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Real-time nitrogen management using decision support-tools increases nitrogen use efficiency of rice

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Abstract Several decision support tools have been proposed for precision nitrogen (N) fertilizer application in rice (*Oryza sativa* L.) to increase nitrogen use efficiency (NUE) and grain yields. However, a comparison of their effectiveness has not been well documented. A field experiment was conducted in western Terai of Nepal during 2017–2018 to identify the appropriate decision support tool for improving NUE and grain yields. Nine N fertilizer management treatments were laid out in a randomized complete block design with three replications. The treatments included a GreenSeeker (GS) optical sensor, soil plant analysis development (SPAD) meter, leaf color

chart (LCC), each of these treatments with basal application of N at 25 kg ha⁻¹, urea briquette deep placement (UDP), and the existing government-recommended practice (RP, 100 kg N ha⁻¹). N fertilizer application guided by decision support tools had a significant ($p < 0.05$) effect on grain yields. UDP produced the highest grain yield (6.80 Mg ha⁻¹) among the treatments. Grain yields were not significantly different among GS, LCC (in combination with basal 25 kg N ha⁻¹), RP, and UDP treatments. However, GS, UDP, and LCC saved N input by 54%, 22%, and 21%, respectively, compared to RP. In addition, GS produced a significantly higher agronomic N use efficiency (ANUE), partial factor productivity of N (PFPN), apparent N recovery (ANR), and utilization efficiency of N (UEN) compared to RP. These results suggest that application of N fertilizer guided by the GS decision support tool can save significant amount of N fertilizer compared to the current RP without compromising grain yield.

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Keywords Leaf color chart · GreenSeeker optical sensor · SPAD meter · Grain yield · Nitrogen fertilizer recommendation

Introduction

Rice plays an important role in the food security of more than 50% of the world's population (Langaro

et al. 2016). In Nepal, rice supplies about 40% of the food calorie intake and contributes 21% to the agricultural gross domestic product and 7% to the gross domestic product (CDD 2015). However, domestic production is not sufficient to meet the country's demand due to low rice productivity. The low productivity is associated with declining soil fertility, insufficient and imbalanced use of fertilizers, intensive cropping systems, use of traditional varieties, lack of irrigation facilities, and poor farmer awareness of improved crop management practices (Baral et al. 2019). However, the government is attempting to improve soil fertility and apply fertilizer based on soil test report to attain self-sufficiency in rice for the country by increasing productivity, in which nitrogen (N) management is the most important, although challenging, endeavor.

In Nepal, the current N fertilizer recommendation for rice (*Oryza sativa* L.) is based on irrigation regime only and fixed for the whole country despite variability in soils, agro-climate and management. For example, 60:20:20 kg N, phosphorus (P_2O_5), potassium (K_2O) ha^{-1} are recommended for rainfed and 100:30:30 kg N, P_2O_5 , K_2O ha^{-1} for irrigated rice, respectively. Also, the timing of N application is predetermined, such as during transplanting, maximum tillering, and panicle initiation stages. These fixed rates and -time of applications may not synchronize N supply with crop N demand (Alam et al. 2013). Excess of N supply than plant demand may increase potential of N loss into environment via volatilization, leaching, nitrification and denitrification (Buresh et al. 2008; Rochette et al. 2013; Liu et al. 2020) resulting in lower ($\sim 30\%$) nitrogen use efficiency (NUE) (Joshy 1997; Adhikari et al. 1999; Baral et al. 2020). N management strategies should focus on improving the synchrony between N supply from the applied N fertilizer and crop N demand, thus plant uptake of N increases and N losses are minimized, leading to increased NUE (Yoseftabar 2013).

Previous studies have focused on various strategies to increase NUE, including the use of slow- and controlled-release fertilizers, coated (polymer, sulfur) fertilizers, nitrification inhibitors, and improved placement methods (Jones et al. 2007; Harmandeep et al. 2010; Alam et al. 2013; Bhat et al. 2013; Singh et al. 2015; Gaihre et al. 2015). Different types of decision support tools, such as the GreenSeeker (GS) optical sensor (Ali et al. 2015; Chittapur et al. 2015), soil plant

analysis development (SPAD) chlorophyll meter (Peng et al. 1996; Cabangon et al. 2011; Xiong et al. 2015), and leaf color chart (LCC) (Alam et al. 2013), have been introduced for real-time N management. However, the comprehensive assessment and comparison of these decision support tools have been meager, particularly in the Asian countries, such as Nepal. The decision to use one of these tools depends on its cost, user-friendliness, and the time it takes to use the tool.

The GS measures normalized difference vegetation index (NDVI), a unit which is based on the reflectance at red and near infrared (NIR) regions. NDVI is an empirically derived vegetation index related to leaf area index that predicts biomass and yield (Raun et al. 2002). NDVI measured at panicle initiation stage positively correlates with rice grain yield (Xue et al. 2014; Harrell et al. 2011). GS-guided N fertilizer application increases N recovery efficiency by 6–22% and agronomic efficiency by 5–12 kg grain kg^{-1} N applied over conventional practice without any yield penalty (Singh et al. 2015). Using the response index calculated from NDVI, a precise N fertilization time can be identified without a penalty in the yield.

