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Optimisation of nitrogen levels using leaf colour chart as influenced on soil fertility and productivity of maize (*Zea mays* L.) in sandy clay loam soils

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Abstract

The present study was conducted to address the inefficient management of nitrogenous fertilisers in maize (*Zea mays* L.) cultivation. On-farm trials were carried out during the rabi seasons of 2023–24 and 2024–25 in farmers' fields at different locations in NTR district, Andhra Pradesh. The experiments were conducted using a randomised complete block design (RCBD) with three replications at each location. The results showed that leaf colour chart (LCC)-based nitrogen management increased grain yield to 5563.5 kg ha^{-1}, representing a 7.87 % increase over farmers' practice (5148.5 kg ha^{-1}). The technology index, extension gap and technology gap were 9.57 %, 415 kg ha^{-1} and 586.5 kg ha^{-1}, respectively. The benefit-cost ratio was higher under LCC-based nitrogen management (2.31) than under farmers' practice (1.90). These findings demonstrate the usefulness of LCC-guided, need-based nitrogen management for sustaining maize productivity and improving fertiliser-use efficiency. The study also highlights the practical value of the LCC as a simple tool for guiding farmers towards more efficient nitrogen management. Higher grain yield and net returns were obtained with need-based application of 200 kg N ha^{-1} using an LCC score of 5 as the critical threshold. This approach resulted in a saving of 100 kg N ha^{-1} compared with farmers' practice. The demonstrated technology also contributed to increased farmer awareness and encouraged the adoption of improved nitrogen-management practices. Overall, LCC–guided nitrogen management offers a practical approach for improving nitrogen-use efficiency while sustaining maize productivity under farmer-field conditions.

Keywords: critical limit; extension gap; leaf colour chart; maize; nitrogen management; technology gap; technology index

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1. Introduction

Nitrogen is one of the major nutrients required for crop production and plays an important role in achieving higher and more sustainable yields. Efficient nitrogen management requires the application of an appropriate quantity of nitrogen according to crop demand and at the appropriate stage of crop growth. However, variations in soil characteristics, inherent soil nitrogen supply and crop nitrogen requirements at different growth stages make precise nitrogen management challenging. Applying nitrogen according to crop demand is therefore important for achieving profitable crop production, maintaining soil health, reducing gaseous nitrogen losses and improving nitrogen-use efficiency.

Real-time, site-specific nitrogen management involves applying nitrogen at the right rate and at the appropriate crop-growth stage to improve fertiliser-use efficiency, particularly during critical periods of crop nitrogen demand. Several tools, including GreenSeeker, chlorophyll meters and leaf colour charts (LCC), are available for real-time nitrogen management. Among these, the LCC is a simple, inexpensive, portable and farmer-friendly tool. It allows the user to assess leaf colour by comparing the colour of the crop leaves with standardised colour shades. This makes the assessment of crop nitrogen status simpler than with more sophisticated instruments. Farmers often associate darker green leaves with better crop growth and may therefore apply nitrogen even when additional fertiliser is not required. Such unnecessary applications can contribute to soil and groundwater contamination and raise environmental concerns (1). Continued excessive fertiliser application can also contribute to deterioration of soil health, which is an important concern for sustainable crop production. In this context, site-specific nutrient management using the LCC may provide a practical option, particularly for

small and marginal farmers (2). Nutrient management has played an important role in achieving food-grain self-sufficiency in world agriculture. However, the need for precise and responsive nitrogen management in maize (*Zea mays* L.) has become increasingly important from both economic and environmental perspectives. Static fertiliser recommendations based on average crop responses can result in excessive fertiliser application in some years and inadequate nitrogen supply in years when nitrogen losses are high (3). Uncertainty in determining the optimum nitrogen application rate may reduce profitability because maize responses to applied nitrogen varies with environmental and soil conditions. Such uncertainty can be reduced through more accurate location and time-specific recommendations that improve the precision of fertiliser application and promote balanced nutrient management. In recent years, several precision tools have been used for nitrogen management, particularly in rice, maize and cotton (4–6).

