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Evaluating Leaf Color Chart-Based Nitrogen Management and Tillage Methods for Improved Maize Yield, Nitrogen Use Efficiency and Economic Returns in Chitwan, Nepal

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ABSTRACT

Optimizing nitrogen management in maize is critical for enhancing yield and resource use efficiency, particularly in Nepal. This study evaluates the impact of real-time nitrogen management using a Leaf color chart (LCC) under different tillage practices in winter maize. The experiment was arranged in a strip plot design with three replications comprising two tillage methods (conventional tillage and zero tillage) as the main plot factor and six nutrient management practices namely nitrogen omission (0 kg N ha^{-1}), recommended dose of nitrogen (120 kg N ha^{-1}), nitrogen application through leaf color chart (LCC) values 3 (45 kg N ha^{-1}), LCC values 4 (88.33 kg N ha^{-1}, LCC values 5 (119.7 kg N ha^{-1}) and LCC values 6 (140 kg N ha^{-1}) as subplot factors. Results showed that LCC 5 (119.7 kg N ha^{-1}) achieved the highest grain yield (4,814.26 kg ha^{-1}) and economic returns (NRs 53,376.3 ha^{-1} net return, B:C ratio 1.77). Grain yield from conventional tillage (3947 kg ha^{-1}) was somewhat higher than zero tillage (3326 kg ha^{-1}), but the differences were statistically insignificant. Nitrogen use efficiency and nitrogen uptake parameters were significantly influenced by nitrogen management, with LCC 5 exhibiting superior agronomic efficiency (28.60 kg grain kg^{-1} N) and recovery efficiency (0.77 kg N uptake kg^{-1} N applied). The LCC 5 treatment achieved the optimal balance between yield, nitrogen use efficiency, and economic returns, making it a suitable option for farmers aiming to optimize nitrogen use and maximize profits in maize cultivation. Thus, farmers should implement the LCC tool rather than relying on fixed schedules and quantities for nitrogen fertilizer application.

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Introduction

Maize (*Zea mays* L.) is the most widely produced cereal globally, driven by its growing demand as a staple food and animal feed. With a productivity rate of 3.16 t ha^{-1} and an area of 940,256 ha, maize is the second most significant crop in Nepal after rice, yielding 2,969,222 t (MOALD, 2024). Maize plays an important role in animal feed, food security, and livelihood generation. Maize is primarily grown by smaller holder farmers across the mid-hills, inner terai, and terai regions. In many hill districts, it serves as a staple food, often consumed as roasted maize, maize flour, or traditional dishes. Additionally, maize is a key ingredient in the rapidly expanding poultry and livestock feed industry in Nepal. Nepal faces a significant gap between maize demand and supply, primarily due to the lack of high-yielding varieties, low plant populations, poor management practices, high cultivation costs, and an imbalanced use of nitrogen fertilizers. Among the many factors that affect agricultural productivity, tillage and nitrogen management practices are two critical elements that significantly impact the yield and growth of maize.

Agronomic techniques such as tillage and nitrogen (N) fertilizer management are essential for enhancing maize production and growth. Tillage affects the physical, chemical, and biological properties of soil, including aeration, water infiltration, nutrient cycling, and root development, which ultimately influence crop productivity. Tillage can improve the physical state of soil by promoting root development and increasing nutrient uptake (Arif et al., 2007). Several studies in Nepal and the broader South Asian context have shown how tillage practices affect maize productivity. For instance, Karki et al. (2015) found that conventional tillage (CT) increased plant population and grain yield in hybrid maize compared to zero tillage (ZT) in Chitwan, Nepal. Zhou et al. (2024) found that deep tillage significantly increased both grain yield and nitrogen use efficiency by improving soil fertility and root access to nutrients. Islam et al. (2024) demonstrated that no-tillage with straw mulching improved nitrogen fertilizer recovery and significantly boosted maize yields under field conditions. Similarly, Pandey et al. (2020) and Paudel et al. (2020) reported that ZT combined with mulching improved water use efficiency and maize yield in the Terai. Ghimire et al. (2021) demonstrated that conservation tillage enhanced soil nutrient availability and long-term productivity.

