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RESEARCH ARTICLE

Calibration of leaf colour chart for need-based nitrogen management in *Rabi* maize under varied planting density in rainfed agriculture

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Abstract

Efficient nitrogen management is critical to improving maize (*Zea mays* L.) productivity and sustainability under rainfed conditions, where excessive or untimely N use can result in environmental degradation and low nitrogen use efficiency (NUE). Two years of field studies were conducted during consecutive *Rabi* seasons (2017-18 and 2018-19) at the wetland Farm of S.V. Agricultural College, Tirupati, to calibrate the lead colour chart (LCC) for increasing grain yield, NUE and nutrient uptake under varied planting densities. The study intended to establish threshold leaf greenness values as practical guides for in-season, need based nitrogen top dressing in maize. A split-split plot design was used with three planting densities (66666, 83333 and 111111 plants ha^{-1}), three nitrogen levels (30, 35 and 40 kg N ha^{-1}) and three LCC thresholds (4, 4.5 and 5). Results showed that highest planting density (111111 plants ha^{-1}) combined with 40 kg N ha^{-1} applied in splits based on LCC 5 significantly improved plant growth parameters, chlorophyll content, dry matter accumulation and kernel yield (5.36 t ha^{-1}), along with enhanced nitrogen uptake (114.1 kg ha^{-1}) and NUE (31.4 kg grain per kg N). Regression analysis revealed that dry weight (R^2 = 0.96), LAI (R^2 = 0.84) and NUE (R^2 = 0.70) were the strongest predictors of yield. LCC based nitrogen scheduling synchronized N supply with crop demand, minimized losses and improved soil N balance. These findings validate that LCC is an effective, ow cost tool for enhancing maize productivity and nutrient efficient under rainfed conditions.

Keywords: leaf colour chart; maize; nitrogen use efficiency; planting density; rainfed agriculture

Introduction

In recent years, maize (*Zea Mays* L.) has emerged as one of the most important cereal crops in India, with production of 28.7 million tonnes sown in an area of 9.3 million hectares and with a productivity of 3.1 t ha^{-1} (1). Although India contributes only about 2 % of the global maize production (2, 3), the crop holds significant potential due to its versatility and adaptability across agro-climatic zones. Maize crop is highly exhaustive and depletes substantial amounts of soil nutrients to support high biomass and grain production (4). Prolonged and imbalanced use of chemical fertilizers, particularly nitrogen, has led to the emergence of multi-nutrient deficiency in soils. To address these challenges the adoption of the "4R" nutrient stewardship principles applying right source of nutrients, right quantity, right time and in the right place has been recommended to improve nutrient use efficiency (NUE), production, farm profitability and environmental sustainability (5). However, maize productivity has been increasingly threatened by climate change-related factors such as erratic rainfall, heat stress and nutrient losses (6). This necessitates dynamic adjustments in agronomic practices, particularly in nitrogen management, planting density and water management, to align with plant growth stages and environmental conditions (7). Optimizing fertilizers application not only enhances yield but also reduces input costs, thereby improving farmers profit margin (8). Inefficient nitrogen management practices led to high cost of production, reduced nutrient use efficiency, lower profit and significant environmental problems (9, 10). Major reasons for poor nitrogen utilization in maize crop are mainly due to usage of excessive nitrogenous fertilizers by farmers in the absence of nutrient recommendations as well as without assessing the crop-N demand and crop stage (11). Nitrogen losses from the soil-plant system via leaching, volatilization and runoff are significant, with up to 60 % of surface-applied urea potentially lost as ammonia, especially under high-temperature conditions and in the absence of incorporation (12, 13).

Plant population is another critical factor limiting maize growth and yield. Planting density influence canopy architecture, light interception, photosynthesis and simulate partitioning (14). While increasing density may decrease yield per plant, it can enhance yield per unit area due to better utilization of resources (15). Therefore, planting density and nitrogen management are key determinants of productivity and nitrogen use efficiency (NUE) in intensive maize cropping system.

To answer the questions of when, where, how much of fertilizers and how to apply the fertilizers, few techniques like tissue tests and SPAD meters could be used. Nevertheless, owing to its expensive cost, chlorophyll meter usage by the farmers in developing countries is restricted. In this context, the leaf colour chart (LCC) has emerged as a practical, farmer-friendly tool for real-time assessment of crop nitrogen status (16). LCC is an ideal tool to optimize N use in maize and it comprises of series of six green coloured shades horizontally ranging from light yellowish green to dark green colour strips fabricated with veins resembling those of maize leaves that are used to compare with a leaf in the same light conditions. The methodology is based on the results that shows link between leaf chlorophyll and nitrogen content. Need-based nitrogen application using LCC has been shown to improve NUE and reduce nitrogen losses, including potential reduction in N_2O emission and associated global warming by 11-14 % (17). However, despite its potential, systematic calibration of LCC for maize, especially under rainfed and variable plant density conditions, remains underexplored. Therefore, this study was undertaken to calibrate the LCC for augmenting grain yield and NUE in *Rabi* maize under varied planting densities in rainfed agriculture.