The SPAD chlorophyll meter is used to determine the N content of leaves and can indicate N deficiency prior to the stage that affects crop yield (Peng et al. 1996). Critical SPAD values for rice range from 32 to 37.5, as determined for semi-dwarf indica varieties across different regions in India (Singh 2008). Generally, two approaches have been followed to guide real-time N application using a SPAD meter: (1) when the SPAD value is lower than the set critical reading (Singh et al. 2002; Maiti et al. 2004) and (2) when the sufficiency index (defined as the SPAD value of the plot divided by the SPAD value of a nutrient not-limited reference plot) falls below 0.90 in rice (Hussain et al. 2000). Despite the greater reliability of the latter, the first approach is more popular because it does not require a nutrient not-limited area and is therefore easier to use. SPAD meter-based N management significantly increases NUE (45–110%) compared with farmers' fertilizer practices (Peng et al. 1996; Singh et al. 2015).

The LCC is a handheld plastic strip that can be used as a complementary decision-making tool to determine real-time crop N demand. Conceptually, the LCC is based on the close link between leaf chlorophyll content and leaf N content over different growth stages. The LCC depicts gradients of green hues that

are based on the wavelength characteristics of rice leaves, from yellowish-green to dark green, with scale value from 1 to 5. The critical color shade on the LCC must be determined to guide N application in rice. The LCC critical value differs by variety. Shukla et al. (2004) reported LCC of 3, 4, and 5 as the critical values for basmati, inbred, and hybrid rice cultivars, respectively. In northeastern India, Maiti et al. (2004) established a LCC of 4 as the critical value for transplanted rice and that the use of LCC could save 20–42 kg N ha⁻¹, which increased the NUE by 59–68% compared with the recommended fixed-time split N application. Similarly, Marahatta (2017) reported that LCC-guided N management increased yield by 0.31 mt ha⁻¹ compared to farmers' practice. LCC has now been used successfully to guide fertilizer N application in rice, wheat, and maize (Singh et al. 2010; Yoseftabar 2013).

NUE in lowland rice fields can also be increased by improved placement. For example, placing urea 0.07–0.10 m deep at root zone which is commonly called urea deep placement (UDP) is an effective method for increasing grain yield and NUE. In general, UDP increases rice yields by up to 20% and doubles N recovery compared to conventional broadcast application (Bandaogo et al. 2014; Gaihre et al. 2018; Islam et al. 2016; Miah et al. 2016).

Despite the availability of various decision-making tools, effective N fertilizer management in rice remains a major challenge to researchers and producers. In Nepal, only a few studies (Marahatta 2017; Subedi et al. 2017) have been conducted on N management of rice using decision support tools as an alternative to the current RP. Those studies were limited to LCC only. There is a need to determine the effectiveness of different N management practices on NUE and grain yields compared to the existing RP of fertilizer application. Therefore, this study was conducted to identify efficient and appropriate methods and decision support tools to increase grain yields and NUE in rice.

Materials and methods

Experimental site and weather conditions

The field experiments were conducted at the Regional Agricultural Research Station (28°11'30" N and

81°58'89" E), Khajura, Banke District, Nepal, during monsoon season (July to October) in 2017 and 2018. The dominant cropping pattern in the study area is rainfed rice followed by wheat. The climate is subtropical with a wet summer and dry winter. Average annual rainfall ranges from 1000 mm to 1500 mm, but more than 80% of annual rainfall is distributed during monsoon season. Winter is dry with low rainfall (Fig. S1). Initial soil physical and chemical properties of the experimental plots are given in Table 1.

Chemical analysis of soil and plant samples

Soil samples were collected from each plot before planting and after harvesting to analyze soil organic matter, pH, total N, available P₂O₅, and exchangeable K₂O. Total N was estimated using the micro-Kjeldahl distillation procedure (Bremner and Mulvaney 1982). Available phosphorus was extracted with sodium bicarbonate (0.5 M) at 8.5 pH (Olsen's reagent), and the concentrations were measured using a spectrophotometer (Olsen et al. 1954). Available K was extracted with neutral ammonium acetate and determined using a flame photometer (Jackson 1973). Soil organic matter was determined by following the Walkley–Black digestion method (Walkley and Black 1934). The N content of plant samples was analyzed following Bremner and Mulvaney (1982).

Experimental design and crop management

The nine fertilizer treatments, including the different decision support tools and their combination with basal application, were laid out in a randomized complete block design in three replicates. The treatments were (1) control (0 kg N ha⁻¹, N₀), (2) GS-guided N application (GS), (3) SPAD-guided N application (SPAD), (4) LCC-guided N application (LCC), (5) GS-guided N application with 25 kg N ha⁻¹ as basal (GS-N₂₅), (6) SPAD-guided N application with 25 kg N ha⁻¹ as basal (SPAD-N₂₅), (7) LCC-guided N application with 25 kg N ha⁻¹ as basal (LCC-N₂₅), (8) current government-recommended rate of 100 kg N ha⁻¹ broadcast in three splits (RP-N₁₀₀) (AICC 2016), and (9) UDP at 78 kg N ha⁻¹ (UDP) (Baral et al. 2020).

