported to be significantly different (higher) than the control plot. The LCC treatment had the second–highest value at 10.76 t ha^{-1} and was not significantly different from the RDF treatment, which had a value of 9.95 t ha^{-1}. Straw yields obtained from SPAD and UDP applied plots were significantly lower than those of RDF and GS, with yield values of 9.70 and 9.61, respectively. The control (N0) treatment had the lowest value at 6.22 t ha^{-1} and was significantly lower than all other treatments.

Harvest Index (HI %)

The mean harvest index was 0.37. Nitrogen management practices showed a significant effect on the harvest index. The harvest index ranged from 0.34 to 0.40. The lowest harvest index was found on the control (0.34), and the harvest index of all other N–applied treatments differed significantly.

Financial analysis

Different treatments were applied to a crop, with the Control (N0) treatment having the lowest Cost of cultivation at 61.600 NRs. thousand ha^{-1}. The UDP treatment had the second–lowest Cost at 63.600 NRs. Thousand ha^{-1}, not significantly different from the RDF treatment at 63.940 NRs. thousand ha^{-1}. The LCC treatment had the highest Cost at 64.225 NRs. Thousand ha^{-1}, statistically similar to the GS treatment at 64.600 NRs. thousand ha^{-1}. Regarding gross return, the LCC treatment resulted in highest return of 126.286 NRs. thousand ha^{-1}, while the Control treatment (N0) had the lowest (63.080 NRs. thousand ha^{-1}). Regarding net returns, the LCC treatment again led with 62.061 NRs. Thousand ha^{-1}, similar to the UDP treatment at 58.760 NRs. thousand ha^{-1}. The SPAD and GS treatments showed comparable net returns (56.315 NRs. thousand ha^{-1} and 54.593 NRs. thousand ha^{-1}, respectively). LCC treatment had the highest B: C ratio at 1.96, similar to the UDP treatment (1.92), while the Control treatment (N0) had the lowest (1.02). Overall, the LCC treatment outperformed other treatments in various economic parameters, while the Control treatment consistently showed inferior results.

Table 8. Cost of cultivation, gross return, net return, and B:C ratio as influenced by precision nitrogen management at Kumroj, Chitwan, 2022.

Treatments	Cost of cultivation (NRs. thousand ha^{-1})	Gross return (NRs. thousand ha^{-1})	Net return (NRs. thousand ha^{-1})	B:C Ratio
GS	64.600	119.193^{ab}	54.593^{abc}	1.84^{ab}
SPAD	65.475	121.790^{a}	56.315^{ab}	1.86^{ab}
LCC	64.225	126.286^{a}	62.061^{a}	1.96^{a}
PCU	65.200	110.390^{b}	45.190^{c}	1.69^{b}
UDP	63.600	122.360^{a}	58.760^{a}	1.92^{a}
RDF	63.940	110.580^{b}	46.640^{bc}	1.72^{b}
Control (N_0)	61.600	63.080^{c}	1.480^{d}	1.02^{c}
ANOVA (p)		0.000***	0.000***	0.000***
CV		5.19	12.37	5.15
SEm (±)		3317.76	3317.76	0.05
Grand mean		110525.7	46434.29	1.72

(1 USD = NRs. 131.40); Note: RDF, Recommended dose fertilizer (120 kg N ha^{-1}); SPAD < 36, 25 kg N ha^{-1} when SPAD reading less than 36; LCC ≤ 4, 25 kg N ha^{-1} when LCC reading less than or equal to 4; GS < 0.80, 25 kg N ha^{-1} when GS reading less than 0.80; PCU (120 kg N ha^{-1}), Polymer coated urea; UDP (78 kg N ha^{-1}), Urea deep placement. SPAD, soil plant analysis development; LCC, leaf color chart; GS, Green seeker. Treatment means followed by a common letter(s) are not significantly different from each other based on DMRT at the 5% level of significance; DAT, days after transplanting; DMRT, Duncan's Multiple Range Test; CV, coefficient of variation; SEm, standard error of the mean.

Discussion

Precision nitrogen management significantly influenced the height of the plants. UDP and SPAD treatments, where a lower dose of nitrogen was applied, displayed increased and commensurate plant heights. Baral et al. (2021) found similar results in their study, where UDP–treated plants had the highest plant heights compared to other precise nitrogen management methods. This phenomenon can be attributed to the enhanced nutrient availability throughout the entire growth period, fostering more significant vegetative expansion of the crops (Woyema et al., 2012). Similarly, Ali et al. (2018) found that increasing nitrogen levels led to taller plants due to enhanced photosynthesis rates, assimilated production, and plant dry matter.

