FAST
Food Agricultural Sciences and Technology (FAST)
2026; *12*(1). https://doi.org/10.14456/fast.2026.6

Research Article

Optimizing nitrogen management practices to enhance nutrient use efficiency and growth of maize (*Zea mays* L.)

Janaki Budha[1*], Sandesh Bhatta[1], Babu Ram Khanal[1] and Vesh Raj Thapa[2]

[1] *Department of Soil Science and Agri-engineering, Agriculture and Forestry University, Rampur, Chitwan, Nepal*
[2] *Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE 68583, United States*
* *Corresponding author: janakibudha354@gmail.com*

Abstract - Efficient nitrogen (N) management is crucial for improving growth, yield, and nitrogen use efficiency (NUE) of maize (*Zea mays* L.) while maintaining environmental quality. This study evaluated growth parameters, yield attributes, soil nutrient dynamics, nitrogen uptake, and NUE under various N sources and management practices on the sandy loam soil of Chitwan, Nepal. The experiment was designed as a randomized complete block with three replications, incorporating the following treatments: N check, N all at basal dose, N at three split doses, polymer-coated urea (PCU), neem-coated urea (NCU), urea deep placement (UDP), leaf color chart (LCC $\leq$4.5), and soil plant analysis development (SPAD $\leq$40) meter. The results depicted that the slow-releasing nitrogen sources, such as PCU, NCU, and UDP, along with split applications, outperformed conventional methods significantly. PCU emerged as the most effective treatment, achieving the highest plant height, yield, and nitrogen uptake. Compared to conventional applications, PCU increased grain yield by 11.2%, LCC ($\leq$4.5) improved agronomic efficiency by 54.2%, and UDP enhanced recovery efficiency by 61.5%. These findings suggest that integrating slow-release and split-application practices can optimize N use and support sustainable maize production, with PCU being the best among all other treatments.

Keywords: Maize, nitrogen management, nitrogen uptake, nitrogen use efficiency, slow-release fertilizer

Received: 18th May 2025,
Revised: 11th July 2025,
Accepted: 22nd July 2025

Citation: Budha, J., Bhatta, S., Khanal, B. R., & Thapa, V. R. (2025). Optimizing nitrogen management practices to enhance nutrient use efficiency and growth of maize (*Zea mays* L.). *Food Agricultural Sciences and Technology (FAST)*, *12*(1), 59-76. https://doi.org/10.14456/fast.2026.6

1. Introduction

In Nepal, maize (*Zea mays* L.) is the second most important cereal crop after rice in terms of both area and production. It plays a critical role in the country's agrarian economy, particularly in the mid-hill and mountain regions, where it serves as a staple food and a primary source of income for smallholder farmers through local markets (Sapkota et al., 2017). Economically, it is a key crop in the country's agricultural development programs and agro-based industries such as poultry and feed production. Nutritionally, maize is a rich source of carbohydrates and provides essential nutrients, including protein, dietary fiber, vitamins (such as vitamin B-complex), and minerals like magnesium and phosphorus (Bathla et al., 2019). It contributes to dietary diversity and food energy intake, especially in regions where alternative food sources are limited. From a food security perspective, improving maize productivity and the quality of its plant materials, such as grains, stover, and cobs, is vital for sustaining food availability, enhancing nutritional outcomes, and increasing resilience to climate-related challenges. As Nepal continues to face issues like population growth, declining arable land, and climate variability, strengthening maize-based production systems is essential for achieving long-term food and nutritional security.

Maize productivity relies heavily on balanced and adequate nutrient availability, particularly nitrogen (N), a fundamental component of amino acids, proteins, and chlorophyll. In Nepal, granular urea is the primary source of N due to its affordability and rapid plant response (Maharjan et al., 2016). Despite the importance of nitrogen, its efficient use in maize cultivation remains a significant challenge, particularly in developing countries like Nepal, where resource constraints and environmental concerns persist (Devkota et al., 2016).

Urea has low nitrogen use efficiency (NUE), with more than half of the applied N being lost through volatilization, denitrification, and leaching (Yang et al., 2011). These losses lead to environmental issues such as groundwater contamination, eutrophication, biodiversity loss, and greenhouse gas emissions. Additionally, excessive urea application negatively impacts soil physical and chemical properties (Fugice et al., 2018)._Also, application of urea on the surface is subject to immobilization and significant loss to the atmosphere as NH_3–N (Shapiro et al., 2016). To enhance NUE and mitigate environmental harm, it is vital to identify optimal N application methods that align N supply with plant demand throughout the growth season (Gagnon et al., 2012).

Several innovative N management approaches have been developed to address these challenges, including split application, slow-release fertilizers, controlled-release coatings, deep placement technologies, and precision tools like LCC and SPAD. Split N fertilizer applications can boost grain yield, NUE, and profitability while reducing N input (Chen et al., 2015). Slow-release N sources, as a single basal dose, offer an effective solution, reducing labor and time (Li et al., 2017). Controlled-release N fertilizers are encapsulated or coated urea that act as a physical barrier to inhibit the quick release of urea (Shapiro et al., 2016), improve soil fertility, reduces N deficiency, and lowers environmental pollution (Chang-Ai et al., 2016), decreasing N requirements by 20–30% compared to traditional practices while maintaining maize yields (Xie et al., 2019). Urea briquettes, a slow-releasing N fertilizer, placed 7–10 cm deep near the root zone, reduce runoff and volatilization losses, enhancing NUE (Azeem et al., 2014). Decision support tools like the leaf color chart (LCC) and soil plant analysis development (SPAD) meter synchronize N supply with maize needs, improving NUE and reducing environmental N loss

(Karthik et al., 2022). These strategies aim to enhance nitrogen availability in synchrony with crop uptake while reducing losses.