Among these precision-management tools, the LCC is particularly useful because of its suitability for assessing the nitrogen status of maize. Its usefulness has also been indicated through spectral reflectance measurements in rice and maize leaves (7, 8). The LCC helps identify the need for nitrogen application in maize by providing an indication of crop nitrogen status in relation to soil nitrogen supply and crop demand. It can therefore serve as a practical tool for optimising nitrogen use irrespective of the source of nitrogen applied (7). One of the major challenges in modern agriculture is improving nutrient-use efficiency, particularly nitrogen-use efficiency. Maize is a nutrient-demanding crop and consequently requires relatively high fertiliser inputs. Insufficient nutrient availability can restrict crop growth, resulting in reduced yields and lower economic returns. Conversely, excessive application of nitrogenous fertilisers without considering crop nutrient requirements, recommended fertiliser rates and crop-growth stage can lead to nutrient imbalances and economic losses. Efficient nitrogen management using the LCC can help improve maize yield while supporting more effective fertiliser use and soil health. Leaf colour provides a visible indicator of crop nitrogen status and can therefore help farmers make more informed nitrogen-application decisions.

Despite these advantages, the use of LCC-based nitrogen management remains limited in South Asian countries and is particularly limited in Andhra Pradesh. The LCC provides a simple, rapid and non-destructive method for assessing the nitrogen status of maize leaves. The tool consists of a high-quality plastic strip containing a series of colour panels representing different levels of leaf greenness. The colour range extends from yellowish green to dark green and represents a continuum from nitrogen deficiency to excessive leaf nitrogen content (9). The LCCs therefore provide an indirect assessment of leaf nitrogen status by visually comparing the greenness of the leaf with the standardised colour panels (10).

Considering these advantages, on-farm trials (OFTs) were conducted systematically at different locations in farmers' fields in NTR district, Andhra Pradesh. The objective was to demonstrate the usefulness of the technology and encourage farmers to adopt balanced nutrient-management practices in maize. In addition to its potential socioeconomic benefits, this resource-management approach may help reduce problems associated with excessive nitrogen supply, including lodging, nutrient deficiencies and luxury consumption, while helping to maintain soil nutrient status for subsequent crop production. The OFTs can therefore serve as an effective extension intervention by demonstrating practical approaches to sustainable crop production through improved fertiliser management. They also provide an opportunity to assess the technology under farmers' field conditions and identify gaps between recommended practices and existing farmer practices. Therefore, the present study was conducted to evaluate real-time nitrogen fertiliser management using a plant-based LCC in comparison with soil-test-based recommendations and farmers' blanket fertiliser practices. The study aimed to assess the relative effectiveness of LCC–based nitrogen management in improving nitrogen-use efficiency and maize yield while reducing unnecessary nitrogen application and supporting sustainable soil management.

2. Materials and Methods

Study area and soil characteristics

The study was conducted during the rabi seasons of 2023–24 and 2024–25 in farmers' fields at different locations in NTR district, Andhra Pradesh. The details of the experimental sites are presented in Table 1. The soils at the study locations were sandy clay loam in texture and slightly alkaline in reaction, with pH values generally ranging from 7.42–8.09. The soils were non-saline, with electrical conductivity ranging from 0.55 to 1.08 dS m^{-1}. Organic carbon content was low, ranging from 0.32–0.58 %. The soils were low in available nitrogen, with values of 224.00 and 269 kg ha^{-1}, high in available phosphorus, with values of 68 and 142 kg ha^{-1} and medium in available potassium, with values of 234 and 384 kg ha^{-1}.

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Table 1. Soil properties of the demonstration plots of different villages of studied areas

Particulars of villages	GPS coordinates (Lat. /Long.)	pH	EC	OC	Avail.N	Avail.P	Avail.K
			dS m^{-1}	%		Kg ha^{-1}	
Gandrai	16.951/80.061	7.72	0.92	0.32	245	98	234
Takellapad	16.962/80.065	7.43	0.87	0.45	267	96	296
Balusupadu	16.967/80.125	7.79	0.85	0.51	234	128	303
Takellapadu	16.914/80.086	8.01	1.04	0.38	248	142	354
SM Peta	16.919/80.091	7.92	1.08	0.58	224	98	268
Pochampalli	16.962/80.131	7.45	0.75	0.36	239	76	258
Pallagiri	16.923/80.056	7.85	0.69	0.34	257	84	282
Balusupadu	16.925/80.065	7.77	0.55	0.39	268	68	384
Gandrai	16.781/80.321	7.42	0.59	0.45	259	78	306
Pallagiri	16.832/80.171	8.09	0.81	0.48	269	86	310
	Range	7.42–8.09	0.55–1.08	0.32–0.58	224–269	68–142	234–384
	Mean	7.75	0.82	0.43	251.00	95.40	299.50

Avail.N: available nitrogen; Avail.P: available phosphorus; Avail.K: available potassium; Lat. /Long.: latitude/longitude.