Sukkha Dhan-3, a drought-tolerant variety of rice recommended for drought-prone areas, was selected

Table 1 Initial physical and chemical properties of the soil sample of the experimental field at Regional Agricultural Research Station (RARS), Khajura, Banke, Nepal

Parameter	Unit	Value	Analysis method
Organic matter	%	1.43	Walkley and Black (1934)
Total N	%	0.11	Kjeldahl Bremner and Mulvaney (1982)
Available P ₂ O ₅	kg ha ⁻¹	40.6	Modified Olsen et al. (1954)
Exchangeable K ₂ O	kg ha ⁻¹	62	Ammonium Acetate Jackson (1967)
Soil pH (1:2)		6.5	Potentiometric Jackson (1973)
Soil bulk density	Mg m ⁻³	1.44	
Soil texture		Silty Clay Loam (Sand 26%, Silt 38%, Clay 36%)	Hydrometric Bouyoucos (1927)
Water-soluble boron	mcg g ⁻¹	0.84	Hot Water Extraction, Spectrophotometric Berger and Truog (1939)
Water-soluble sulfur	%	< 0.1	Turbidimetric Verma (1977)
Exchangeable magnesium	mEq 100 g ⁻¹	2.39	Pryanishnikov, EDTA Titrimetric Method,
Copper	mcg g ⁻¹	0.58	DTPA Extraction and AAS Lindsay and Norvell (1978)
Zinc	mcg g ⁻¹	0.21	Acid digestion
Manganese	mcg g ⁻¹	6.18	
Iron	mcg g ⁻¹	23.94	
Molybdenum	mcg g ⁻¹	0.06	Acid digestion

for the field trial. Two to three rice seedlings (25 days old) per hill were transplanted in each experimental plot (3.6 m × 4 m) at a distance of 0.20 m × 0.20 m. Phosphorus and potassium were applied in all plots at a rate of 30 kg P₂O₅ ha⁻¹ and 30 kg K₂O ha⁻¹ during final land preparation. The N fertilizer rate and methods were applied as specified in the treatments, which are presented in Table 2. Other cultural operations, such as weeding, irrigation, and pest control, were performed as required and were the same for all the treatments.

Nitrogen fertilizer management across treatments

For RP-N₁₀₀, granular urea was broadcast in three equal splits: one week after transplanting, 25–30 days after transplanting (DAT), and before panicle initiation. For UDP, urea briquettes were deep placed at 0.07–0.10 m soil depth at the center of four rice hills in a single dose one week after transplanting, as suggested by Gaihre et al. (2015). Each briquette was 2.7 g, which amounted to 78 kg N ha⁻¹. In the GS-, SPAD-, and LCC-guided treatments, the amount

of N applied was based on the response index and critical values as described below.

N management with GreenSeeker and measurement of NDVI

For GS, spectral reflectance was measured using a handheld optical sensor commercially available by the name of GreenSeeker Crop Sensor (NTech Industries, Inc., Ukiah, California, USA). A response index value of 1.25 was used as the threshold to guide the timing of application (Raun et al. 2002). If the response index value of a GS-guided plot was above 1.25, then N was topdressed in the that plot at 25 kg N ha⁻¹. Response index was calculated by dividing the NDVI reading from the non-N-limited plots by that of the GS-guided plot (Raun et al. 2002). Measurement was carried out by holding the unit at a height of about 0.30 m above the plant canopy and walking at a constant speed (Raun et al. 2002). Ten readings were recorded from each plot during the measurement (30, 45 and 60DAT). NDVI was calculated from the spectral reflectance as:

Table 2 Total nitrogen fertilizer applied, application timing, and fertilizer saving across all fertilizer treatments in 2017 and 2018

Treatments	N applied (kg ha ⁻¹)													N saving (%)	
	2017														Two year mean
	Basal			30 DAT			45 DAT			60 DAT			Mean		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3			
Control (N ₀)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
GS	0	0	0	25	25	25	25	25	25	0	0	0	50.0	45.8	54.2
SPAD	0	0	0	25	25	25	0	0	0	25	25	25	50.0	45.8	54.2
LCC	0	0	0	25	25	0	25	25	25	25	25	25	66.7	58.3	41.7
GS-N ₂₅	25	25	25	25	25	25	0	0	0	0	0	0	50.0	50	50.0
SPAD- N ₂₅	25	25	25	0	0	25	0	25	0	25	0	25	58.3	54.2	45.8
LCC-N ₂₅	25	25	25	25	25	25	25	0	0	25	25	25	83.3	79.2	20.8
RP-N ₁₀₀	33.3	33.3	33.3	33.3	33.3	33.3	0	0	0	33.3	33.3	33.3	100	100	0
UDP	78	78	78	0	0	0	0	0	0	0	0	0	78	78	22

Treatments	N applied (kg ha ⁻¹)													N saving (%)	
	2018														Two year mean
	Basal			30 DAT			45 DAT			60 DAT			Mean		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3			
Control (N ₀)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
GS	0	0	0	25	25	25	25	0	25	0	0	0	41.7	45.8	54.2
SPAD	0	0	0	0	25	25	25	0	0	0	25	25	41.7	45.8	54.2
LCC	0	0	0	25	25	25	25	0	0	0	25	25	50.0	58.3	41.7
GS-N ₂₅	25	25	25	25	25	25	0	0	0	0	0	0	50.0	50	50.0
SPAD- N ₂₅	25	25	25	25	0	0	0	25	0	0	0	25	50.0	54.2	45.8
LCC-N ₂₅	25	25	25	25	25	25	25	0	25	0	25	0	75.0	79.2	20.8
RP-N ₁₀₀	33.3	33.3	33.3	33.3	33.3	33.3	0	0	0	33.3	33.3	33.3	100	100	0
UDP	78	78	78	0	0	0	0	0	0	0	0	0	78	78	22

GS, GreenSeeker optical sensor-guided N management; SPAD, soil plant analysis development (chlorophyll meter)-guided N management; LCC, leaf color chart-guided N management; N₂₅, basal application of N at 25 kg ha⁻¹; UDP, urea briquette deep placement. R represents replication

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED}) \quad (1)$$

where NIR and RED are the fractions of near infrared and red radiation reflected back from the sensed area, respectively.