Materials and methods

Experimental site

A field experiment was conducted for two consecutive *Rabi* seasons (2017-18 and 2018-19) at the wetland farm of Sri Venkateswara Agricultural College, Tirupati (13.6°N, 79.3°E and 182.9 m above mean sea level), Andhra Pradesh, India.

The experimental soil was sandy clay loam and exhibited the following initial properties:

- Electrical conductivity: 0.14-0.15 dS m^{-1} (normal)
- pH: 7.8-7.9 (slightly to moderately alkaline)
- Organic carbon: 0.27-0.28 % (low)
- Available nitrogen: 180-183 kg ha^{-1} (low)
- Available phosphorus (Olsen P): 25.3-26.2 kg ha^{-1} (medium)
- Available potassium: 185-190 kg ha^{-1} (medium)

Experimental design

Experiment was laid out in Split-Split plot design with three replications. The maize hybrid (DHM-117) was sown during *Rabi* season using three spacing arrangements representing varied planting densities:

- P_1: 75 cm × 20 cm (66666 plants ha^{-1})
- P_2: 60 cm × 20 cm (83333 plants ha^{-1})
- P_3: 45 cm × 20 cm (111111 plants ha^{-1})

Treatments details

Main plot factor: planting density

- P_1: 66666 plants ha^{-1}
- P_2: 83333 plants ha^{-1}
- P_3: 111111 plants ha^{-1}

Sub-plot factor: nitrogen levels

- N_1: 30 kg N ha^{-1}
- N_2: 35 kg N ha^{-1}
- N_3: 40 kg N ha^{-1}

Sub-sub plot factor: LCC threshold values

- L_1: LCC 4
- L_2: LCC 4.5
- L_3: LCC 5

Fertilizer application

All treatments received a uniform basal dose of:

- 60 kg N ha^{-1} (as urea)
- 80 kg P_2O_5 ha^{-1} (as single superphosphate)
- 80 kg K_2O ha^{-1} (as muriate of potash)

The remaining nitrogen (up to a total of 240 kg N ha^{-1}) was applied in splits based on LCC readings taken every 10 days between 21 days after sowing (DAS) and the silking stage (i.e., 21, 31, 41, 51 and 61 DAS).

Leaf colour chart (LCC) protocol

A six-panel LCC was used to assess crop nitrogen status visually. For each treatment:

- Readings were taken from the middle portion of the youngest fully expanded leaf of 10 randomly selected plants.
- LCC observations were performed between 8:00 AM and 11:00 AM.
- During observation, the LCC was shielded from direct sunlight and the leaf being assessed was also kept shaded.
- If six or more leaves in a plot had a shade lighter than the threshold (LCC 4, 4.5 or 5), a top-dressing of nitrogen was applied according to the treatment.

The total nitrogen applied across treatments during the two seasons is summarized in Table 1.

Data collection and measurements

- Data pertaining to growth and yield attributes of five randomly selected plants was recorded from each net plot.
- Plant height, dry matter accumulation and yield components: measured using standard protocols.
- Leaf area index of crop was measured by using LI-COR model LI -300 portable leaf area meter.
- Chlorophyll content assessed non-destructively using the SPAD -502 meter (Minolta, Japan).
- Crop growth rate (rate of dry matter production per unit ground area per unit time) and was calculated by the formula (18).

Table 1. Mean quantity of fertilizer N applied under various treatments based on LCC for two years

		Total quantity of fertilizer N applied and saved (kg ha^{-1})				
		L_1	L_2	L_3	Mean for each treatment combination	Mean N applied
	N_1	145.0	155.0	165.0	155.0	
P_1	N_2	153.2	159.1	176.5	162.9	162.2
	N_3	159.9	166.5	179.8	168.7	
	N_1	155.0	165.0	180.0	166.6	
P_2	N_2	164.8	170.7	194.0	176.5	174.3
	N_3	166.4	179.6	193.2	179.7	
	N_1	160.0	170.0	190.0	173.3	
P_3	N_2	171.3	183.2	194.2	182.9	184.6
	N_3	179.8	193.1	219.8	197.5	
Mean for L		161.7	171.3	188.0		

$$CGR\left(gm^{-2}day^{-1}\right)=\frac{W_2-W_1}{t_2-t_1}\times\frac{1}{P}$$

Where, CGR: Crop growth rate (g m^2 day^{-1}), W_1 and W_2: Dry matter (g) at t_1 and t_2, respectively and P: Ground area (m^2).