Although various nitrogen management strategies have been explored individually, limited studies have systematically compared multiple N management approaches under the same agroecological conditions. This study was conducted to bridge the knowledge gap by evaluating and comparing different nitrogen management practices, including slow-release formulations and placement strategies, to identify the most efficient approach for enhancing productivity and NUE in maize. The findings aim to support evidence-based recommendations of N management approach for sustainable maize cultivation.

2. Materials and methods

2.1 Experimental site

The field experiment was conducted on slightly acidic sandy loam soil with pH 6.5, organic matter 2.6%, total nitrogen content 0.1%, available phosphorus 59 kg ha^{-1}, and available potassium 126 kg ha^{-1}, during late spring to early monsoon at the Horticulture Farm (27°40' N latitude, 84° 23' E longitude, altitude 256 meter above sea level), Agriculture and Forestry University (AFU), Rampur, Chitwan, Nepal. The experimental site has a humid-subtropical climate with cool winters when temperatures fall below 10°C and hot summers when temperatures rise up to 35°C.

2.2 Experimental design and treatments

The experiment was conducted in a randomized complete block design (RCBD) with eight treatments and three replications. Replications were one meter apart, and each plot was 0.5 meters apart. Each treatment plot measured 7.2 m^2 (3.6 m × 2 m), comprising 48 plants, six lines each with eight plants (66,667 plants ha^{-1}) at a spacing of 0.6 m between rows and 0.25 m between plants. Two maize seeds of Rampur Hybrid 10, a heavy feeder hybrid variety of maize relevant to climate of experimental site, were sown per hill 5 cm below the soil surface and thinned to one plant per hill 21 days after sowing. The total experimental area was 313.25 m^2, with 1152 total plants. The recommended fertilizer dose in the experiment site (Chitwan) for hybrid maize is 180:60:60 N:P:K kg/ha by Nepal Agriculture and Research Council (Koirala et al., 2020).

Table 1. Treatment combinations.

SN	Treatment	Detail
1	N check	0:60:60 kg ha^{-1} NPK, at basal
2	N all at basal	180:60:60 kg ha^{-1} NPK, N applied from normal urea all as basal dose
3	N at three splits	180:60:60 kg ha^{-1} NPK, N applied from normal urea at three splits: basal, knee height (25 DAS), and silking stages (65 DAS)
4	PCU	180:60:60 kg ha^{-1} NPK, polymer-coated urea, applied all as basal dose
5	NCU	180:60:60 kg ha^{-1} NPK, neem oil-coated urea @ 5ml kg^{-1}, applied at basal
6	UDP	165.6:60:60 kg ha^{-1} NPK, 5.4 g $plant^{-1}$ (two urea briquettes of an average size of 2.7 g) after germination (10 DAS) at 10 cm below and 5 cm away from seedlings
7	LCC (≤4.5)	108:60:60 kg ha^{-1} NPK was applied in total, at the rate of 20% urea of 180 kg N ha^{-1} per application, applied thrice, at basal and when threshold was met on LCC at critical value 4.5 at 21 DAS and 41 DAS according to readings taken at 10-day intervals
8	SPAD (≤40)	72:60:60 kg ha^{-1} NPK was applied in total, at the rate of 20% urea of 180 kg N ha^{-1} per application, applied twice, at basal and when threshold was met on SPAD reading at critical value 40 at 21 DAS according to readings taken at 10-day intervals

Note: NPK=nitrogen, phosphorus, potassium; PCU = polymer-coated urea; NCU = neem-coated urea; UDP = urea deep placement; LCC = leaf color chart; SPAD = soil plant analysis development; DAS = days after sowing.

Blended fertilizers, Single Super Phosphate (16% P_2O_5) and Muriate of Potash (60% K_2O), were applied once during planting in all plots, including the N check plot. N fertilizers were applied as per treatments, at the same depth as seed placement and 5 cm distant from the seeds. 100% of recommended N (180 kg ha^{-1}) was supplied through N all at basal, N at 3 Splits, PCU, and NCU, whereas 91.61% through UDP, 60% through LCC, and 40% through SPAD. For decision support tools, readings were taken from the top, middle, and basal parts of the fully expanded flag leaf before the silking stage because it is the youngest and most actively photosynthesizing leaf at that stage, providing an accurate indication of the plant's nitrogen status. Readings from the top, middle, and basal portions ensure a more representative average of chlorophyll content or greenness. After silking, the ear leaf becomes the most physiologically active and functionally important leaf contributing to grain filling, making it the most appropriate for nutrient status assessment during the reproductive stage; therefore, the ear leaf was used after silking. LCC and SPAD readings were conducted between 8:00 and 11:00 a.m. at 10-day intervals starting from 21 days after sowing. N was applied based on the set critical limits of LCC and SPAD.