Conventional agricultural practices such as intensive tillage and reliance on external inputs can lead to soil erosion, soil compaction and organic matter loss. In contrast, conservation tillage methods like zero tillage offer an alternative solution. Zero tillage (ZT) is known to enhance soil organic carbon, conserve moisture, and reduce labor and fuel requirements, contributing to long-term sustainability (Jat et al., 2011). These practices typically reduce production costs, increase crop productivity, enhance soil properties, and improve water and nutrient use efficiency. At the same time, zero tillage has some shortcomings: higher weed infestation, higher nitrogen loss, poor seed germination and poor initial seedling vigor. Dahal et al. (2014) mentioned that the grain yield produced under no tillage (6.64 t ha^{-1}) was significantly higher in comparison to conventional tillage (5.39 t ha^{-1}) during the spring season of 2014 at Rampur, Chitwan, Nepal. Chauhan et al. (2010) also support the benefits of CT in improving maize root development and nutrient uptake under certain conditions.

Nitrogen is recognized as the primary yield-limiting factor in maize production. Nepalese farmers don't use chemical fertilizers as per recommendation and they don't have the concept of, the right time, right dose, right source and right way of fertilizer application. Farmers only use urea if it is readily available in the market (Blinder et al., 2000). As an essential nutrient, nitrogen deficiency can lead to significant loss, ultimately impairing both growth and overall yield. Nitrogen efficiency depends on the rate, timing, and method of application. Simic et al (2020) noted that both under- and over-application of nitrogen reduce yield potential either through nutrient deficiency or loss via leaching and volatilization. It is therefore vital to manage nitrogen levels effectively to ensure optimal results. As maize plants have varying nitrogen needs during their growth, it is crucial to adjust fertilizer applications accordingly. Swamy et al. (2016) and Hu et al. (2021) showed that split nitrogen application based on LCC thresholds improved grain yield, agronomic efficiency, and nitrogen recovery. The efficiency of nitrogen consumption can be increased by coordinating fertilizer timing with plant needs through a real-time nitrogen management system (Singh et al., 2022). Real-Time Nitrogen Management (RTNM) has emerged as a transformative approach for synchronizing nitrogen supply with plant demand (Reena et al., 2017). Real-time nitrogen management determines when to apply nitrogen fertilizer by periodically assessing crop nitrogen status (Witt et al., 2005). Pandey and Chaudhary (2014), in a study from Chitwan, Nepal, observed that split application of nitrogen, when combined with conventional tillage, resulted in a significant increase in spring maize yield.

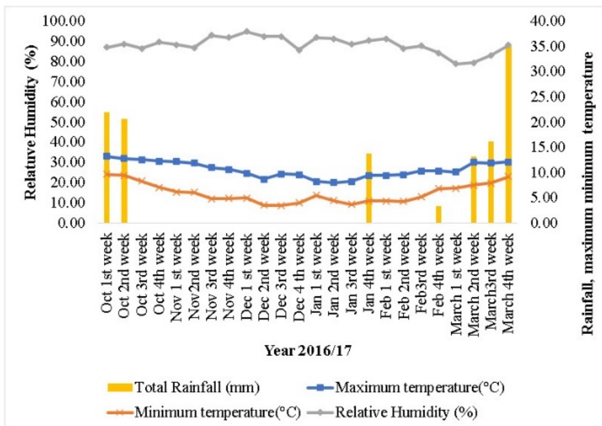
A straightforward and suitable technique for farmers to regulate nitrogen in real time is the leaf color chart (LCC) (Singh et al., 2024). Compared to the chlorophyll meter, Sen et al. (2011) demonstrated that LCC-guided nitrogen application significantly increased Nitrogen Use Efficiency(NUE) and yield in rice, with similar findings extended to maize by Singh et al. (2022, 2024). By monitoring leaf greenness, LCC enables farmers to make informed decisions about nitrogen top-dressing, reducing excess application while maintaining or enhancing yields. LCC-based nitrogen management achieved comparable or higher maize yields with reduced nitrogen input and higher nitrogen use efficiency (NUE) compared to conventional blanket applications (Pandey et al., 2024). Leaf color chart (LCC) based nitrogen management in maize improves nitrogen use efficiency by allowing farmers to adjust nitrogen application based on real-time leaf color assessments, leading to reduced nitrogen losses and enhanced yields compared to blanket recommendations (Singh, 2022).