Nitrogen management with SPAD meter

The critical SPAD values for semi-dwarf indica rice varieties were set 35–37; thus, we used average, i.e., 36 as the critical value for our study (Shukla et al. 2004; Singh 2008). SPAD values were obtained using the handheld Minolta SPAD-502. Measurement was

done by inserting the middle portion of the upper most fully expanded, disease-free young leaf in the slit of the SPAD meter. Ten measurements were taken from 10 randomly selected plants per plot, and these were averaged. The readings were measured at 30 DAT, 45 DAT, and 60 DAT. If the reading fell below the assumed critical value, then the plot was topdressed with 25 kg N ha⁻¹.

Nitrogen management with leaf color chart

Leaf color index derived from the LCC, designed by the International Rice Research Institute (IRRI), was used to guide fertilization. The measurements were taken at same times and intervals as NDVI and SPAD measurements. LCC values were measured by selecting fully matured and disease-free upper leaves. Measurements were taken from 10 randomly selected plants per plot. If the average reading of a plot fell below the critical value, i.e., 4, then the plot was topdressed with 25 kg N ha⁻¹. The amount of N topdressing within a treatment also differed due to variability among replications, i.e., some plots received fertilizer application and some did not. Similarly, the critical value for each treatment could vary due to the plot reading within a treatment.

Measurement and data collection

Plant growth and yield

Plant heights and number of tillers per hill were measured from each plot at harvest from 10 randomly selected rice hills, avoiding the border row. Periodic dry matter production was measured at 30 DAT, 60 DAT, and harvest. Two hills next to the border row were destructively harvested from each plot, and the dry matter was measured after drying in an oven at 65–70 °C for 48 h.

Ten panicles from each plot were randomly selected to measure panicle length and number of grains per panicle. Grain yields were recorded after drying and cleaning. Grain moisture was measured with a portable digital moisture meter (SKZ111B-2). Grain yields were recorded after drying and cleaning and yield was calculated at 14% grain moisture content. A test weight (1,000-grain weight) was recorded from each plot. Fresh weight of straw was recorded immediately after harvest, and dry weight was recorded after oven-drying at 70 °C. Harvest index was calculated from grain and straw yields using the following equation.

$$\text{Harvest index} = \text{Grain yield} / \text{Biological yield} \times 100 \quad (2)$$

Nitrogen use efficiency calculation

Different forms of NUE were calculated as shown below (Ladha et al. 2005).

$$\text{Partial factor productivity of N (PFPN)} = \text{GY}_N / \text{F}_N \quad (3)$$

$$\text{Apparent N recovery (ANR)} = (\text{UN}_N - \text{UN}_0) / \text{F}_N \quad (4)$$

$$\text{Agronomic N use efficiency (ANUE)} = (\text{GY}_N - \text{GY}_0) / \text{F}_N \quad (5)$$

$$\text{Physiological efficiency of applied N (PEN)} = (\text{GY}_N - \text{GY}_0) / (\text{UN}_N - \text{UN}_0) \quad (6)$$

$$\text{Internal efficiency of N (IUE)} = \text{GY}_N / \text{UN}_N \quad (7)$$

$$\text{Utilization efficiency of N (UEN)} = \text{PEN} \times \text{ANR} \quad (8)$$

where GY_N, grain yield in N applied treatment (kg); F_N, N fertilizer applied (kg); GY₀, grain yield in control treatment (kg); UN_N, N uptake in N applied treatment (kg); and UN₀, N uptake in control treatment (kg).

Data analysis

The data analysis was carried out using Genstat 13.2 (VSN International Ltd, Hemel Hempstead, United Kingdom). Two-way analysis of variance (ANOVA) was used to test the effect of treatments, year and their interaction. Normality and homogeneity of variance were tested using histogram and Levene's test, respectively. The significant differences among the means were tested using the Tukey's honest significance difference (HSD) test at a 5% significance level. When interaction effect was significant between treatment and year, then results were presented separately for each season.

Results

Plant growth and yield components

N application significantly affected plant height, number of effective tillers, number of grains per panicle (Table 3), and dry matter production across

different growth stages (Fig. 1). UDP produced the tallest plant among all of the treatments, but it was not significantly different from the LCC treatment. The number of tillers was 18% higher in UDP than in SPAD-N₂₅ and was on par with GS, GS-N₂₅, RP-N₁₀₀, LCC, LCC-N₂₅, and SPAD. The highest number of grains per panicle was found in UDP, though grain numbers among the treatments were not different except for control (Table 3). There was a significant interaction between treatment and year on total dry matter accumulation at 30 DAT and at harvest (Fig. 1). In 2017, there was no significant difference in dry matter accumulation at 30 DAT among the treatments. However, in 2018, UDP produced two times more dry matter compared to GS.

Grain and straw yield

Application of N fertilizer guided by decision support tool and method significantly ($p < 0.05$) affected grain and straw yields (Table 3). GS, GS-N₂₅, and LCC-N₂₅ produced grain yields similar to UDP and RP-N₁₀₀, while SPAD and LCC produced significantly ($p < 0.05$) lower yields. There was a significant

interaction between treatment and year on straw yields. In 2017, GS produced the highest straw yield (66% higher than control), while in 2018, the highest straw yield was obtained in RP-N₁₀₀, which was 74% higher than control. There was a strong positive relationship between grain yield and N uptake (Fig. S2). Though the grain yields produced by GS, GS-N₂₅, and LCC-N₂₅ were similar to UDP and RP-N₁₀₀, the amount of N applied was much lower in decision support tool-guided application, ranging from 21 to 54 kg N ha⁻¹ (Table 2).