Leaf colour chart-based nitrogen management

A six-panel LCC, developed for maize by scientists at Punjab Agricultural University (PAU), Ludhiana, was used in the experiment (11). The LCC observations were recorded following the methodology described earlier (4, 12, 13). The LCC readings were first recorded at 21–25 days after sowing (DAS) from 10 randomly selected maize plants in each experimental plot. The readings were taken from the third fully expanded and healthy leaf from the top of the plant by visually matching its colour with the LCC colour shades. The average score of the 10 selected plants was then calculated. The third fully expanded leaf was selected because its colour is closely associated with the nitrogen status of maize. At the tasselling stage, the ear leaf was used as the index leaf for measurement (14). For each observation, the middle portion of the leaf was placed over the LCC colour strips for comparison. All readings were taken between 8:00 and 10:00 am and were recorded by the same person to maintain consistency. When the average LCC reading fell below the critical LCC value, nitrogen fertiliser was applied according to the recommended treatment schedule. The LCC observations were subsequently taken at regular intervals of 7–10 days using the same 10 selected plants and continued up to the tasselling and silking stages.

On-farm trials and experimental treatments

The study was conducted through ICAR-ATARI-X, Krishi Vigyan Kendra, Garikapadu, ANGRAU, NTR district, Andhra Pradesh, during the rabi seasons of 2023–24 and 2024–25. Demonstrations were conducted in farmers' fields located in Gandrai, Balusupadu, Takkellapadu, S.M. Peta, Pochampalli and Pallagiri villages. The experiments were conducted as OFTs to address productivity and economic losses associated with sandy clay loam soils, lodging, excessive nutrient supply and pest incidence, particularly fall armyworm. The average productivity of the villages was 5.8 t ha^{-1}. The climate of NTR district is semiarid subtropical, characterised by dry and hot summers and cold winters. The annual average rainfall is approximately 1061 mm, with most rainfall occurring from the latter part of June to mid-September. The major constraints identified in the villages included variations in soil type, particularly mixed red and black soils, improper fertiliser management, low organic matter, salinity, limited economic resources and uncertainty in rainfall. Except for improper fertiliser management in maize, several of these factors were beyond the immediate control of farmers. Therefore, improved crop and fertiliser management was considered an important intervention. Participatory rural appraisal (PRA) and survey activities indicated that farmers generally cultivated rabi maize using variable and often inappropriate quantities of N, P and K fertilisers. The general recommendation for rabi maize was 200–240:80:80 kg $N_2O_{52}O$ ha^{-1}. In Andhra Pradesh, the general N:P fertiliser-use ratio was reported as 4:2:1. However, substantial variation was observed in farmers' fertiliser-management practices, particularly in maize. Small, tenant and marginal farmers were predominant in the study villages and the survey was therefore conducted using a participatory approach.

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Five farmers from each village were selected during each season over the two-year study period and were considered as replications. The experiment consisted of three treatments:

T_1: LCC-based nitrogen management

T_2: Soil-test-based nitrogen management (STBF)

T_3: Farmers' practice involving blanket fertiliser recommendations using complex fertilisers and urea.

Under T_1, nitrogen was applied at 30 kg N ha^{-1} during top-dressing stages based on an LCC threshold score of 5. Nitrogen was applied in split doses up to the tasselling and silking stages, while phosphorus and potassium were applied according to soil-test recommendations at 80:80 kg ha^{-1}. During abiotic-stress management, 13–0-45 was also applied at 5 g L^{-1} because maize is an exhaustive crop. Soil samples were collected and analysed for physicochemical properties to assess treatment effects on soil fertility. Soil analysis was carried out using standard procedures and the cost economics of the treatments was also calculated (15).