2.3 Data collection and soil analysis

Five central plants per plot were randomly selected and tagged for data collection, excluding border plants. Morphological characteristics, including plant height and leaf number, were recorded at 30, 60, 90, and 110 DAS. Plant height was measured from the base of the plant to the base of the flag leaf using a measuring tape, and leaf numbers were counted from individual plants to calculate the average.

Stover yield was measured at harvest (110 DAS). Stover from individual plots was harvested manually and weighed in the field and its moisture content was determined by the gravimetric method. Grain yield and thousand-grain weight were recorded after shelling and drying the grain. A Wile-55 moisture meter was used to measure grain moisture content. Grain and stover yield per hectare were adjusted to 14% moisture using the formula (Dhakal et al., 2020):

$$\text{Grain or stover yield} = \frac{((100-\text{MC})\times \text{plot yield (kg)}\times 10000\ (\text{m2}))}{((100-14)\times \text{net plot area (m2)})} \quad (1)$$

Where MC is the moisture content of the grains expressed in percentage.

After harvest, crop debris was removed, and soil samples from 5 different spots in each plot were collected using a soil auger from a depth of 20 cm and mixed to obtain a composite sample for each individual plot. The samples were taken to the laboratory and left for 24 hours to air-dry and a final sample was prepared using a 10-mesh sieve. Soil samples were then analyzed for total N using a semimicro-Kjeldahl distillation unit (Nelson & Sommers, 1980), available phosphorus following the sodium bicarbonate extraction method (Olsen et al., 1954), available potassium using the ammonium acetate extraction method using sulphuric acid (Pratt, 1965), organic matter by wet digestion (Walkley & Black, 1934), and pH using a pH electrode with soil water ratio 1:2.5. Soil texture was determined by the hydrometer method (Gee & Bauder, 1986), and bulk density by the core method (Blake & Hartge, 1986).

Plant samples (stalk, leaves, and cob husk) were collected at harvest, chopped, oven-dried, and ground into a powder form for laboratory analysis of total N content using the semimicro-Kjeldahl distillation unit. Total N uptake by grain and stover was calculated using equations (2) and (3), respectively, and total N uptake by equation (4) (Dobermann, 2007):

$$\text{Grain nitrogen uptake (GNU)} = \frac{\text{N content in grain (\%)}\times \text{grain yield (kg ha}^{-1})}{100} \quad (2)$$

$$\text{Stover nitrogen uptake (SNU)} = \frac{\text{N content in stover (\%)}\times \text{stover yield (kg ha}^{-1})}{100} \quad (3)$$

Total nitrogen uptake (TNU) = GNU + SNU

Agronomic efficiency and nitrogen recovery efficiency (NRE) were calculated using equations (5) and (6), respectively (Dobermann, 2007):

Agronomic efficiency (AE; kg kg^{-1} N)

$$= \frac{YN-Y0}{FN}\ldots \quad (5)$$

Nitrogen recovery efficiency (NRE, kg kg^{-1}N) $= \frac{UN - U0}{FN}$ (6)

where, YN = grain yield of treatments receiving N fertilizer

Y0 = grain yield in control plot

FN = rate of N applied

UN = total plant N uptake in aboveground biomass at maturity (kg ha^{-1}) in plots receiving N

U0 = total N uptake in aboveground biomass at maturity (kg ha^{-1}) in control plots

2.4 Statistical analysis

Data from field experiments and laboratory analyses were entered into MS Excel and subjected to analysis of variance (ANOVA) using R-studio 4.3.1 for RCBD. ANOVA was used to compare means across different treatments and assess the effect of treatments on the response of variables. Mean calculation of the set of data, standard deviation, correlation between yield and nitrogen uptake, and graphical representation were performed using MS Excel. A post hoc Duncan's multiple range test (DMRT) at a 5% level of significance was used for mean separations.

3. Results

3.1 Growth parameters

The heights of maize plants, recorded at different growth stages (30, 60, 90, and 110 days after sowing), were notably impacted by various nitrogen sources and management practices at $P < 0.001$ (Figure 1). At the end of the first month of sowing

(30 DAS), the maximum plant height was recorded with the treatment, N application all at basal. Whereas, PCU treatment resulted in the tallest plants at the 2nd (60 DAS), 3rd (90 DAS), and last (110 DAS) recordings of data. At 60 DAS, PCU, UDP, and NCU resulted in statistically similar maize plant heights. Compared to the basal application of nitrogen (N), PCU, UDP, NCU, and the three-split N application produced maize plants that were 3.7%, 2.3%, 1.5%, and 0.8% taller, respectively. By harvest (110 DAS), these differences increased to 5.6%, 3.85%, 2.98%, and 3.56%, respectively. Overall, PCU treated plots exhibited best performance among all treatments. Nevertheless, the decision support tools, LCC at a critical value of 4.5 and SPAD at a critical value of 40 could not outweigh the performance of basal application. The lowest plant height was observed with the N check in each recording.