Nitrogen use efficiency (NUE) was calculated by using the following formula as given in the previous studies (19) and for nitrogen uptake straw and grain samples were estimated by micro Kjeldahl method. Nitrogen balance for the system was worked out as

$$X = a - (b + c)$$

Where, X: Nitrogen (kg ha^{-1}) gain or loss at the end of the crop season; a: Sum of initial status of the available nitrogen in soil and addition of nitrogen through inorganic sources; b: Quantity of nitrogen (kg ha^{-1}) removed by crop and c: Actual balance of available nitrogen at the end of crop season.

Statistical analysis

Data were analysed using analysis of variance (ANOVA) following the Fisher's method (20). Critical difference (C.D.) at 0.05 probability level and Standard error of mean (SEm±) were computed. Treatment differences if not significant were denoted as NS. Correlation and regression analyses were conducted to determine the relationship between different using SPSS v17.0.

Results and Discussion

Effect of planting density, nitrogen levels and LCC threshold values on growth attributes

Plant height

Plant height was significantly influenced by planting density and nitrogen levels (Table 2). Highest plant height (217.7 cm) was recorded at the highest planting density (111111 plants ha^{-1}), followed by 215.7 cm at 83333 plants ha^{-1} and 211.3 cm at 66666 plants ha^{-1}. This increase in plant height at higher densities can be attributed at inter plant competition for light, which promotes vertical elongation (21). Application of 40 kg N ha^{-1}using LCC 5 threshold further enhanced plant height, likely due to improved chlorophyll content and photosynthesis rate, which contribute to stem elongation (22). However, interactions among planting density, nitrogen fertilizer level and LCC threshold for plant height were non-significant.

Leaf area index (LAI)

The leaf area index increased proportionally with planting density, with the maximum LAI (4.0) was noticed with higher planting density *viz*., 111111 plants ha^{-1} (Table 2). Similarly, LAI increased with increase in nitrogen levels and maximum LAI (3.30) was observed at 40 kg N ha^{-1} using LCC. This can be attributed to more plants per unit area contributing collectively to greater canopy coverage. Enhanced nitrogen availability supports the development of more and larger leaves and stimulates the production of photosynthetic pigments and auxins which together increase the LAI (23). Interaction of planting density, nitrogen levels and LCC threshold values were non-significant.

Chlorophyll content

SPAD values, which reflects chlorophyll content increased up to 90 DAS and declined thereafter at harvest. This decline was minimal, likely due to stary green mature of the hybrids used (Table 2). Higher panting densities of crop generally showed reduced SPAD values, possibly due to increased intra specific competition and lower nitrogen availability per plant (11). In contrast, higher nitrogen levels significantly improved SPAD readings, with 40kgNha^{-1} and LCC 5 yielding the highest values. Increase in SPAD reading with each successive increment of nitrogen might be attributed to the fact that nitrogen is an integral part of chlorophyll, which converts light into chemical energy needed for photosynthesis and adequate supply of nitrogen might result in high photosynthetic activity, vigorous vegetative growth and a dark green colour. A strong positive correlation between LCC shades and SPAD readings suggest that LCC is a reliable tool for real time nitrogen assessment (24). However, interactions were not statistically traceable during any of the two years of study.

Dry matter accumulation

The first pre-requisite for higher yield is higher production of total dry matter per unit area. Planting density had a significant effect on dry matter accumulation and maximum dry matter accumulation at harvest (Table 2). Maximum dry matter at harvest (17.6 t ha^{-1}) was recorded at the highest planting density (111111 plants ha^{-1}), likely due to the cumulative contributions of more plants per unit area. Similarly, nitrogen application at 40 kg ha^{-1} using LCC 5 resulted in the highest biomass (15.9 t ha^{-1}), due to sustained supply of nitrogen renders in maintaining higher auxin levels which in turn have favourable effect on cell enlargement, resulting in higher plant height and LAI for better interception and utilization of radiant energy, leading to higher photosynthetic rate, which ultimately resulted in higher accumulation of dry matter (25). Interaction between higher planting density and higher nitrogen level (P_3N_3) recorded maximum dry matter accumulation during both the years of study and it was statistically superior to other treatment combinations (Fig. 1). While other interactions were non-significant.