Adoption gap and yield-gap analysis

The identified adoption gaps were categorised into three groups: full adoption or no gap, partial adoption or partial gap and no adoption or full gap. These categories were assigned scores of 1, 2 and 3, respectively. Yield data were collected from new technology, existing technology and farmers' practice using the random crop-cutting method.

The adoption gap index was calculated using the following formula (2):

Adoption gap index = [(Total number of improved practices − Number of improved practices followed by the farmer) / Total number of improved practices] × 100

Yield parameters from both the demonstrations and check plots were recorded. Based on the yield data, the extension gap, technology gap, yield gap and technology index were calculated according to the procedures (16, 17).

Extension gap (q ha^{-1}) = Demonstration yield − Yield under existing farmers' practice

Technology gap (q ha^{-1}) = Potential yield − Demonstration yield

Additional return = Demonstration return − Farmers' practice return

Yield gap (%) = [appropriate yield-gap calculation] × 100

Technology index = [appropriate technology-index calculation] × 100

Note: The mathematical expressions for yield gap and technology index were not fully represented in the uploaded source. They should be inserted from the original manuscript/table before submission rather than reconstructed.

Calculations and statistical analysis

A graphical approach was used to establish the threshold leaf greenness value by examining the relationship between LCC score and relative grain yield (18). This relationship was used to guide site-specific nitrogen management in maize at different crop-growth stages. A threshold value represents the level below which the crop may experience nutrient deficiency, whereas values above the threshold indicate that additional nitrogen may not produce a significant response (19). Relative grain yield was expressed as the ratio of the observed yield to the maximum yield. The experimental data were analysed using analysis of variance (ANOVA), Duncan's multiple range test (DMRT) and other simple statistical tools in MS Excel.

3. Results and Discussion

Soil fertility status

The soils at the experimental locations were characterised by low to medium carbon content, high available phosphorus and medium to high available potassium. The pH and electrical conductivity values across the villages were within the reported normal range. Organic carbon, available phosphorus and available potassium were determined using standard procedures and the detailed results are presented in Table 1.

Growth attributes

Need-based nitrogen application guided by the LCC resulted in lower plant height than nitrogen application at fixed time intervals (Table 2). In general, the increase in cob weight with increasing LCC scores indicated greater uptake of nitrogen when fertiliser application was synchronised with crop demand. An increase in nitrogen application at fixed time intervals resulted in a significant increase in test weight (20). Similarly, increasing the LCC threshold for nitrogen application resulted in a significant increase in plant height. Additional nitrogen application at the silking stage at each threshold also tended to increase plant height, indicating that the crop responded to increased nitrogen availability. Nitrogen application guided by the LCC resulted in significantly lower plant height than nitrogen application at fixed intervals. However, among treatments in which nitrogen was managed according to LCC scores at successive intervals up to the reproductive stage, differences in plant height were relatively small and non-significant, possibly because of the crop's capacity to utilise available nitrogen. The results indicated that plant height responded more strongly when nitrogen was managed at an LCC score of 5.0 at the silking stage (21).

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Table 2. Pooled data of biometrical observations of the experiment

Parameter	T1	T2	T3	*F*-value	Significance
Plant height (cm)	345.00[a]	326.67[b]	333.67[ab]	4.54	NS at 5 %
Plants/m²	8.33[a]	8.00[a]	8.00[a]	0.14	NS
Cobs/plant	1.67[a]	1.67[a]	3.00[a]	3.20	NS
Rows/cob	16.67[a]	17.33[a]	16.33[a]	0.78	NS
Grains/row	41.67[a]	43.00[a]	44.00[a]	1.95	NS
Test weight (g)	24.00[a]	24.00[a]	24.00[a]	0.00	NS
Cob weight (g)	259.00[a]	246.33[b]	242.67[b]	7.06	Significant
Seed weight/25 m² (kg)	16.50[a]	14.90[b]	14.47[b]	22.28	Significant

One-way analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT) at 5 % significance level; T_1: leaf colour chart-based nitrogen management; T_2: Soil-test-based nitrogen management; T_3: Farmers' practice involving blanket fertiliser recommendations using complex fertilisers and urea.