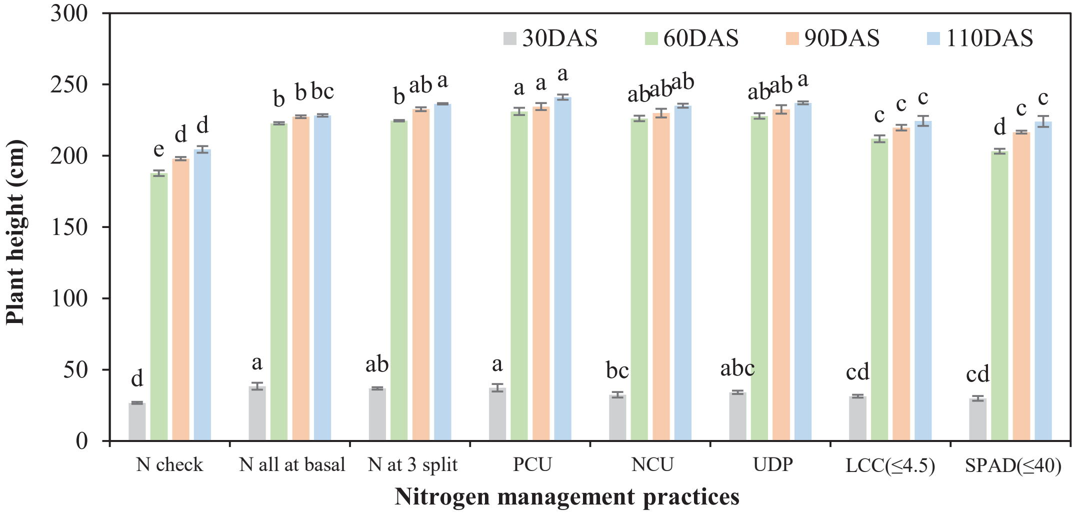

Figure 1. Effect of N source and management on maize plant height at various growth stages. DAS = days after sowing; Different letters in lowercase indicate significant differences in mean value, while the same letter(s) indicate non-significant effect of treatments at 5% level of significance and the mean was separated by Duncan Multiple Range Test (DMRT).

The number of maize leaves per plant was significantly affected by different N management practices (Figure 2). At 30 days after sowing (DAS), the highest number of functional leaves (8.20) was observed in the treatment where the full dose of nitrogen was applied at the basal stage. At 60 DAS, the application of polymer-coated urea (PCU) resulted in the greatest number of functional leaves (15.07), statistically similar to UDP (15), N at 3-splits (14.93), and basal application (14.13), followed by NCU (14.07). By 90 DAS, PCU continued to outperform other treatments, recording the highest number of functional leaves (13.93). At harvest (110 DAS), UDP has more functional leaves (5.07). The nitrogen control (N check) consistently exhibited the lowest number of functional leaves across all growth stages.

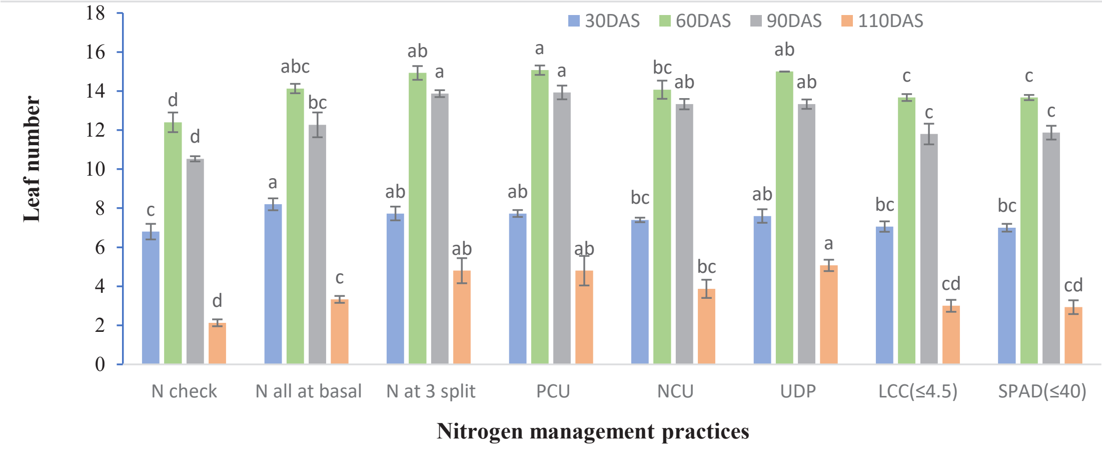

Figure 2. Effect of N source on maize leaf number at various growth stages.

3.2 Yield attributes

The effect of nitrogen sources and management practices on maize yield parameters, thousand kernel weight (TKW), grain yield, and stover yield was found to be significant at $P < 0.001$ (Figure 3). The highest TKW was observed in the plots with the PCU and UDP treatments (both resulted in 355.33 kg ha^{-1}), 11.74% higher compared to N at all basal (318 kg ha^{-1}). TKW of NCU (353 kg ha^{-1}), and N at 3 splits (352.33 kg ha^{-1}) treated plots outweighed N all at basal by 11% and 10.79%, respectively. The highest maize grain and stover yields were recorded with PCU, 10.99 t ha^{-1} and 11.80 t ha^{-1}, respectively. These values were 11.23% and 11.80% higher than those obtained from the N all-at-basal treatment, which produced 9.88 t ha^{-1} grain yield and 10.98 t ha^{-1} stover yield. Whereas, the lowest TKW, grain yield and stover yield were obtained with the N check treatment.