In the initial crop growth stages, the LAI remained low, gradually increasing as the crop matured over a specific period. Notably, the LAI peaked at 60 DAT, exhibiting a decline thereafter. Notably, this decrease in LAI observed in the PCU, UDP, and RDF treatments was attributed to parasitic leaves on the lower parts of the crop. However, in the case of the SPAD and LCC treatments, the LAI did not decrease at 75 DAS. Our findings concur with Reena et al. (2017), potentially influenced by later–stage nitrogen application that prolonged leaf vitality. The observed increase in LAI with splitting dose of nitrogen levels might be linked to producing a more significant number of functional leaves. Increased nitrogen application is associated with higher cellular protein content and larger plant cell sizes, leading to greater leaf area and increased photosynthesis rates, resulting in taller plants (Wysocki, 2007). Rahman et al. (2011) observed that higher nitrogen dose and split applications increased photosynthetic rates and leaf area, enhancing total dry matter production which concurs with the findings of our study. LCC, SPAD, and GS treatments showed more significant dry matter accumulation, possibly due to prolonged nitrogen availability, facilitating continuous photosynthate synthesis (Bhardwaj et al., 2010). Deng et al. (2021) found that the PCU treatment had the highest mass due to increased dry matter accumulation in the shoot. The highest grain yield in the UDP treatment followed by the PCU treatment supports this trend. A higher number of tillers were observed in precision nitrogen management methods, including PCU, UDP, SPAD, GS, and LCC. Similarly, Ullah et al. (2018) found that higher nitrogen levels were associated with an increased total number of tillers. This could be attributed to reduced tiller mortality and enhanced tiller production from the main stem due to nitrogen application precisely timed to the crop's needs. This trend aligns with Ali et al. (2011), who noted that increased nitrogen application led to more tillers per square meter. Notably, treatments receiving more nitrogen exhibited a significantly greater total number of tillers per square meter than those without nitrogen application. These findings also correspond with the conclusions of Yousaf et al. (2014). Baral et al. (2021) noted that in the Rupandehi, Morang, and Banke districts of Nepal, the adoption of LCC and Green Seeker (GS)–guided nitrogen management led to significantly increased spike length, higher tiller density, greater thousand–grain weight, and elevated grain yield. These outcomes align with our findings, further supporting the effectiveness of this approach when contrasted with the recommended fixed–time nitrogen splitting and control methods. Reena et al. (2017) discovered that the NUE and yield determination study on wheat, utilizing SPAD and LCC–based nitrogen management, showed that the recommended nitrogen level of 150 kg N ha^{-1} led to enhanced plant attributes and yield. Nonetheless, real–time management with 105 kg N ha^{-1} at specific growth stages resulted comparable results, highlighting the significance of precise nitrogen timing. This observation is in alignment with our findings.

All treatments resulted significantly greater thousand–grain weights compared to those without nitrogen application. Panicle length demonstrated an upward trend with rising nitrogen dose, notably in plots managed using UDP, GS, LCC, and PCU techniques. Similarly, Rai and Khadka (2009) documented a linear spike length increase in response to higher nitrogen dose. Another component is grain yield from the RDF treatment, which was statistically on par with LCC and SPAD, despite these treatments utilizing less nitrogen than RDF. This could be attributed to the improved synchronization of nitrogen availability with the crop's need until the reproductive growth stage. This synchronization led to heightened photosynthesis rates, promoting more significant growth, plant height, and biomass production (Reena et al., 2017; Barad et al., 2018) this likely spurred root growth and functional activity, increasing nutrient extraction from the soil environment to the aerial parts (Barad et al., 2018). Our experimental results for grain yield and total nitrogen uptake align closely with earlier studies (Chittapur et al., 2015; Ghosh et al., 2020), suggesting that precision nitrogen management methods like GS and SPAD values can effectively increase grain and straw yield (Ali et al., 2014). Measuring SPAD, GS, and LCC values at 45 DAT allows for rectifying nitrogen deficiency by applying top-dressing and reducing nitrogen losses from the prevailing recommended practices. Compared to control plots, significantly higher grain yields were observed in treatments involving SPAD, LCC, UDP, and GS. This trend was also noted by Baral et al. (2021), who found increased grain yields in precision nitrogen management methods employing GS, SPAD, and LCC in contrast to N–absent plots. This yield enhancement stemmed from the precision application of nitrogen according to crop requirements.

Conclusion

The study demonstrated the significant impact of precision nitrogen management on spring rice's growth and yield parameters. PCU and UDP treatments consistently outperformed others regarding early plant growth, tiller production, and above–ground dry matter. Financial analysis revealed that LCC and UDP treatments revealed the highest returns and B:C ratios, indicating their economic viability. The use of Green Seeker resulted in the highest straw yield. At the same time, strategies like SPAD and UDP demonstrated lower nitrogen usage (80 kg ha^{-1} and 78 kg ha^{-1}, respectively), underscoring the potential to save nitrogen resources. The rice farmers in Chitwan can be suggested to practice the nitrogen management tools like PCU and UDP for a better yield. The long–term impacts of precision nitrogen management on soil health, nutrient cycling, and sustainable agricultural practices should be explored for future research.

Ethical Statement

Not applicable for this study.

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