Yield attributes

The number of days required to reach 50 % tasselling and silking was significantly influenced by the different nitrogen-management strategies. These values were slightly higher under nitrogen applications at fixed intervals than under LCC-based nitrogen management. In general, 50 % tasselling and silking varied significantly among treatments receiving nitrogen at different LCC thresholds, ranging from < 3 to < 5, as well as at the silking stage at LCC thresholds of < 3.5, < 4.5 and < 5.5. The anthesis–silking interval (ASI) followed a similar trend to that observed for 50 % tasselling and silking. Maize under farmers' practice reached tasselling later than plants receiving nitrogen through fixed-time and LCC-based management (22, 23). The results further indicated that applying an additional 35 kg N ha^{-1} at the tasselling and silking stages provided a significant yield advantage over farmers' practice at the respective LCC thresholds. Soil-available nitrogen decreased from the initial level under all treatments (24). Available nitrogen differed significantly among treatments receiving different LCC thresholds and nitrogen levels and generally increased with increasing LCC values. This indicates a relationship between LCC-guided nitrogen management, nitrogen application levels and the measured soil fertility status (25, 26). The adoption of improved crop-production technologies, including plant-protection measures, is also important for maintaining maize productivity and profitability (Table 3) (27).

Development and validation of threshold leaf colour chart values

The threshold or critical LCC value refers to the optimum LCC score below which leaf greenness indicates that the nitrogen supply may be insufficient to achieve potential yield. Considerable variation in LCC readings was observed at different crop-growth stages irrespective of the amount of fertiliser nitrogen applied. Field observations indicated that an appropriate LCC threshold could therefore be useful for managing nitrogen efficiently at different stages of crop growth. Similar findings have been reported for zinc fertilisation in tomato, where appropriate nutrient management contributed to promising yields and economic sustainability (28). In the present study, Cate–Nelson graphical analysis of LCC readings and relative grain yield (Fig. 1) identified an LCC threshold value of 5.0 as optimal for achieving potential yield. Thus, a leaf-greenness level corresponding to an LCC score of 5.0 in rabi maize indicated sufficient nitrogen availability, whereas readings below this threshold indicated an increased crop requirement for fertiliser nitrogen. Similar observations have also been reported (29–31). The results of the experiments conducted during 2023–24 and 2024–25 in the adopted villages of KVK Garikapadu are presented in Fig. 1. Grain yield of maize cultivars increased significantly under LCC-guided nitrogen application compared with farmers' practice. Nitrogen top-dressing guided by an LCC threshold of 5 produced significantly higher yields than both soil-test-based nitrogen recommendations and farmers' practice. LCC threshold 5-based nitrogen management was more economical while producing comparable or improved yields and saving 20 % of nitrogen fertiliser compared with farmers' practice. Under farmers' practice, additional top-dressing resulted in an extra nitrogen application of 60 kg N ha^{-1} and lodging was also observed. This may have been associated with increased crop succulence without a corresponding yield benefit. The mean grain yield obtained with an LCC threshold of 5 increased by 4.5 % over soil-test-based nitrogen application and by 7.87 % over farmers' practice. These findings are consistent with earlier reports that demonstrated higher grain yields and improved nitrogen-recovery efficiency under LCC-based nitrogen management in maize (13, 32).

Economic analysis of maize grain yield

The grain yield and yield-gap analysis of maize are presented in Table 4. The results showed that average maize grain yield increased by 7.87 %, from 5148.5 kg ha^{-1} under farmers' practice to 5563.5 kg ha^{-1} under the demonstration treatment involving technological interventions.