Crop growth rate (CGR)

Crop growth rate (CGR) was significantly influenced by planting

Table 2. Plant height, leaf area index, SPAD, dry weight and CGR of maize as influenced by planting density, nitrogen levels and LCC threshold values

	Plant height (cm)	Leaf area index	SPAD reading	Dry matter production (t ha^{-1})	Crop growth rate (g m^{-2} day^{-1})
Planting density (plants ha^{-1})					
P_1: 66666	211.3	2.55	39.8	12.9	11.4
P_2: 83333	215.7	3.04	37.9	15	10.6
P_3: 111111	217.8	4.00	36.7	17.6	12.5
SEm±	0.50	0.02	0.21	0.04	0.18
CD (P = 0.05)	1.97	0.06	0.82	0.18	0.72
Nitrogen levels (kg ha^{-1})					
N_1: 30	211.9	3.10	36.8	14.3	10.8
N_2: 35	214.6	3.19	38.30	15.1	11.4
N_3: 40	218.3	3.30	39.4	16.0	12.4
SEm±	0.85	0.02	0.48	0.05	0.24
CD (P = 0.05)	2.63	0.06	1.49	0.14	0.73
LCC threshold values					
L_1: LCC 4	209.5	3.09	36.2	14.3	11.2
L_2: LCC 4.5	214.9	3.21	38.3	15.2	11.7
L_3: LCC 5	220.4	3.29	39.9	15.9	11.8
SEm±	1.32	0.02	0.34	0.06	0.35
CD (P = 0.05)	3.77	0.06	0.97	0.16	NS
Interaction					
PXN					
SEm±	1.48	0.03	0.84	0.08	0.41
CD (P = 0.05)	NS	NS	NS	0.24	NS
PXL					
SEm±	2.28	0.03	0.59	0.1	0.61
CD (P = 0.05)	NS	NS	NS	0.27	NS
NXL					
SEm±	2.28	0.03	0.59	0.1	0.61
CD (P = 0.05)	NS	NS	NS	NS	NS
PXNXL					
SEm±	3.95	0.06	1.02	0.17	1.05
CD (P = 0.05)	NS	NS	NS	NS	NS