Despite the demonstrated benefits of LCC-based nitrogen management, its application in maize remains underexplored, particularly in regions like Nepal. Conventional blanket fertilizer recommendations fail to determine field-specific variation in demand and supply of nutrients, leading to suboptimal nitrogen use (Dobermann & White, 1999). This study represents the first systematic exploration of LCC-guided nitrogen management in maize under Nepal's conditions. This study aims to evaluate the effect of real-time nitrogen management using Leaf Color Chart (LCC) at different critical values on maize yield, nitrogen use efficiency, and economic returns. Similarly, this research tries to identify the most efficient and profitable combination of tillage and nitrogen management practices for sustainable maize cultivation in Chitwan, Nepal.

Materials and Method

Experimental site

The study was conducted at the research field of the National Maize Research Program (NMRP), Rampur, Chitwan, Nepal, situated at 27°40′ N latitude, 84°19′ E longitude, and an altitude of 256 m above sea level. Composite soil samples were taken from zero-tillage and conventional tillage plots at depths of 0–15 cm and 15–30 cm, respectively. The soil was sandy loam with low nitrogen (0.07%), medium organic matter (3.53%), potassium (204.28 kg ha^{-1}), and high phosphorus (212.80 kg ha^{-1}) (Table 1). The pH was slightly acidic (5.6). During the experiment, temperatures varied from 8.89°C to 33.17°C, and total rainfall was 124.4 mm (Figure 1).



(Source: NMRP, 2016/17)

Figure 1. Weather conditions during the experimentation period at NMRP, Rampur, Chitwan, 2016/17.

Table 1. Physical and chemical characteristics of the soil at the National Maize Research Program (NMRP) in Rampur, Chitwan in 2016–17.

S. N.	Properties	Average content	Rating	Methods
1	Physical properties			
	Sand (%)	70.30	Sandy loam	Hydrometer method
	Silt (%)	17.40		
	Clay (%)	12.30		
2	Chemical properties			
	Soil pH	5.6	Acidic	Beckman Glass electrode pH meter
	Soil organic matter (%)	3.53	Medium	
	Total nitrogen (%)	0.07	Low	Kjeldahl distillation
	Available phosphorus (kg ha^{-1})	212.80	High	Spectrophotometer
	Available potassium (kg ha^{-1})	204.28	Medium	Ammonium acetate

Experimental design and treatment details

A split-plot design with three replications was used in the experiment. The size of individual plot was 27 m^2. The main plot components included two tillage techniques (conventional tillage and zero tillage), whereas sub-plot factors comprised six nitrogen management treatments.

Treatments details

Main plot factor: Tillage methods
1: No till planting (ZT)
2: Conventional tillage (CT)
Subplot factor: Nitrogen management practice
1. 0 kg nitrogen per hectare
2. Recommended dose of nitrogen (120 Kg N ha^{-1})
3. Nitrogen dose at LCC value 3
4. Nitrogen dose at LCC value 4
5. Nitrogen dose at LCC value 5
6. Nitrogen dose at LCC value 6