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Table 3. Difference between technological intervention through on-farm trials in Maize

Sl.No.	Technology intervention particulars	Demo plot (on-farm trials)	Existing technology	Farmers practice	Gap
1	Good quality seed	Followed	Followed	Followed	No gap
2	Seed rate (Kg ha^{-1})	12.5 kg ha^{-1}	15 kg ha^{-1}	20 kg ha^{-1}	Full gap
3	Sowing method	Hand push seed drill	Seed drill/ tractor sowing/dibbling	Seed drill/ tractor sowing/dibbling	Partial gap
4	Spacing	Followed	Followed	Followed rarely	Partial gap
5	Seed treatment with Cyantraniliprole + Thiamethoxam	Followed	Followed	Not Followed	Full gap
6	Weed Management with both pre-emergence and post emergence herbicides	Followed	Post emergence only followed	Post emergence only followed	Partial gap
7	Soil test-based fertiliser application	Not followed	Followed	Not followed	Full gap
8	Usage of straight fertilisers	Followed	Not followed	Not followed	Full gap
9	Usage of complex fertilisers only as basal	Followed	Not Followed	Not followed	Full Gap
10	Bio fertilisers usage	Followed	Not followed	Not followed	Full gap
11	Micronutrients application	Followed	Followed	Not followed	Full gap
12	Usage of LCC	Followed	Not followed	Not followed	Full gap
13	Irrigation Management	Followed	Fallowed	Followed rarely	Partial gap
14	Installation of S. frugiperda pheromone traps	Not followed	Not followed	No Pheromone traps used	Full gap
15	Azadirachtin 10000 ppm spray 10 to 15 DAS	Followed	Not followed	Followed rarely	Partial gap
16	Use of bio-formulation Metarhiziumanisopliae	Followed	Not followed	Followed rarely	Partial gap
17	Use of advanced chemical cyantraniliprole 10.26 % OD	Followed	Not followed	Indiscriminate use of insecticides with similar mode of action	Partial Gap
18	Use of 13–0-45 or 19:19:19 at abiotic stress conditions	Followed	Not followed	Not followed	Full gap

The economic analysis presented in Table 4 includes the cost of cultivation, gross returns, net returns and the benefit-cost ratio. The results indicated that maize under the recommended approach recorded higher gross returns of Rs. 127012.50 ha^{-1} compared with Rs. 117601.50 ha^{-1} under farmers' practice. These findings are consistent with earlier reports showing improvements in maize yield and net returns following improved nutrient-management practices (33, 34). Over the two-year period, the recommended approach resulted in an average additional return of Rs. 15911 ha^{-1}. Similar results have been reported previously (35, 36). The benefit–cost ratio was also higher under the recommended approach (2.31) than under farmers' practice (1.90). The greater grain output and market value of the produce may have contributed to the higher net returns and benefit ratio observed under the demonstration treatment.

Overall, the results indicated improved profitability and economic viability with the adoption of LCC-based nitrogen management combined with good agricultural practices under the local agro-ecological conditions (37). Higher returns and benefit ratios under improved practices in frontline demonstrations have also been reported previously (38, 39).

Maize grain-yield gap analysis

Extension gap

The difference in productivity between the demonstration treatment and farmers' practice was considered the extension gap. This gap reflects the level of awareness and adoption of improved agricultural practices among farmers. The average extension gap recorded in the study (Table 5) was 415 kg ha^{-1}. The observed extension gap indicates the need for effective extension activities to improve farmers' awareness and adoption of LCC-based nitrogen management.

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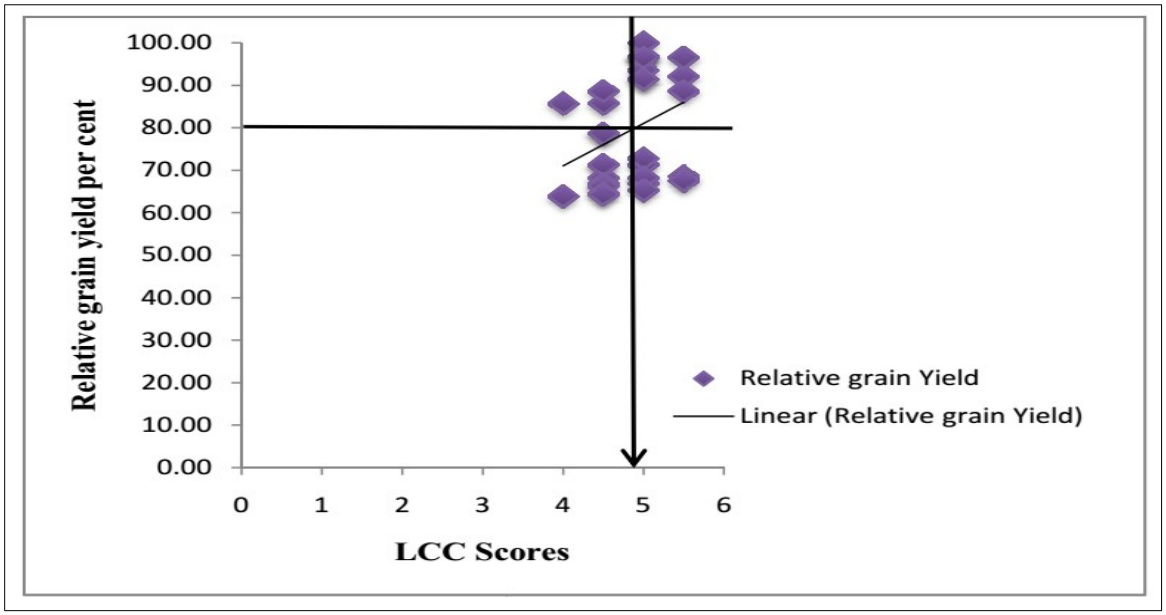