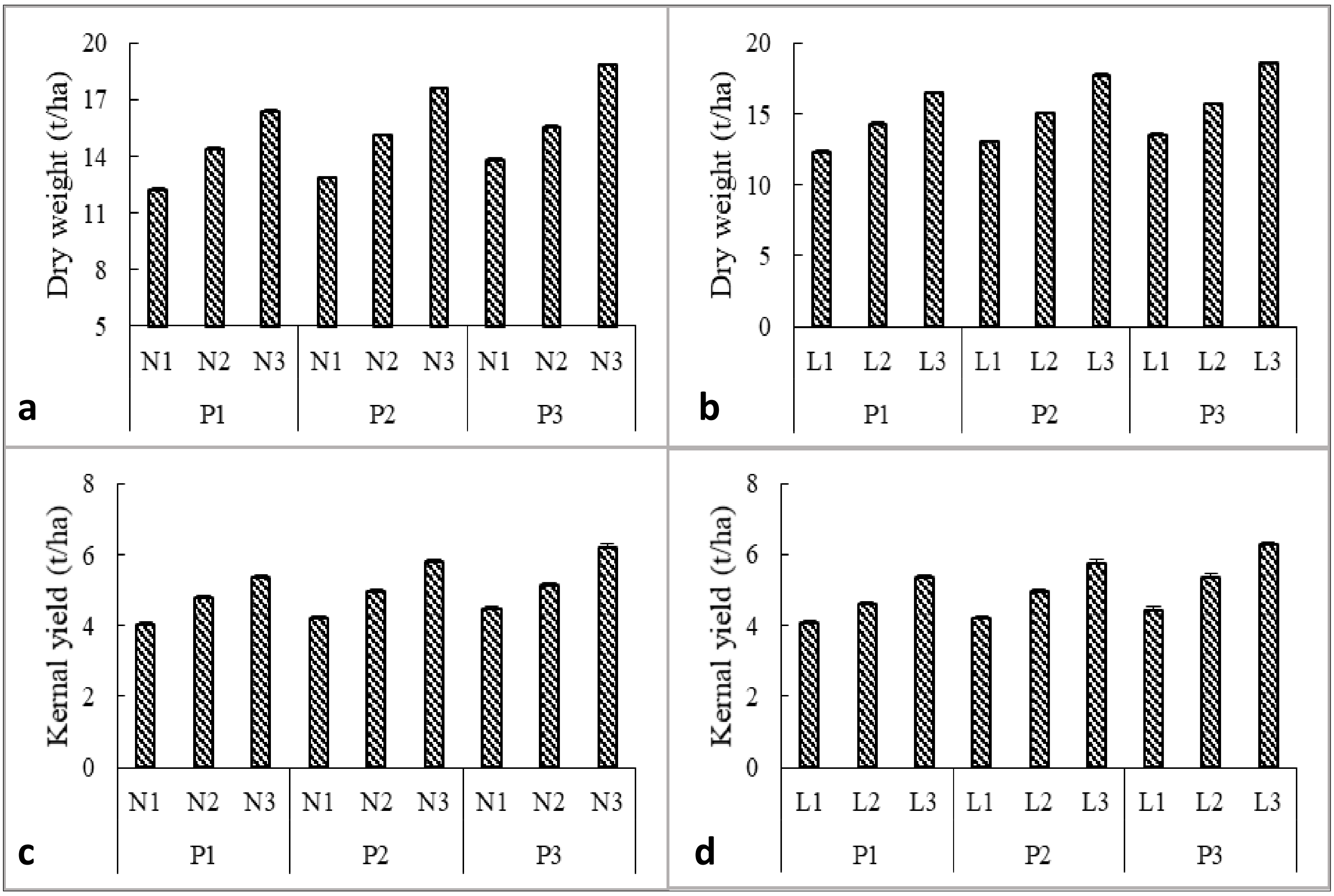

Fig. 1. Interaction effect: planting density and nitrogen levels on dry weight and kernal yield (a & c, respectively) and planting density and leaf color chart on dry weight and kernal yield (b & d, respectively).

density, nitrogen level and LCC threshold. The maximum CGR (12.5 g m^{-2} day^{-1}) and minimum (11.4 g m^{-2} day^{-1}) crop growth rate was found at higher plant population (111111 plants ha^{-1}) and lower density (66666 plants ha^{-1}), respectively (Table 2). This trend can be attributed to increased interception of solar radiation and improved radiation-use efficiency in denser plant canopies. CGR also increases progressively with nitrogen doses from 30 to 40 kg ha^{-1} at different splits based on LCC readings. The highest CGR was achieved with 40 kg N ha^{-1} and LCC threshold 5, suggesting that frequent and adequate nitrogen application throughout the growth cycle enhanced nutrient uptake, stimulated vegetative growth and supported sustained dry matter accumulation (26). The increase in CGR under LCC 5 treatment can be linked to improved synchronization of nitrogen supply with crop demand at critical growth stages, leading to rapid development of photosynthetically active tissues such as stems and leaves. However, interaction effects among planting density, nitrogen level and LCC threshold were not statistically significant in either year of the study.

Effect of planting density, nitrogen levels and LCC threshold values on yield attributes

Cob length

Average cob length of maize was 4.85 % higher in lower plant density of (66666 plants ha^{-1}) compared to higher plant density (111111 plants ha^{-1}) (Table 3). Reduced inter plant competition at lower densities likely allowed for better resource utilisation of nutrients, water and sunlight, resulting in increased assimilate accumulation and longer cobs. Cob length also increased significantly with application of higher level of nitrogen compared to lower levels. Improved vegetative growth coupled with early tasseling and silking, extended the grain filling period and enhanced cob development.

Notably, the LCC threshold 5 resulted in a 7.67 % increase in cob length compared to LCC 4.5, attributed to enhanced plant performance reflected in greater plant height, LAI and higher dry matter production and its accumulation. These findings align with earlier reports (27). Interactions of three factors were found to be non-significant during both the years.

Hundred seed weight

A decline in hundred seed weight was observed with increased plant density, decreasing from 33.0 g at 66666 plants ha^{-1} to 30.5 g at 111111 plants ha^{-1}. The higher seed weight at lower plant density is attributed to better dry matter production and more efficient source-to-sink translocation, supporting longer grain development.

Application of 40 kg N ha^{-1} resulted in highest seed weight compared to other treatments. The enhanced biomass production and sink strength due to higher nitrogen availability may have contributed to this effect (28). Additionally, LCC 5 threshold yielded highest seed weight (33.3 g), outperforming LCC 4.5 (31.6 g) and LCC 4 (30.3 g). This suggest that using LCC 5 as decision support tool ensured timely and adequate nitrogen availability, thereby improving grain filling, these observations are consistent with earlier studies (13).

Kernel yield

Kernel yield significantly increased with each successive increase in planting density from 66666 plants ha^{-1} to 111111 plants ha^{-1} during both the years of the study. The lowest kernel yield (4.23 t ha^{-1}) was recorded at the lowest planting density (66666 plants ha^{-1}) which might be due to lower populations per unit area, which could not be offset by improved yield attributes per plants (29).

Among nitrogen treatments, 40 kg N ha^{-1} recorded significantly highest kernel yield (5.28 t ha^{-1}) followed 35 kg N ha^{-1} (4.99 t ha^{-1}) and 30 kg N ha^{-1} (4.72 t ha^{-1}). The increase in kernel

Table 3. Cob length, text weight, kernel yield, nitrogen uptake and nitrogen use efficiency of maize as influenced by planting density, nitrogen levels and LCC threshold values