Cultural Practices

To eradicate weeds from the field, zero-tillage plots were treated with glyphosate 47SL at a prescribed dosage of 5 milliliters per liter of water. Conventional tillage plots were plowed and harrowed twice before sowing. Basal application of phosphorus and potash along with 20 kg nitrogen per hectare was applied during sowing for all treatments, except the control. Subsequent Nitrogen applications were done by observing LCC readings. Seeds of the Rampur composite genotype were sown on October 7, 2016, using a Jap planter with 60 cm row spacing and 25 cm plant spacing. Gap filling was performed at 4 and 8 days after sowing (DAS), and thinning was done at 15 DAS to ensure a uniform plant population. Cypermethrin (2 ml per liter of water) was applied at 35 DAS to control cutworms. Three surface irrigations were conducted at 40, 75, and 95 DAS. Plots were weed-free through inter-cultivation and hand weeding was done at 21 and 45 DAS. On March 27, 2017, harvesting was done from the net plot area. Following winnowing and sun drying, grains were separated, and biomass and cobs were weighed. The data on nitrogen uptake, nitrogen use efficiency, grain yield and economics were recorded.

Leaf Color Chart (LCC) Readings

Leaf color intensity was measured weekly from 21 DAS and then in every 10 days until 70 DAS using an LCC. The third fully expanded leaf from the top was chosen from ten randomly sampled plants. Measurements were taken after 3:00 PM, avoiding direct sunlight. Nitrogen was applied if readings fell below the critical value.

Statistical Analysis

Statistical tools such as MSTAT 3.8.1, GENSTAT 15.1, and EXCEL 2010 were utilized to perform analysis of variance (ANOVA) and other data analyses. A simple regression and correlation analysis were conducted among designated parameters following the methodology of Gomez and Gomez (1984). An ANOVA was used to identify significant effects, and treatment differences were assessed at a 5% level of significance.

Results and discussion

Effect on Grain Yield

Nitrogen management techniques had a major effect on grain yield, but tillage techniques had no effect at all. Grain yield from conventional tillage was somewhat higher than zero tillage (3947 kg ha^{-1} vs. 3326 kg ha^{-1}), but the difference was not statistically significant (Table 3). In this experiment, the highest grain yield was obtained with nutrient management through the critical value of LCC 5. The higher yield observed in the LCC-5 treatment was due to better nutrition, leading to an increased number of grains per cob and higher test weight. It is seen from the table (2) that LCC-6 and LCC-5 plots received higher split of nitrogen fertilizer. The higher Grain yield in LCC-5 may result from applying more nitrogen in more split applications than at other levels (Narasimhan et al., 1999). Mathukia et al. (2014) reported that real-time nitrogen application using LCC 5 in split doses results to higher grain yield in maize in Gujarat, India. These findings align closely with those of Maiti and Das (2006), while other studies also emphasize that more numbers of split results increase the grain yield (Hu et al., 2021; Ghmire et al., 2023; Ojeniyiet al., 2024 Swamy et al. 2016). Porpavai et al. (2002) noted that applying nitrogen at LCC 5 aligned with crop needs and reduced losses from denitrification and volatilization through more split applications, achieving the highest grain yield. Fayz et al. (2022) reported that various nitrogen management strategies using LCC ≤ 5@30 kg N ha^{-1} treatment yielded the highest grain yield (6.13 and 5.91 q ha^{-1}) in 2019 and 2020, respectively.Kumar et al. (2021) found that using Leaf Color Chart (LCC) threshold value 5 significantly improved maize grain yield by 12.30% and 12.25% over recommended practices in 2015 and 2016, respectively, demonstrating the effectiveness of precise nitrogen management strategies.

Table 2. Quantity of N applied in different treatments (kg ha-1)

Treatment	Nitrogen applied kg ha-1 on respective dates for each treatment based on LCC values							
	Sowing day	22 DAS	32 DAS	42 DAS	52 DAS	62 DAS	72 DAS	Total nitrogen applied
Control plot	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rec. Dose of nitrogen	40.00	0.00	0.00	40.00	0.00	0.00	40.00	120.00
LCC <3	20.00	0.00	0.00	0.00	12.50	12.50	0.00	45.00
LCC <4	20.00	13.33	16.67	20.83	8.33	4.17	0.00	83.33
LCC <5	20.00	20.00	25.00	25.00	25.00	4.17	0.00	119.17
LCC < 6	20.00	20.00	25.00	25.00	25.00	0.00	25.00	140.00

Note: LCC, Leaf color chart; DAS, Days after sowing; Rec. Dose, recommended dose

Table 3. Productivity and economics of maize as influenced by tillage methods and nitrogen management practice during winter season at NMRP, Rampur, Chitwan, Nepal, 2016/2017.