Fig. 1. Cate and Nelson graphic analysis of leaf colour chart scores with relative grain yield. LCC: leaf colour chart.

Table 4. Pooled data of economic indicators of the experiment

Year	Treatments	Average yield (kg/ha)	Gross returns (Rs/ha)	Cost of cultivation (Rs/ha)	Net returns (Rs/ha)	B:C Ratio	Percentage increase in yield
	T_1	4620	110880	55000	55880	2.02	6.69
2023–24	T_2	4460	107040	58000	49040	1.85	3.00
	T_3	4330	103920	60000	43920	1.73	-
	T_1	6507	143145	55000	88145	2.60	9.05
2024–25	T_2	6325	139159	60000	79159	2.32	5.99
	T_3	5967	131283	63000	68282	2.08	-
	T_1	5563.5	127012.5	55000	72012.5	2.31	7.87
Pooled data	T_2	5392.5	123099.5	59000	64099.5	2.08	4.50
	T_3	5148.5	117601.5	61500	56101	1.90	-

Table 5. Grain Yield and Gap Analysis of the experiment

Year	No. of demonstration	Average yield (Kg/ha)		Percentage increase in demonstration	Additional return	Potential yield	Yield gap	Extension gap	Technology gap	Technology index
		Demonstration	Farmers practice							
2023–24	05	4620	4330	6.69	11960	5500	6.69	290	880	7.03
2024–25	05	6507	5967	9.05	19863	6800	9.05	540	293	4.31
Average	05	5563.5	5148.5	7.87	15911	6150	8.06	415	586.5	5.67

Demonstrations, training programmes, field-level communication and other extension interventions can help farmers understand the benefits and practical use of the technology and may contribute to reducing the extension gap. Similar findings were reported, where the extension gap decreased from 136.08 q ha^{-1} to 78.78 q ha^{-1} (40). The present results are also consistent with earlier findings of which indicated that progressive adoption of improved crop-production technologies and high-yielding varieties can contribute to reducing extension gaps (41, 42). The findings are also comparable with those reports associated higher extension yield gaps with limited awareness and adoption of improved farm technologies and emphasised the need to create awareness and motivate farmers to adopt improved practices in place of existing local practices (43).

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Technology gap

The technology gap represents the difference between potential yield and yield achieved under the demonstration. In the present study, the technology gap was 586.5 kg ha^{-1} (Table 5). The technology gap declined from 880 kg ha^{-1} to 293 kg ha^{-1} over the study period, indicating improved performance under the demonstrated technology. The observed technology gap may be related to differences in soil fertility, weather conditions and crop-management practices across locations. Therefore, location-specific recommendations and precise application of the technology may be required to further reduce the technology gap. A similar trend was reported where the technology gap decreased from 424.71 q ha^{-1} to 394.58 q ha^{-1} (40). The present findings are also in agreement with earlier reports (42).

Technology index

The technology index provides an indication of the feasibility of a demonstrated technology under farmers' field conditions and the prevailing agro-climatic environment. A lower technology index generally indicates greater feasibility of the technology, whereas a higher value indicates relatively lower feasibility.