	Cob length (cm)	Test weight (g)	Kernel yield (t ha^{-1})	N uptake (kg ha^{-1})	NUE
Planting density (plants ha^{-1})					
P_1: 66666	16.8	33.1	4.23	89.70	26.2
P_2: 83333	16.0	31.7	4.96	109.9	28.5
P_3: 111111	15.7	30.5	5.79	127.1	31.4
SEm±	0.07	0.23	0.04	1.96	0.23
CD (P = 0.05)	0.27	0.90	0.14	7.71	0.91
Nitrogen levels (kg ha^{-1})					
N_1: 30	15.7	29.7	4.72	103.5	28.5
N_2: 35	16.0	31.9	4.99	108.6	28.6
N_3: 40	16.4	33.7	5.28	114.7	28.9
SEm±	0.10	0.16	0.04	1.06	0.24
CD (P = 0.05)	0.30	0.49	0.13	3.28	NS
LCC threshold values					
L_1: LCC 4	15.7	30.3	4.66	105.0	28.8
L_2: LCC 4.5	16.3	31.6	4.96	107.7	28.8
L_3: LCC 5	16.9	33.3	5.36	114.1	28.4
SEm±	0.09	0.16	0.05	1.29	0.28
CD (P = 0.05)	0.27	0.47	0.14	3.70	NS
Interaction					
PXN					
SEm±	0.17	0.27	0.07	1.84	0.42
CD (P = 0.05)	NS	NS	0.22	NS	NS
PXL					
SEm±	0.16	0.28	0.15	2.23	0.49
CD (P = 0.05)	NS	NS	0.42	NS	NS
NXL					
SEm±	0.16	0.28	84.6	2.23	0.49
CD (P = 0.05)	NS	NS	NS	NS	NS
PXNXL					
SEm±	0.28	0.49	146.5	3.87	0.85
CD (P = 0.05)	NS	NS	NS	NS	NS

yield with higher nitrogen levels is attributed to enhance vegetative growth, better nutrient availability and improved translocation of assimilates to the developing kernels. Use of LCC 5 threshold resulted in significantly higher kernel yield (5.36 t ha^{-1}) compared to LCC 4.5 (4.96 t ha^{-1}) and LCC 4 (4.66 t ha^{-1}) (Table 3). This suggests that nitrogen application guided by LCC 5 was better synchronized with crop demand across critical growth stages, improving nitrogen use efficiency (NUE) and reducing losses through volatilization and denitrification (21). Significant interaction effects were observed between planting density and nitrogen levels as well as planting density and LCC threshold. The combination of higher planting density with higher nitrogen levels (P_3N_3) recorded maximum kernel yield during both the years of field study and it was statistically superior to all other treatment combinations (Fig. 1). The lower kernel yield was observed with the combination of low planting density along with lower application of nitrogen (P_1N_1). Similar interaction effect was also noted in the previous research (30).

Nitrogen uptake

Nitrogen uptake was significantly by planting density, nitrogen level and LCC threshold values (Table 3). However, interaction effect among all three tested factors were found to be non-significant during both the years of study. Nitrogen uptake increased with higher density, this can be attributed to increased competition among the plants for available nitrogen under higher planting density, which likely stimulated greater biomass production and dry matter accumulation. Enhanced crop growth at higher densities contributed to improve nutrient absorption.

Among nitrogen treatments, application of 40 kg N ha^{-1} at different splits resulted in higher nutrient uptake, while lowest nutrient uptake was recorded with application of 30 kg N ha^{-1}. This improvement in uptake at higher nitrogen levels with various split applications might be due to better root growth and development, increased root surface area and enhanced cation exchange capacity all of which promote greater uptake of nutrients.

N uptake was significantly higher under the LCC 5 threshold compared in LCC 4.5 and LCC 4 during both the years of study (Table 3). The real time application of nitrogen in five splits guided by LCC 5 likely ensured better synchronization of nitrogen supply with crop demand, thereby improving uptake efficiency. These results were in alignment with the previous findings (30). Overall, higher nutrient uptake under optimal conditions may also attributes to increased yield contributing traits, enhanced photosynthetic activity and improved translocation (31), which collectively support the crops nutrient acquisition.

Nitrogen use efficiency (NUE)

Higher planting density (111111 plants ha^{-1}) recorded significantly higher nitrogen use efficiency (31.4) compared to lower plant densities (Table 3). This improvement is likely due to nitrogen availability with crop demand through split applications, minimizing losses and enhancing uptake. These results are in alignment with earlier findings (29).

Among nitrogen levels, application of 40 kg ha^{-1} resulted in highest NUE, which was statistically at par with the application of 35 kg N ha^{-1} (28.6).

The improved NUE at higher rates may be attributed to enhanced synchrony between nitrogen supply and crop uptake through precise timing of applications. On the contrary, lower NUE observed with 30 kg ha^{-1} due to insufficient nitrogen supply during critical growth stages, resulting in mismatch with crop nitrogen demand. While the nitrogen levels and planting densities significantly influenced NUE, the effect of LCC threshold levels on NUE was found to be non-significant during both years of the study (32). However, NUE tended to be higher with LCC-based split applications, suggesting better temporal matching of nitrogen delivery with crop needs.