Treatment	Grain yield (kg ha⁻¹)	Economic analysis (NRs. ha-1)			
		Total production cost	Gross return	Net return	B:C ratio
Tillage					
Zero tillage	3326	66217.75	85297.54	19079.79	1.27
Con. Tillage	3947	67867.75	100555.6	32687.87	1.47
SEm (±)	194.9	225.6	4477	4477	0.07
LSD (0.05)	1186.1	1373	27271.8	27241.8	0.4
CV%	9.3	0.6	8.3	30	8.5
P value	Ns	0.025	Ns	Ns	Ns
Nitrogen management practice					
Control (0 kg N ha-1)	1981.24d	62235.15	51608.2d	-10626.9c	0.83d
Rec. Dose (120 kg N ha-1)	4449.00a	69174.28	113059.1a	43884.9a	1.63a
LCC <3 (45 kg N ha-1)	2599.41c	64630.80	67004.4c	2373.6c	1.04c
LCC <4 (83.33 kg N ha-1)	3462.69b	66863.97	87829.2b	20965.3b	1.31b
LCC <5 (119.7 kg N ha-1)	4814.26a	68978.10	122354.3a	53376.3a	1.77a
LCC <6 (140 kg N ha-1)	4511.00a	70374.28	115704.1a	45329.9a	1.64a
SEm (±)	184.8	390.8	4500	4500	0.07
LSD (0.05)	545.2	1152.8	13277.4	13277.4	0.20
CV%	12.4	1.4	11.9	42.6	12.20
P value	0.001	<0.001	0.001	0.001	0.00
Grand Total	3636	67202	92926.58	25883.83	1.37
Interaction		Ns	Ns	Ns	Ns

Note: LCC, Leaf color chart; Rec. Dose, recommended dose; Ns, non-significance; Sem, standard error of the mean; LSD, least significant difference; CV, coefficient of variation; Treatments mean followed by different letter (s) are significantly different from each other based on DMRT at 5% level of significance

Economic Returns

Conventional tillage incurred higher production costs (NRs 67,867.75 ha-1) but achieved better economic returns (gross return: NRs 100,555.6 ha⁻¹; net return: NRs 32,687.87 ha⁻¹; B:C ratio: 1.47) compared to zero tillage (Table 3). Similar finding was reported by Jyosthna et al. (2023), who observed that conventional tillage significantly increased maize yields compared to zero tillage, resulting in higher net benefits. Among the nitrogen management practices, LCC <5 (119.7 kg N ha⁻¹) was the most profitable, with the highest gross return (NRs 122,354.3 ha⁻¹), net return (NRs 53,376.3 ha⁻¹), and B:C ratio (1.77), significantly outperforming other treatments except for LCC <6 and the recommended nitrogen dose, which were statistically at par (Table 3). LCC-based strategies often reduce fertilizer costs by minimizing over-application. Singh et al. (2014) reported a 29% saving in nitrogen fertilizer without compromising yield. The control plot recorded the lowest performance across all parameters. This data suggests that conventional tillage combined with nitrogen management through the LCC as critical value 5 is the most economical practice of appropriate nitrogen management. LCC 5 proved most economically beneficial, highlighting the effectiveness of tailored nutrient management strategies (Riar et al., 2023). Ram et al. (2022) identified the use of Leaf Color Chart (LCC) value less than 5 as the most profitable nitrogen management practice, reporting the highest gross and net returns.