Periodic NDVI, SPAD, and LCC values and their relationship with grain yield

Periodic NDVI, SPAD, and LCC values measured from each treatment are presented in Fig. S3. Across the treatments, the NDVI readings were lower at 30 DAT compared to 45 DAT. The NDVI values at 45 DAT and 60 DAT were similar. The UDP treatment had the highest value compared to other treatments at 30DAT and 45 DAT. The SPAD values were higher at 45 DAT, compared to 30 DAT and 60 DAT. The LCC values at 30 DAT, 45 DAT, and 60 DAT did not show

Table 3 Plant height, number of panicles per hill, grains per panicle, grain yield, total biomass yields, harvest index, and 1,000 grain weight for all treatments. Values are the average of two years (n = 6), except for straw yield (n = 3)

Treatments	Plant height (m)	No of Tillers m ⁻²	Grains panicle ⁻¹	Grain yield (Mgha ⁻¹)	Straw yield (Mg ha ⁻¹)		Harvest index	1,000 grain wt. (g)
					2017	2018		
Control (N ₀)	0.86d	207.9cd	128.6b	3.80c	6.22b	6.08b	0.43	23.48
GS	0.99bc	260.8ab	142.1ab	6.10ab	10.31a	7.57ab	0.44	25.59
SPAD	0.96cd	267.5ab	144.8ab	5.58b	10.16a	9.12ab	0.40	25.31
LCC	1.09ab	267.1ab	151.9a	5.81b	9.83a	8.08ab	0.43	25.43
GS-N ₂₅	0.98bc	267.9ab	156.5a	6.13ab	8.47ab	9.54a	0.43	25.77
SPAD-N ₂₅	0.99bc	252.9b	144.5ab	5.61b	8.70ab	9.42a	0.41	25.8
LCC-N ₂₅	1.022abc	285.4ab	150.7ab	6.18ab	9.65a	8.05ab	0.44	24.96
RP-N ₁₀₀	0.98b	272.1ab	158.6a	6.44ab	10.04a	10.59a	0.42	25.98
UDP	1.11a	299.2a	161.6a	6.80a	9.28a	10.03a	0.45	26.09
ANOVA (<i>p</i> values)								
Treatment (T)	< 0.01	< 0.001	0.002	< 0.0001	0.001	0.005	0.10	0.23
Year (Y)	0.03	0.002	0.001	0.871	0.497		0.01	0.024
T x Y	0.179	0.301	0.803	0.128	0.018		0.201	0.317

Within a column, means followed by the same letter(s) are not significant at a 5% probability level as determined by Tukey's honest significance difference (HSD) test. GS, GreenSeeker optical sensor guided N management; SPAD, soil plant analysis development (chlorophyll meter) guided N management; LCC, leaf color chart guided N management; N₂₅, basal application of N at 25 kg ha⁻¹; UDP, urea briquette deep placement

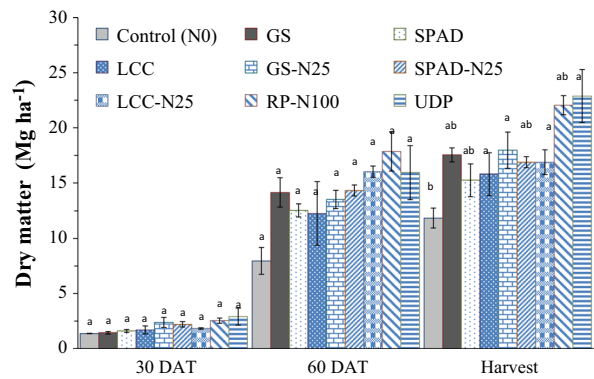
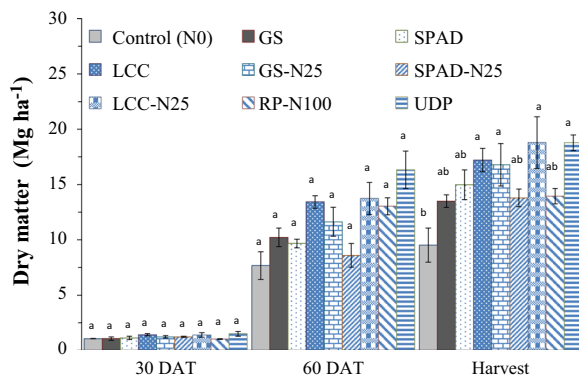


Fig. 1 Effect of fertilizer application technique on periodic total dry matter yield at 30 DAT, 60 DAT, and at harvest in 2017 and 2018. Within a growth stage, mean followed by same letter(s) are not significant at a 5% probability level as determined by Tukey’s honest significance difference (HSD) test. DAT, days after transplanting; GS, GreenSeeker optical

sensor-guided N management; SPAD, soil plant analysis development (chlorophyll meter)-guided N management; LCC, leaf color chart-guided N management; N₂₅, basal application of N at 25 kg ha⁻¹; UDP, urea briquette deep placement

a consistent trend compared to those shown by NDVI and SPAD. The NDVI value and SPAD values showed a positive correlation (Fig. S4). The values of NDVI and SPAD at 45 DAT positively correlated with grain yields (Fig. 2) and total N uptake (Fig. 3).

Similarly, the PFPN measured in GS was 117% higher than RP-N₁₀₀ and 60% higher than UDP. The lowest PFPN (64 kg kg⁻¹ N) was in the current RP-N₁₀₀. GS-N₂₅ produced the highest ANR (84%) among the treatments, which was significantly higher than RP-N₁₀₀ (45%). However, it was not significantly different than in the UDP, GS, LCC, and SPAD treatments.