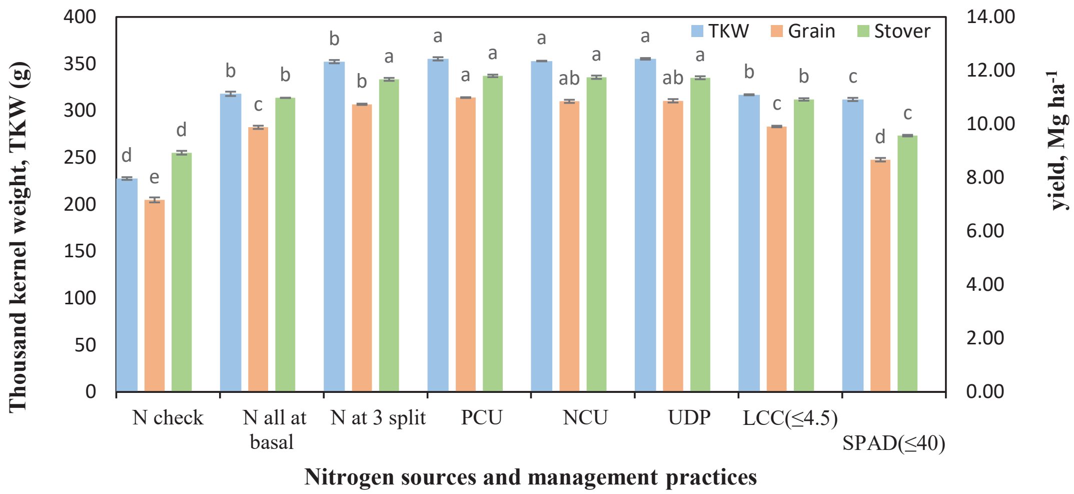

Figure 3. Effect of N source and management on maize thousand kernel weight (TKW), grain yield (GY), and stover yield (SY)**.** Different letters in lowercase indicate significant differences in mean value, while same letter(s) indicates non-significant effect of treatments at 5% level of significance and mean was separated by DMRT.

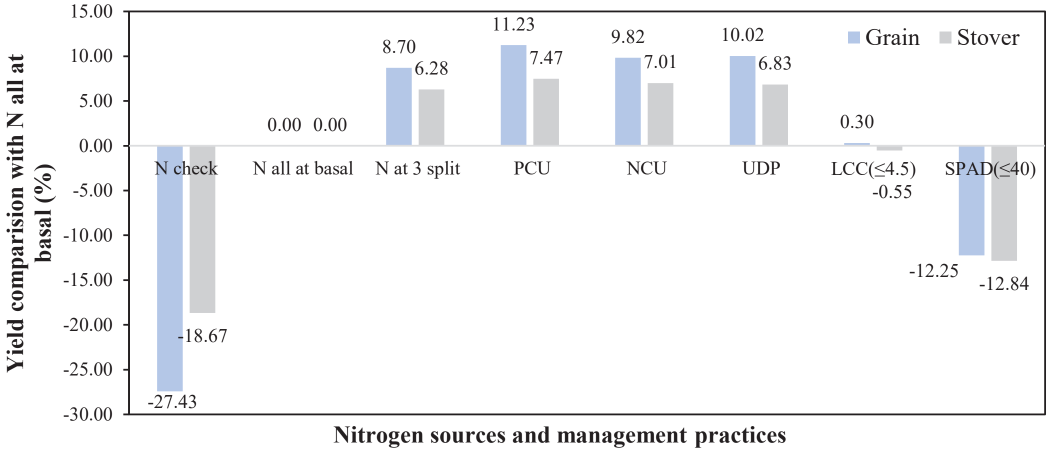

Figure 4. Grain and stover yield advantage of different N treatments over conventional urea application (N all at basal).

3.3 Soil parameters

There was no significant difference in soil organic matter content, whereas pH was affected at $P < 0.01$. High pH was obtained in the N check treatment than with N2 application treatments, indicating the increment in acidic ions in N N-treated soil. NPK content of soil was significantly affected at $P < 0.001$. N was highest in the UDP-treated plot, followed by PCU, NCU, and N at 3 splits. The highest phosphorus (P) and potassium (K) levels were found in the N check treatment, indicating higher P and K uptake in N-treated plots (Table 2).

Table 2. Effect of different nitrogen sources and management practices on soil samples collected at harvest (110 DAS).