Soil nitrogen balance

Soil available nitrogen balance sheet for two years was calculated based on native and applied nitrogen to the soil and uptake by the crop (Fig. 2). The balance sheet delineated net change in the soil available nitrogen status. The soil available nitrogen balance was affected owing to various planting densities, nitrogen levels and LCC threshold values, during both the years of field study. Highest net nitrogen loss was recorded in treatment combination $P_3N_1L_3$ (high planting density at lower rate of nitrogen application along with higher level of LCC threshold) with a deficit of -48.5 kg ha^{-1} during the first year and -68.7 kg ha^{-1} in the second year. This suggests that low nitrogen inputs at high crop demand scenarios

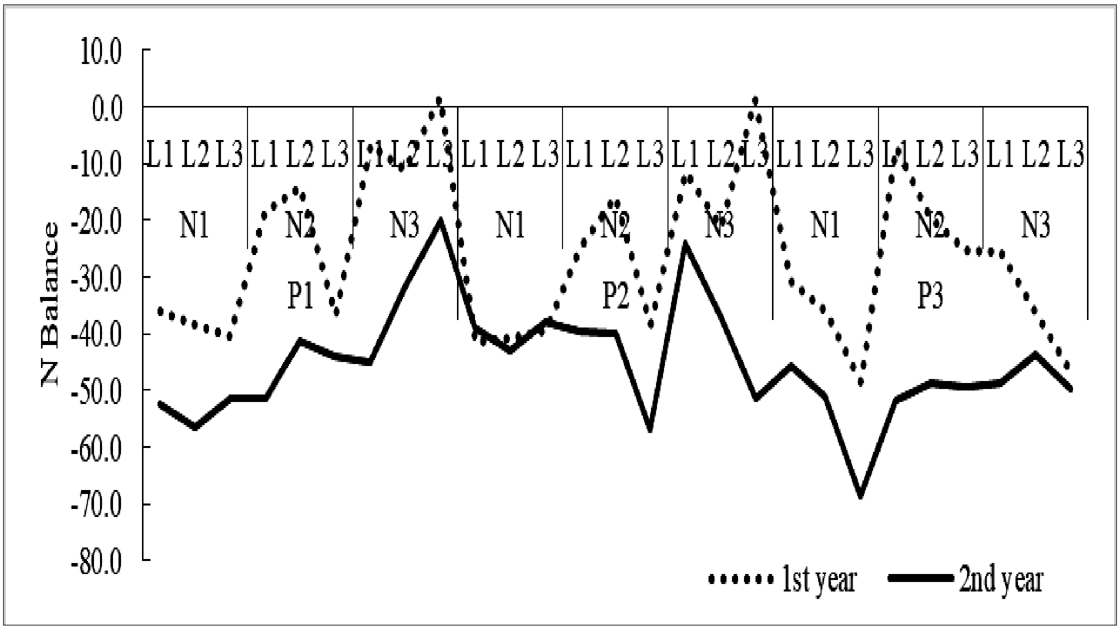

Fig. 2. Effect of planting density, nitrogen levels and leaf colour chart on N balance during 2017-2019 under maize crop.

led to depletion of soil nitrogen reserves.

Conversely, higher net gain of soil nitrogen was recorded in $P_1N_3L_3$ (low planting density, high nitrogen application and LCC 5), indicating a surplus due to improved nitrogen management. The greater net gain in these treatments is attributed to the higher number of split doses and lower crop uptake resulting from reduced plant population pressure. Overall, maize, being a high-demand crop, caused negative nitrogen balances under most treatments, highlighting the importance of precise nitrogen management for maintaining long-term soil fertility (31). Higher LCC thresholds, particularly LCC 5, contributed to better crop uptake and more balanced nitrogen use, supporting sustainable nutrient management strategies.

Relationship between growth parameters and yield

Correlation analysis revealed that plant height, leaf area index, dry weight, harvest index, crop growth rate and nutrient use efficiency (NUE) were significantly and positively associated with maize yield at 1 per cent level of significance (r = 0.753**, 0.916**, 0.981**, 0.700**, 0.587** and 0.836**, respectively) (Table 4). These parameters likely contributed to improved physiological efficiency, better biomass accumulation and better translocation of photosynthates to reproductive organs resulting in higher yields (25). In contrast, chlorophyll content at harvest, number of kernels cob and cob length were negatively correlated with yield (r = -0.078, -0.256 and -0.197, respectively). This may be due to physiological constraints under high plant density and nitrogen stress, such as asynchronous flowering, abortion of seed and ultimately reduction in the number of kernels per cob. However, remobilization of nitrogen from leaves to grains during grain filling could have led to reduced chlorophyll content at harvest of the crop.