Nitrogen Uptake

Nitrogen management practices significantly influenced nitrogen uptake. Tillage methods had no statistical effect on nitrogen uptake, though conventional tillage consistently showed slightly higher values than zero tillage (Table 4). The mean grain nitrogen uptake was 50.57 kg ha⁻¹, with the highest uptake was observed under LCC <6 (71.22 kg ha⁻¹), followed by LCC <5 and the recommended dose of nitrogen, while the control plot recorded the lowest (18.62 kg ha⁻¹). Similar results were obtained by Naik et al. (2022), who reported that LCC-based nitrogen management, particularly at a threshold value of 5, significantly enhances nitrogen uptake and grain yield. Similarly, the mean straw nitrogen uptake was 30.81 kg ha⁻¹, with LCC <6 achieving the highest uptake (49.04 kg ha⁻¹) and the control plot the lowest (14.88 kg ha⁻¹). Among nutrient management practices, the critical value of LCC <6 (140 kg N ha⁻¹) recorded the highest total nitrogen uptake (120.26 kg ha⁻¹), significantly outperforming other practices. Similar findings were reported by Singh et al. (2016), who observed that the use of a leaf colour chart (LCC) significantly enhanced nitrogen uptake in maize. In contrast, the control treatment (0 kg N ha⁻¹) recorded the lowest uptake (33.50 kg ha⁻¹).

Table 4. Nitrogen uptake of maize as influenced by tillage methods and nitrogen management practices during winter season at NMRP, Rampur, Chitwan, Nepal, 2016/2017

Treatments	Nitrogen uptake (kg ha^{-1})		
	Grain	Straw	Total
Tillage			
Zero tillage	45.71	30.22	75.93
Con. Tillage	55.44	31.40	86.84
SEm (±)	1.94	1.15	1.81
LSD (0.05)	11.78	6.97	10.98
CV%	6.60	6.40	3.80
P value	Ns	Ns	Ns
Nitrogen management Practice			
Control (0 kg N ha^{-1})	18.62^{d}	14.88^{e}	33.50^{f}
Rec. Dose (120 kg N ha^{-1})	64.97^{a}	32.24^{c}	97.21^{c}
LCC <3 (45 kg N ha^{-1})	32.41^{c}	23.09^{d}	55.51^{e}
LCC <4 (83.33 kg N ha^{-1})	47.17^{b}	25.20^{cd}	72.37^{d}
LCC <5 (119.7 kg N ha^{-1})	69.04^{a}	40.42^{b}	109.46^{b}
LCC <6 (140 kg N ha^{-1})	71.22^{a}	49.04^{a}	120.26^{a}
SEm (±)	1.94	2.59	3.65
LSD (0.05)	7.79	7.63	10.77
CV, %	12.80	20.60	11.00
P value	0.001	0.001	0.001
Grand mean	50.57	30.81	81.38
Interaction	Ns	Ns	Ns

Note: LCC, Leaf color chart; Rec. Dose, recommended dose; Ns, non-significance; Sem, standard error of the mean; LSD, least significant difference; CV, coefficient of variation; Treatments means followed by different letter(s) are significantly different from each other based on DMRT at 5% level of significance

Table 5. Nitrogen use efficiency of maize as influenced by tillage methods and nitrogen management practice during winter season at NMRP, Rampur, Chitwan, Nepal, 2016/2017.