Treatment	OM%	pH	Total N%	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
N check	2.70±p0.36	6.37±0.03^{a}	0.07±0.04^{e}	64.67±1.76^{a}	111.00±1^{a}
N all at basal	2.00±0.37	6.07±0.03^{bc}	0.10±0.06^{cd}	59.67±0.88^{bc}	95.33±2.4^{bc}
N at 3 splits	2.25±0.07	6.10±0.06^{bc}	0.11±0.07^{bc}	55.33±0.88^{d}	90.67±1.45^{cd}
PCU	2.26±0.05	6.20±0.06^{ab}	0.13±0.07^{ab}	55.00±1.73^{d}	88.33±1.66^{d}
NCU	1.81±0.04	6.10±0.06^{bc}	0.12±0.07^{b}	54.00±0.99^{d}	89.33±3.28^{cd}
UDP	2.73±0.51	6.23±0.07^{ab}	0.14±0.53^{a}	52.33±0.88^{d}	92.67±2.6^{bcd}
LCC(≤4.5)	1.92±0.05	6.00±0.1^{c}	0.10±0.05^{cd}	60.33±0.33^{b}	97.67±0.88^{b}
SPAD(≤40)	2.36±0.45	6.00±0.06^{c}	0.09±0.45^{de}	63.00±0.99^{ab}	108.33±0.66^{a}
LSD(0.05)	ns	0.17**	0.02***	3.54***	6.18***
SEm(±)	0.32	0.06	0.006	1.17	2.04
CV (%)	24.65	1.62	9.62	3.46	3.65

Note: OM = organic matter; pH=potential of hydrogen ion; N = total nitrogen; P_2O_5=available phosphorous; K_2O = available potassium; LSD = least significant difference; CV = coefficient of variation; Data represented with the same letter(s) are non-significant effect of treatments at 5% level of significance and mean was separated by DMRT; ** and *** represents significant at 0.01 level of significance, and 0.001 level of significance, respectively; ns, non-significant at the 0.05 probability level.

3.4 Nitrogen uptake

Grain and stover nitrogen uptake in maize were significantly affected by N sources and management practices at P < 0.001 (Figure 5). PCU treatment resulted in the highest grain (156.72 kg ha^{-1}) and stover (86.93 kg ha^{-1}) N uptake. Whereas the lowest N uptake was observed with the N check treatment. PCU, NCU, UDP, and N at 3 split application increased the N uptake of grain by 13.84%, 13.73%, 12.41%, and 11.01% and stover N uptake by 29.05%, 25.01%, 23.68%, and 16.68%, respectively, compared to N all at basal application.

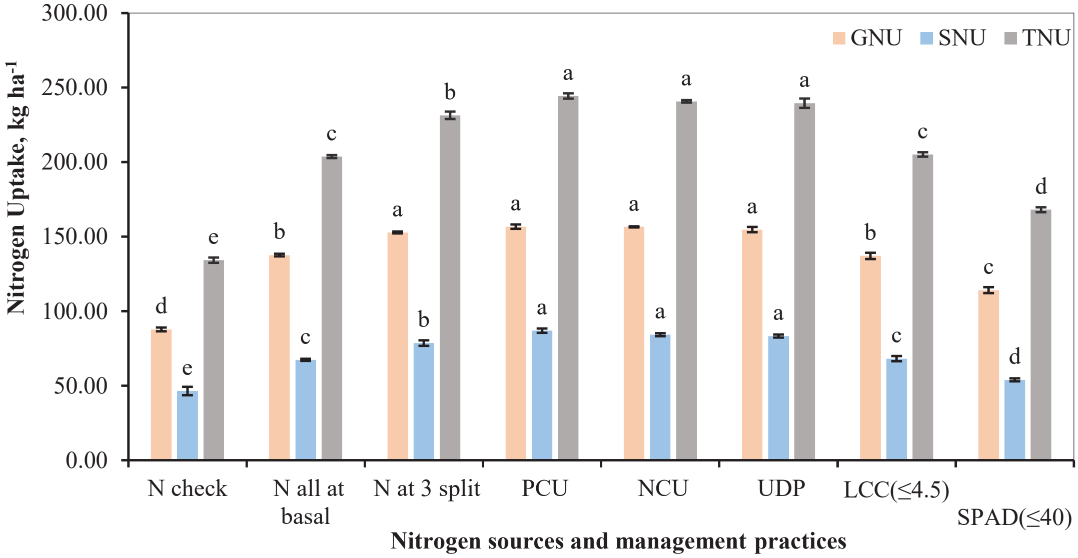

Figure 5. Effect of N source and management on N uptake by grain (GNU) and stover (SNU) of maize. TNU=total nitrogen uptake; Mean was separated by DMRT and different letters in lowercase indicate significant differences in mean value, while same letter(s) indicates non-significant effect of treatments at 5% level of significance.