In the present study, the technology index was 7.03 % during 2023–24 and decreased to 4.31 % during 2024–25. The lower technology index observed during 2024–25 may have been associated with better agricultural practices, improved soil fertility and favourable weather conditions in the study area. Similar results have been reported in maize (43). Comparable findings were also reported where frontline demonstrations reduced the technology index from 56.62 % to 52.61 % (36). The same study also reported that cluster frontline demonstrations in Bengal gram reduced the extension gap, technology gap and technology index (41).

Nitrogen saving

The LCC-based nitrogen management required a lower average nitrogen application of 200 kg N ha^{-1}. According to the reported results, this represented a saving of 100 kg N ha^{-1} compared with the soil-test-based fertiliser treatment and 220 kg N ha^{-1} compared with farmers' practice. Similar findings have been reported previously (25). Under the soil-test-based fertiliser recommendation, the total nitrogen requirement was reported as 300 kg N ha^{-1}, with a nitrogen saving of 60 kg N ha^{-1} compared with farmers' practice, based on the recommended dose of 300 kg N ha^{-1} (Table 6). Under LCC-based management, nitrogen was applied at 30 kg N ha^{-1} as a top dressing in six split applications according to the LCC threshold of 5. This treatment resulted in the maximum kernel yield while reducing nitrogen application by 100 kg N ha^{-1} and 160 kg N ha^{-1} compared with the respective farmers' practice treatments during the two years of investigation. The results demonstrate the potential for synchronising fertiliser nitrogen supply with crop nitrogen demand through LCC-guided management. Similar findings have been reported previously (2, 5).

4. Conclusion

On-farm demonstrations of leaf colour chart (LCC)-based nitrogen management in maize (*Zea mays* L.) conducted during 2023–24 and 2024–25 resulted in an average grain yield of 5563.5 kg ha^{-1}, representing a 7.87 % increase over farmers' practice. The demonstrations also contributed to greater farmer awareness and encouraged the adoption of the technology demonstrated. These yield advantage observed over farmers' practice was accompanied by improved economic returns. Use of an LCC threshold score of 5 enabled a 20 % saving in fertiliser nitrogen while maintaining higher grain yield and net returns. Need-based nitrogen application at 200 kg N ha^{-1} using LCC score 5 as the critical threshold resulted in a reported saving of 100 kg N ha^{-1}. The findings demonstrate the potential of LCC-guided nitrogen management as a practical approach for improving nitrogen-use efficiency and supporting sustainable maize production under farmer-field conditions. The outcomes of the demonstrations also contribute to the development and promotion of scientifically supported nutrient-management strategies for improved natural-resource management and crop productivity. Further studies are being continued to evaluate the integration of liquid biofertilisers with LCC-based nitrogen management in crops with high nitrogen requirements, including cotton, maize and rice, with the broader aim of improving profitability and supporting sustainable crop production.

Table 6. Quantity of fertilisers applied for different treatments (kg ha^{-1}) as influenced by leaf colour chart thresholds under irrigated condition

Treatments	BASAL (kg ha^{-1})			30 DAS (kg ha^{-1})			60 DAS (kg ha^{-1})			90 DAS (kg ha^{-1})			Total (kg ha^{-1})			Saving of fertilisers (kg ha^{-1})		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
T_1	30	80	40	30	0	0	35 + 35*	0	0	35 + 35*	0	40	200	80	80	100 Saved	0	0
T_2	50	60	40	75	0	0	75	0	0	100	28	40	300	60	80	0	20	0
T_3	75	46	30	85	28	0	100	20	0	100	28	14	360	122	60	60 Excess	42	20

Recommended dose of fertilisers: 200 - 240: 80: 80 kg of N, P2O5, K2O ha^{-1}; * LCC N indicates at 75 and 110 DAS; DAS: days after sowing; N: nitrogen; P: phosphorus; K: potassium.

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Authors' contributions

PNSP conceived and designed the study, conducted the field experiment and collected the data. NR and KAR contributed to the experimental design and provided assistance during the field study. MRK performed the statistical analysis and contributed to the interpretation of the results. PNSP drafted and revised the manuscript. IVR, KL, TJR and RP contributed to the literature review and data interpretation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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