Nitrogen uptake and use efficiency

There was a significant interaction between treatment and year on PEN and UEN. In 2017, PEN was found to be the highest in GS, which was statistically similar to GS-N₂₅, SPAD, SPAD-N₂₅, and RP-N₁₀₀ and was 70.6% higher than UDP. In 2018, the highest PEN was found in SPAD. The highest IUE was found in GS, which was 13% higher than UDP. During 2017, the highest UEN was recorded in GS, which was 110% higher than RP-N₁₀₀. However, during 2018, the

Fertilizer treatments, regardless of application method and decision support tool, increased N uptake significantly compared to control in both years. On average, N uptake was higher in 2017 than in 2018. Fertilizer treatments had a significant effect (*p* < 0.05) on the different forms of NUE, including ANUE, PFPN, ANR, PEN, IUE, and UEN (Table 4). GS-guided N application resulted in 93% and 32% more ANUE compared to RP-N₁₀₀ and UDP, respectively (Table 4).

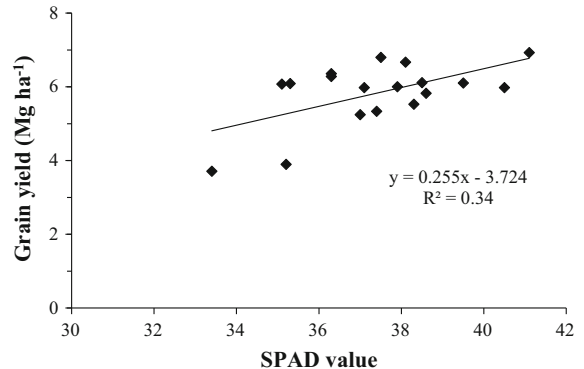
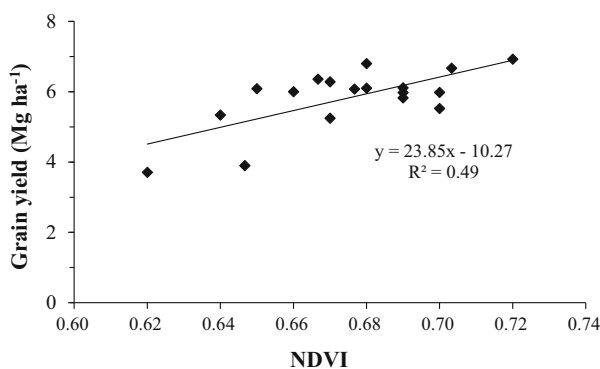


Fig. 2 Relationship between NDVI and SPAD values measured at 45 days after transplanting with grain yield

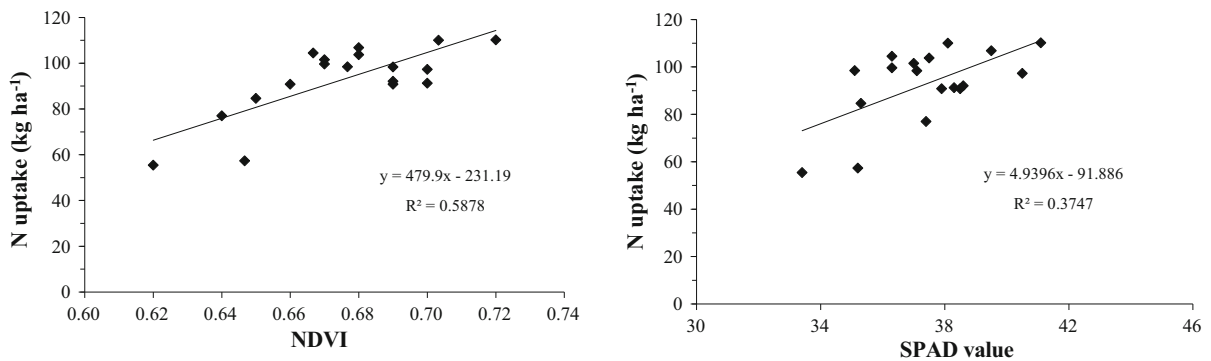


Fig. 3 Relationship between NDVI and SPAD values measured at 45 days after transplanting with total N uptake

highest UEN was found in GS-N₂₅, which was 77.9% higher than RP-N₁₀₀.

Discussion

Effects of decision support tools and application methods on grain yields

Application of N fertilizer guided by GS and LCC critical values and the improved nitrogen placement method (UDP) showed the potential to increase crop yields and NUE while saving a significant amount of N fertilizer compared to the existing government-recommended practice. Benefits of UDP in lowland rice cultivation—increased grain yields and NUE and nitrogen saving—compared to conventional broadcast application are well documented (Savant and Stangel 1990; Alam et al. 2013; Gaihre et al. 2015; Huda et al. 2016; Wu et al. 2017; Baral et al. 2020). These studies show that UDP retains N in the root zone for a longer period of time, which is then available for the plant when needed. In this study, continuous availability of N to plants in the UDP treatment was evident from NDVI and SPAD values measured at 30 DAT, 45 DAT, and 60 DAT (Fig. S2). These values were higher than those for other treatments across different growth stages and were associated with higher N uptake (Fig. 3). In our study, UDP applied at 78 kg N ha⁻¹ in a single application was used as a reference treatment to compare the benefits of the decision support tools in minimizing N input without yield penalty. Similar to previous studies (Huda et al. 2016; Islam et al. 2016), UDP, with 22% less N compared to the government-recommended rate, produced the highest yield among

the treatments tested in this study which was related to continuous availability of N to plants that increased yield-attributing traits such as number of tillers and grains per panicle (Table 3).