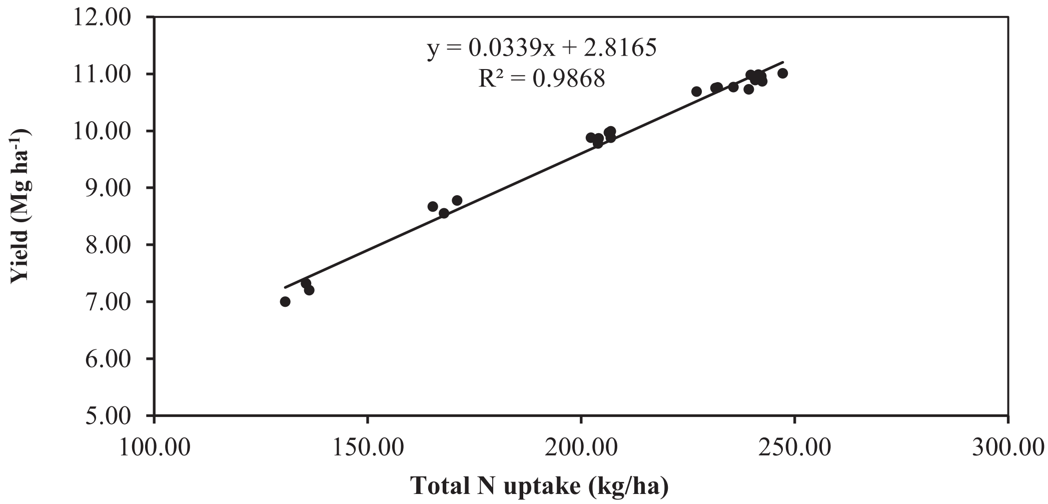

Figure 6. Relationship between total Nitrogen uptake and yield of maize.

A highly significant and strong positive linear relationship ($R^2 = 0.9868$) was observed between total nitrogen uptake and maize yield, indicating that nitrogen uptake accounted for approximately 98.68% of the variability in grain yield. The regression equation ($y = 0.0339x + 2.8165$) implies that for every 1 kg/ha increase in nitrogen uptake, maize yield increased by approximately 33.9 kg ha^{-1}. This strong correlation emphasizes the critical role of nitrogen in enhancing maize productivity and suggests that optimizing N uptake is essential for achieving higher yields under the given management practices.

3.5 Nitrogen use efficiency

Nitrogen Use Efficiency (NUE), including Agronomic Efficiency (AEN) and Recovery Efficiency (REN), was significantly affected by the nitrogen management practices ($P < 0.001$), as depicted in Figure 7. Among the treatments, the LCC (≤4.5) method recorded the highest agronomic efficiency (23.19 kg grain per kg N applied), indicating superior crop yield response per unit of nitrogen used. UDP treatment showed statistically similar AEN values. In terms of recovery efficiency, the UDP treatment resulted in the highest value (0.63 kg N recovered per kg N applied), suggesting effective nitrogen uptake by the crop. This was followed closely by PCU and LCC treatment, which also showed statistically similar REN values. On the other hand, the N applied all at basal resulted in comparatively lower efficiencies in both AEN and REN.

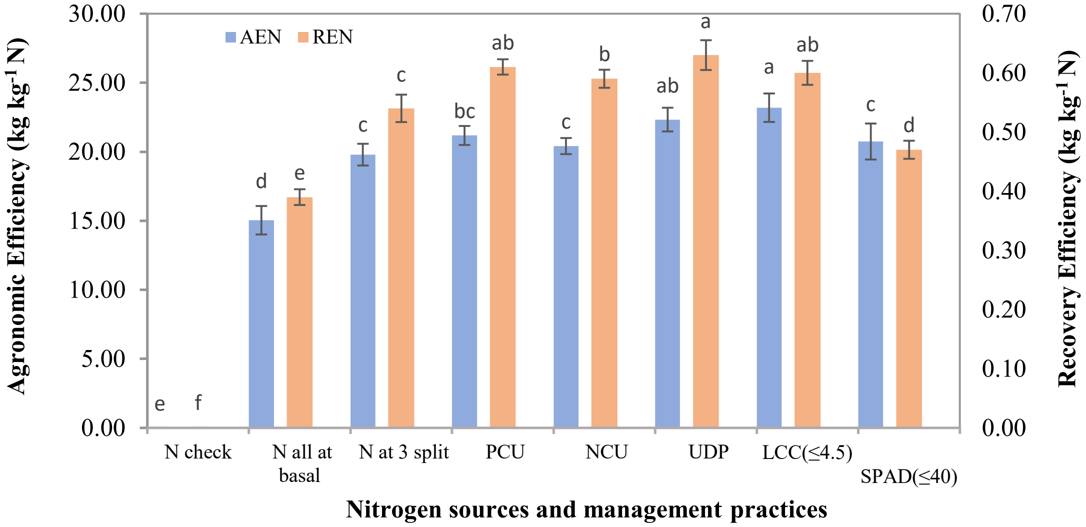

Figure 7. Effect of N source and management on nitrogen use efficiency (NUE), agronomic efficiency (AEN), and recovery efficiency (REN) of maize. Mean is separated by DMRT; different letters in lowercase indicate significant differences in mean value, while the same letter(s) indicate non-significant effect of treatments at 5% level of significance.

All the treatments except the N check resulted in higher nitrogen use efficiency compared to conventional urea. While LCC resulted in the highest agronomic efficiency (54.19 %), UDP gave the highest recovery efficiency (61.54%) over basal application.