These findings are further supported by the regression analysis (Table 5), which indicated that leaf area index, dry weight and nutrient use efficiency had the greatest influence on enhancing crop yields (Y = 1123.62X + 140042, R^2 = 0.84; Y = 0.346227X - 265.53, R^2 = 0.96; Y = 276.9713X - 2949.97, R^2 = 0.84, respectively) compared to other parameters. Higher photosynthetic activity, driven by grater LAI and dry matter production, played a crucial role in enhancing yield. Since leaf is directly linked to light interception and photosynthetic capacity, which influence biomass accumulation and grain filling. The observed differences in NUE and yield may be attributed to improved root architecture, increased nutrient uptake efficiency from subsoil layers, enhanced nutrient mobilization in the rhizosphere and effective internal transport and utilization of nutrients. In addition, the alignment of source-sink relationships and adoption of improved crop management practices contribute to better performance. Genotypic traits such as superior root systems and higher inherent nutrient efficiency, along with site-specific nitrogen management (e.g., LCC-based applications), further support enhanced yields and sustainable nutrient use (33

Conclusion

This study demonstrates that strategic nitrogen management, particularly through real-time application using the LCC, plays a crucial role in enhancing maize productivity under higher planting

Table 4. Correlation matrix between different growth and yield parameters

	Correlations										
	PH	LAI	SPAD	DW	NKPC	CL	Y	HI	TW	CGR	NUE
PH	1	.541**	.369	0.719**	.246	.356	.753**	.705**	.476*	.484*	.375
LAI		1	-.367	.953**	-.531**	-.434*	.916**	.448*	-.254	.581**	.911**
SPAD			1	-.143	.844**	.730**	-.078	.164	.875**	.147	-.484*
DW				1	-.324	-.227	.981**	.595**	.002	.646**	.844**
NKPC					1	.751**	-.256	.130	.761**	-.091	-.563**
CL						1	-.197	.116	.797**	.173	-.545**
Y							1	.700**	.049	.587**	.836**
HI								1	.212	.173	.519**
TW									1	.328	-.380
CGR										1	.392*
NUE											1

**Correlation is significant at the 0.01 level (2 tailed). *Correlation is significant at the 0.05 level (2 tailed). PH: plant height; LAI: leaf area index; SPAD: chlorophyll; DW: dry weight; NKPC: number of kernels per cob; CL: cob length; Y: yield; HI: harvest index; TW: test weight; CGR: crop growth rate; NUE: nitrogen use efficiency.

Table 5. Regression analysis between crop yield and the other attributes

Parameter		Regression equation	R^2	*p* value
Y	X			
Yield	Plant height	Y = 91.92X − 14763	0.57	0.0000
	LAI	Y = 1123.62X + 140042	0.84	0.0000
	SPAD	Y = −24.5634X + 5931.27	0.01	0.7013
	Dry weight	Y = 0.346227X − 265.53	0.96	0.0000
	No of kernels per row	Y = −5.35149X + 7136.47	0.07	0.1981
	Cob length	Y = −263.341X + 9222.52	0.04	0.3186
	HI	Y = 476.527X − 12104.4	0.49	0.0000
	Test weight	Y = 15.92636X + 4488.18	0.00	0.8067
	CGR	Y = 373.5561X + 680.422	0.34	0.0014
	NUE	Y = 276.9713X − 2949.97	0.70	0.0000

densities. The combination of a higher plant density (111111 plants ha^{-1}) with a total nitrogen application of 100 kg ha^{-1} split as 60 kg ha^{-1} basal and 40 kg ha^{-1} top-dressed based on LCC threshold 5 significantly improved kernel yield, nitrogen use efficiency and overall crop performance. The findings underscore the importance of synchronizing nitrogen supply with crop demand through split applications guided by crop growth stages. This approach not only optimizes input use efficiency but also supports sustainable intensification of maize production systems. In the context of modern agriculture, the judicious use of synthetic fertilizers remains vital, but their efficiency can be substantially improved through need-based, site-specific application strategies. Promotion and large-scale adoption of decision-support tools like LCC among farmers can facilitate more efficient nitrogen use, reduce environmental risks and enhance profitability.

Recommendations

I. For Farmers: Adoption of LCC-based nitrogen management should be encouraged to reduce input costs and improve yield sustainably.

II. For Researchers: Further studies are recommended to validate the LCC-based nitrogen management approach across diverse agro-ecological zones, maize genotypes and climatic conditions.

III. For Policymakers: Integration of LCC tools into extension advisory services and subsidy programs can support the broader goal of climate-smart and resource-efficient agriculture.

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Authors' contributions

MR carried out the field trial, data analysis and drafting of the manuscript. SH advised and supervised the full research work critically. APK helped in manuscript drafting and data analysis. KV assisted in manuscript drafting and editing. VU assisted in manuscript editing and data analysis, field trial. All the authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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