Treatments	Nitrogen use efficiency				
	Agronomy Efficiency (AE)	Physiological Efficiency (PE)	Recovery Efficiency (RE)	Partial Factor Productivity (PFP)	Internal Efficiency (IE)
Tillage					
Zero tillage	21.93	5.82	0.63	4.16	46.92
Con. Tillage	25.93	6.36	0.73	5.09	47.25
SEm (±)	2.24	0.49	0.05	0.17	2.71
LSD (0.05)	13.64	2.95	0.29	1.02	16.51
CV, %	16.20	13.80	12.00	8.50	10.00
P value	Ns	Ns	Ns	Ns	Ns
Nutrient management Practice					
Control (0 kg N ha^{-1})	N/A	N/A	N/A	N/A	60.21^{a}
Rec. Dose (120 kg N ha^{-1})	21.65^{b}	41.22^{a}(6.41)	0.53^{b}	17.55^{b}(4.17)	46.89^{b}
LCC <3 (45 kg N ha^{-1})	N/A	50.94^{a}(6.63)	N/A	N/A	46.86^{b}
LCC <4(83.33 kg N ha^{-1})	25.27^{ab}	37.36^{a}(6.06)	0.71^{a}	33.22^{a}(5.49)	47.75^{b}
LCC <5(119.7 kg N ha^{-1})	28.60^{a}	37.29^{a}(6.08)	0.77^{a}	22.53^{ab}(4.73)	44.01^{bc}
LCC < 6(140 kg N ha^{-1})	20.19^{b}	28.35^{a}(5.27)	0.72^{a}	16.88^{b}(4.11)	36.80^{c}
SEm (±)	1.76	0.57	0.06	0.31	3.10
LSD (0.05)	5.42	1.72	0.17	0.94	9.13
CV%	18.00	23.10	19.70	16.10	16.10
P value	0.023	Ns	0.043	0.026	0.001
Grand Total	23.93	6.09	0.68	4.63	47.08
Interaction	0.001	Ns	0.02	Ns	Ns

Note: LCC, Leaf color chart; Rec. Dose, recommended dose; Ns, non-significance; Sem, standard error of the mean; LSD, least significant difference; CV, coefficient of variation; Treatments means followed by different letter (s) are significantly different from each other based on DMRT at 5% level of significance

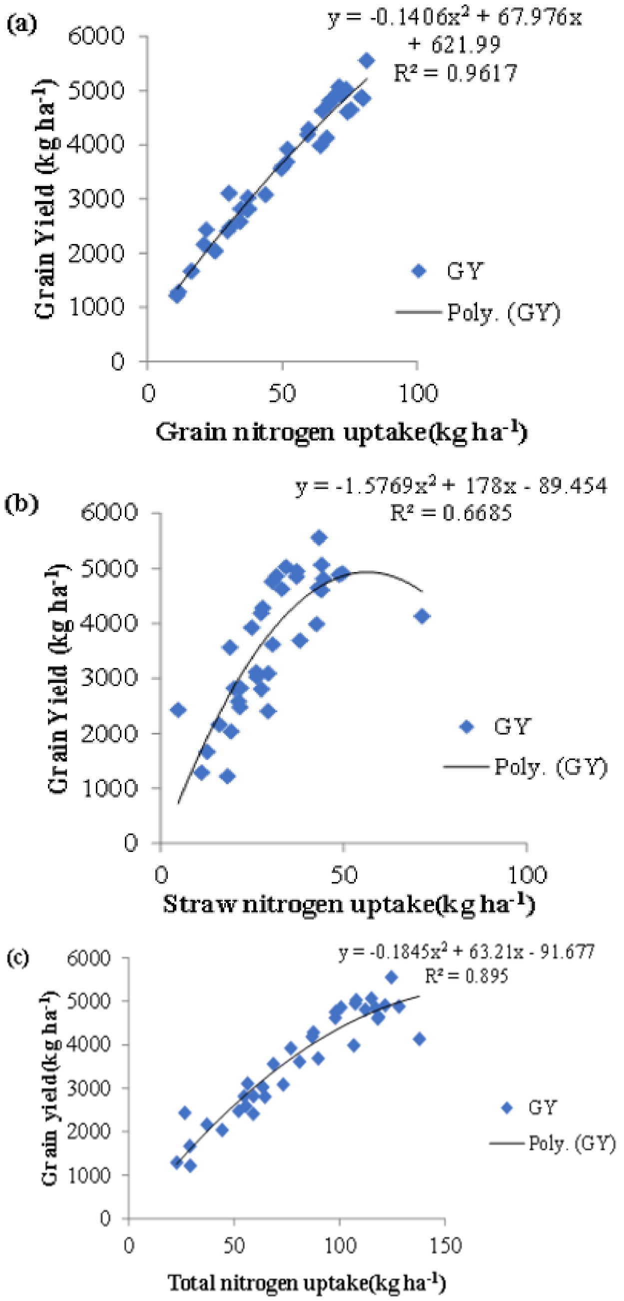


Figure 2. Relationship between grain, straw and total nitrogen uptake and grain yield of winter maize at NMRP, Rampur, Chitwan, Nepal, 2016/17