GS and LCC, in combination with basal application of N at 25 kg ha⁻¹, produced grain yield and yield-attributing traits (number of tillers per hill and grains per panicle) similar to UDP and RP-N₁₀₀ (Table 3). Although the grain yields produced by GS, GS-N₂₅, and LCC-N₂₅ were not different than RP-N₁₀₀, the amount of N fertilizer applied was reduced by 54% with GS, 50% with GS-N₂₅, and 21% with LCC-N₂₅. N saving compared to RP-N₁₀₀ was much higher with GS-guided N management (54%) than with UDP (22%). Similarly, GS-guided N management reduced N use by 46% compared to UDP. In contrast with GS, N management guided by SPAD meter and LCC was less effective in increasing grain yields unless the tools were used in combination with basal N application; however, they reduced the N input significantly compared to RP-N₁₀₀. The lower grain yield in the SPAD and LCC treatments compared to UDP and RP could be due to the limitation of N at the early growth stage of plants (before 30 DAT) or because N application was not precise based on measured critical values. This study suggests that a supply of N until 45 DAT is important for production of yield components, i.e., number of tillers and number of grains per panicle to achieve potential yield. Contrary to our results, other studies (Chittapur et al. 2015; Ghosh et al. 2000; Singh et al. 2010) demonstrated that LCC and SPAD meter helps to achieve higher grain yields with a lower amount of N by synchronizing N supply and plant demand. The lower yields in our study suggest that the critical values adopted to apply N fertilizer may differ

Table 4 Effects of different nitrogen fertilizer management techniques on ANUE, ANR, PFPN, PEN, IUE, and UEN

Treatment	N uptake (kg ha ⁻¹)	ANUE (kg grain kg ⁻¹ applied N)	PPFN (kg grain kg ⁻¹ N)	ANR (%)	UE	PEN		UEN	
						2017	2018	2017	2018
Control (N ₀)	56.44	-	-	-	-	-	-	-	-
GS	87.78	50.7	139.3	68.01 ab	69.75 a	188.0 a	108.5 ab	126.03 a	75.4 abc
SPAD	84.58	39.5	128.6	62.48 abc	66.21 ab	166.8 ab	155.9 a	117.25 ab	83.7 abc
LCC	99.10	34.9	101.7	74.38 a	58.67 bc	117.3 abc	80.8 b	87.03 abc	58.3 bc
GS-N ₂₅	98.52	46.5	122.6	84.31 a	62.28 abc	108.2 bc	115.9 ab	86.46 abc	100.5 a
SPAD-N ₂₅	100.01	34.4	106.6	81.56 a	56.23 c	84.9 c	106.4 ab	64.75 bc	90.6 ab
LCC-N ₂₅	97.72	30.1	78.6	52.12 bc	63.7 abc	136.9 abc	98.9 b	72.46 bc	47.3 c
RP-N ₁₀₀	101.14	26.3	64.3	44.77 c	63.72 ab	149.8 abc	114.9 ab	59.96 c	56.5 bc
UDP	110.17	38.4	87.1	68.01 ab	61.83 bc	110.5 bc	99.5 ab	74.83 abc	68.8 abc
ANOVA (p value)									
Treatments (T)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.006			0.005
Years (Y)	0.047	0.056	0.078	0.985	0.172	0.36			0.365
T x Y	0.173	0.256	0.816	0.559	0.838	0.028			0.006

Within a column, means followed by the same letter(s) are not significant at a 5% probability level as determined by Tukey's honest significance difference (HSD) test. ANUE = Agronomic nitrogen use efficiency, PFPN = Partial factor productivity of nitrogen, ANR = Apparent N recovery, PEN = Physiological efficiency of N, IUE = Internal use efficiency, UEN = Utilization efficiency of N. GS, GreenSeeker optical sensor-guided N management; SPAD, soil plant analysis development (chlorophyll meter)-guided N management; LCC, leaf color chart-guided N management; N₂₅, basal application of N at 25 kg ha⁻¹; UDP, urea briquette deep placement

by variety and should be customized for a particular variety, so that the correct timing of fertilizer application can be identified.

Grain yields in relation to NDVI and SPAD values

NDVI and SPAD values varied by treatment and growth stage. Values measured at 30 DAT were relatively lower compared to their corresponding values measured at 45 DAT and 60 DAT (Fig. S3). Lower values at 30 DAT suggest that the indigenous N supply might be exhausted and N fertilizer should be applied as topdressing before 30 DAT. Grain yield and total N uptake showed a strong positive correlation with NDVI and SPAD values measured at 45 DAT (Figs. 2 and 3). These results are in close agreement with previous studies (Chittapur et al. 2015; Gosh et al., 2020) and indicate that NDVI and SPAD values can predict grain and straw yield (Harrell et al. 2011; Ali et al. 2014). As deficiency of N during the early growth stage leads to a decrease in grain and straw yields, values of NDVI, SPAD, and LCC measured at 45 DAT can provide an opportunity to correct N deficiency by applying N through topdressing, which would help reduce N losses in the current recommended practice. GS-N₂₅ had a grain yield 9.9% higher than SPAD, 9.4% higher than SPAD-N₂₅, and 5.5% higher than LCC. This increased grain yield was due to precision application of N as per crop need.

Nitrogen uptake and use efficiency

Application of N fertilizer guided by GS or SPAD meter reduced N fertilizer use by 41–54% but had a similar N uptake as RP. This is probably due to synchronization of the N supply with plant demand (Yoseftabar 2013). In general, the use of GS and SPAD in combination with basal application of N at 25 kg ha⁻¹ had more N uptake compared to the treatments in which N was applied only as guided by GS and SPAD. In the decision support tool-guided N management practices, the first application of N was applied at 30 DAT, although the plant may have experienced N deficiency in the early stage. These results suggest that the first topdressing of N should be done before 30 DAT or as a basal application to avoid N deficiency in the early stage of plant growth and increase plant N uptake (Tables 2). N applied at the late growth stage (e.g., 60 DAT) was not effective in

increasing N uptake, as observed in the SPAD and LCC treatments (Table 2). These results confirm that sufficient N availability during early plant growth stages can affect N uptake. Although UDP is known to increase NUE in lowland rice, as explained above, GS- and SPAD-guided N management combined with basal N application produced a relatively higher NUE than UDP.

GS-guided N management (including when combined with basal N application) produced a significantly higher NUE (ANUE, PFPN, ANR, and IUE) compared to RP-N₁₀₀ (Table 4). Our results are in agreement with previous studies that reported increased NUE (including ANUE and PFPN) compared to fixed-time application of the recommended rate (Ali et al. 2015; Singh et al. 2015). Our results suggest that improvement in NUE by following the GS-based N management strategy was due to more effective use of applied N than in the current recommended practice. GS-guided N management ensures precision application considering variability within the field (plot to plot) and time (across season). Differences in N by field and season occur due to variability of N-fixing organisms, mineralization of organic matter, and decomposition of crop residue (Singh and Ali 2020). When N input is reduced, NUE obviously increases because of less loss through leaching, volatilization, and runoff (Ladha et al. 2005). Losses increase when N is applied at a higher rate, particularly exceeding plant demand. This is often the case with fixed-time N application following a blanket rate, as in the recommended practice. Although the SPAD meter reduced N input and increased NUE, it was not effective in increasing grain yields. Similarly, a study in China (Yao et al. 2012) showed that GS-based N management increased the PFPN by 48% without a significant change in grain yield. The magnitude of PFPN observed in our study is higher than the average of southern and southeast Asia (63.2 kg kg⁻¹), as reported by Ladha et al. (2005).

As with other forms of NUE, ANR was significantly higher with GS-guided N management (including its combination with basal application at 25 kg ha⁻¹) compared to RP-N₁₀₀. These results suggest that real-time N management, as in GS-guided N application, can significantly reduce the amount of N fertilizer used, reduce N losses to the environment, and increase NUE. The low ANR of RP-N₁₀₀ could be due to poor synchrony between the N supply and crop demand, since 50% of the total N was applied during

transplanting. Another factor contributing to a low ANR could be a fixed-time application at predetermined stages without considering spatial and/or temporal variability of the N supply, as soil N availability, crop N uptake, and N responses differ within fields (Ladha et al. 2005). A large amount of N applied at a uniform rate during transplanting is at risk for environmental loss in areas of overapplication. Similarly, IUE was found to be higher in GS, compared to UDP.

Given the very low NUE at farm level due to poor management of N fertilizer and the spatial variability of soils (Alam et al. 2013; Ladha et al. 2005), the current fixed-time predetermined application rate should be improved to increase NUE and grain yield. In this context, real-time N management using the decision support tools tested in this study is promising, although their effectiveness may vary with different management conditions, soil types, and user knowledge. Use of decision support tools, particularly GS and LCC, with basal 25 kg N ha⁻¹ significantly ($p < 0.01$) reduced the amount of N fertilizer used, while increasing NUE and producing a similar grain yield. GS is used as a diagnostic tool that can indirectly estimate the N status of the growing crops and help determine the appropriate timing and quantity of N required for topdressing in rice and wheat (Singh et al. 2010; Chittapur et al. 2015). It synchronizes N supply with plant demand. However, LCC and SPAD meter were not as effective in this study compared to other studies (Peng et al. 1996; Yoseftabar 2013; Singh et al. 2015). The threshold of LCC and SPAD values should be reviewed for various crop varieties, as the critical limit or threshold values may vary by variety (Shukla et al. 2004; Singh et al. 2008). This study further suggests that the use of a decision support tool is much more effective if combined with basal application of N, particularly in areas where the indigenous N supply does not meet N demand at the early growth stage of the crop.

Enhancement of NUE by 10% in the production of cereal crops would result in savings of about U.S. \$5 billion per year and maintain environmental sustainability (Gupta and Khosla 2012). Interventions to increase NUE and reduce N losses to the environment must be accomplished at the farm level through a combination of improved technologies and government policies that promote the adoption of improved N management practices while sustaining yield. Therefore, there is a

huge scope to improve fertilizer NUE by following the guidance of decision support tools.

Conclusions

Real time nitrogen management using appropriate decision support tool could increase nitrogen use efficiency (NUE) and increase farmers' profit. This study suggests that N management with use of the GreenSeeker (GS) optical sensor and the leaf color chard (LCC) is as effective as urea deep placement (UDP) and the government-recommended practice to increase yield and NUE. In addition, GS and LCC (with 25 kg N ha⁻¹ as basal application) could reduce the amount of N fertilizer use compared to the current government-recommended practice. GS can further reduce N input and improve NUE compared to UDP. However, adoption of GS is more technical, and farmers may require training on its use for its wider adoption. From an application point of view, UDP may not need much technical skill but it is labor intensive, while LCC is easy to use and low cost. This study shows the potential of different N management tools and methods of application that can be beneficial for rice growers to increase NUE without any yield penalty, while reducing environmental problems associated with increased N losses.

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Declarations

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

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