Higher nitrogen uptake in management practices with higher thresholds is due to improved alignment of nitrogen availability with plant needs. Increased nitrogen uptake at LCC-6 may result from frequent split applications and enhanced mineralization of native nitrogen. Swamy et al. (2016) reported that nitrogen management using critical LCC thresholds, such as LCC <5 and NDVI 0.8, significantly enhanced nitrogen uptake and crop productivity. Singh and Singh (2019) indicate that nitrogen management using the Leaf Color Chart (LCC), specifically LCC5, resulted in significantly higher growth, yield, and yield attributes in maize compared to LCC4 and Control, suggesting improved nitrogen uptake efficiency. The relationship between grain, straw, total nitrogen uptake and grain yield was also illustrated in Figure 2.

Nutrient Use Efficiency

Nitrogen use efficiency (NUE) largely depends on synchronizing crop nitrogen demand with available nitrogen supply. Recovery efficiency, Internal efficiency Agronomic efficiency, and partial factor productivity was significantly influenced by nitrogen management practice but not by the tillage methods (Table 5). In the trial, neither tillage techniques nor nitrogen management strategies had a significant impact on physiological efficiency. Agronomic efficiency (AE) was highest under LCC <5 (28.60 kg kg^{-1}) and it was statically similar with nitrogen application through LCC as critical value 4 (25.27 kg kg^{-1}). Nitrogen application through LCC as critical value 4 recorded higher Partial factor productivity which was statically similar with nitrogen application through LCC as critical value 5. Agronomic and recovery efficiencies were highest under LCC <5, likely due to improved matching of nitrogen application with crop needs, resulting in enhanced nutrient uptake and utilization. According to Sen et al. (2011), the cultivars NDR 359 and Sarju 52 had the maximum nitrogen recovery and agronomic efficiency at LCC ≤ 5. The highest internal efficiency was obtained in control plot (60.21), likely because of the absence of external nitrogen application, forcing the crop to utilize endogenous nitrogen reserves efficiently. LCC <6 had the lowest IE (36.80), indicating a dilution effect due to excessive nitrogen.

Nitrogen management practices using LCC <5 and LCC <4 showed improved nitrogen use efficiency (NUE), highlighting the need to synchronize nitrogen application with crop demand. Excess nitrogen application in LCC <6 reduced AE, PFP, and IE, emphasizing the diminishing returns of over-application. Krishnakumar and Haefele (2013) observed that partial factor productivity and agronomic efficiency decreased as the LCC score increased. The highest recovery efficiency was obtained in nitrogen application through LCC as critical value 5 (0.77) which was statically similar with nitrogen application through LCC as critical value 6 and 4. Similarly Sen et al. (2011) also found that synchronizing split nitrogen application with crop demand improves nitrogen recovery efficiency. Studies report higher NUE (up to 12–18%) when using LCC thresholds compared to blanket recommendations (Kumar et al., 2021).

Conclusion

This study demonstrated that nitrogen application based on LCC critical value 5 significantly enhanced maize grain yield, nitrogen use efficiency, and economic return compared to other treatments. While tillage methods had no statistically significant effect on yield and NUE, conventional tillage achieved slightly higher economic returns than zero tillage. Therefore, integrating LCC-5-based nitrogen management with conventional tillage is recommended for maximizing productivity and profitability in winter maize cultivation in Chitwan, Nepal. Additionally, the study primarily focused on short-term yield and economic benefits, and further research may be needed to assess long-term soil health, environmental impacts, and scalability across different agroecological conditions.

Declarations

Author Contribution Statement

D.T.: Conceptualization, Methodology, Performed the Experiments, Data Collection, Investigation, Formal Analysis, Review, Writing the Original Draft

S.M.: Supervision, Conceptualization, Methodology, Review and Editing

Fund statement

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Conflict of Interest

The authors declare no conflict of interest.

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