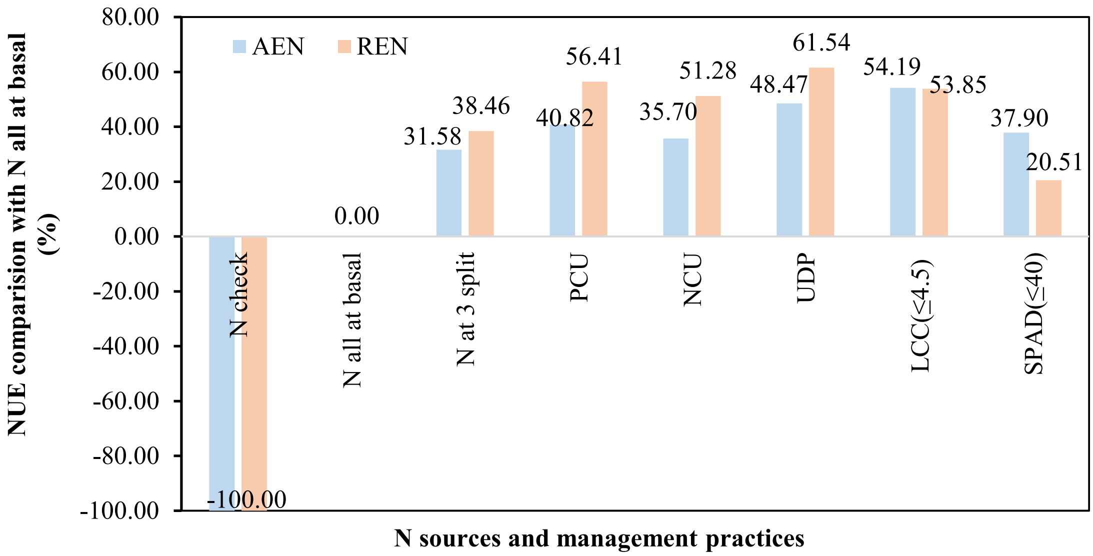

Figure 8. Comparative advantage of nitrogen uses efficiency of different N treatments over N all at basal. NUE = nitrogen use efficiency; AEN = agronomic efficiency of applied N; REN = recovery efficiency of applied N.

Discussion

4.1 Growth parameters

Plant height is directly influenced by the proper supply of nitrogen at various growth stages of maize (Shrestha, 2015). In this study, plant height and leaf number were recorded at 30, 60, 90, and 110 DAS. Though vegetative growth typically ceases after flowering, measuring these traits post-flowering provides valuable insights into growth stabilization and the residual influence of nitrogen treatments. These data serve as important indicators for evaluating treatment effects and understanding crop developmental responses.

At 30 DAS, plant height and leaf number were highest under the N all-at-basal treatment, reflecting early nitrogen availability (Thakur et al., 1998). From 60 DAS onward, PCU-treated plants consistently exhibited the greatest plant height and leaf number, aligning with the slow and sustained nitrogen release provided by its polymer coating, which showed statistically similar results with UDP, NCU, and N at 3-splits. This is supported by Hergert et al. (2011), who observed similar outcomes. The increase in plant height with split applications and slow-release N sources like PCU, NCU, and UDP can be attributed to continuous nitrogen supply, which promotes cell division, elongation (Adhikari et al., 2016), and higher auxin levels (Joshi et al., 2014).

PCU and NCU, coated with semi-natural macromolecules, gradually release nitrogen in synchrony with plant needs (Hergert et al., 2011), while UDP, compacted into dense pellets, has reduced surface area, hence slows down the rate of dissolution compared to conventional urea and when deep-placed at 7–10 cm, minimizes volatilization and runoff, ensuring steady nitrogen availability near the root zone (Varadachari & Goertz, 2010). These mechanisms collectively supported superior growth performance. In contrast, poor performance by decision support tools (LCC at critical value 4.5 and SPAD at 40) likely resulted from insufficient nitrogen supply during key growth phases. The fixed threshold values may not have reflected the dynamic N demand of the crop, causing delayed or suboptimal N application. This aligns with Singh et al. (2016), who reported improved growth with LCC thresholds of 5–5.5 and SPAD readings of 45.4. Future research should explore stage-specific or adjusted thresholds to enhance the precision and effectiveness of these tools.

4.2 Yield attributes

The higher dry matter accumulation in grains observed with the slow- and controlled-release nitrogen sources in our study is likely due to the continuous availability of nitrogen over an extended period, which supports prolonged grain filling. This finding aligns with Cheetham et al. (2006), who reported that sustained nitrogen availability enhances dry matter deposition. Similarly, Dhakal et al. (2021) noted that adequate nitrogen supply improves kernel integrity and supports grain development, which was evident in our treatments involving PCU, UDP, and NCU.

Our results also corroborate those of Beshir et al. (2019), who found greater dry mass accumulation and yield under improved nitrogen management strategies that reduce N losses. In our study, treatments such as PCU and N at 3 splits reduced nitrogen loss and enhanced dry matter accumulation, supporting their conclusions. Furthermore, the grain and stover yield improvements observed in these treatments (as shown in Figure 4) are consistent with findings by Umesha et al. (2017), who attributed increased yield to better nitrogen synchronization and reduced volatilization and denitrification.

Additionally, Ye et al. (2013) reported enhanced root growth and dry matter accumulation with PCU, which aligns with our observation of greater biomass in PCU-treated plots. Ashraf et al. (2016) emphasized the role of nitrogen in improving pollination and sink development, leading to increased grains per cob and grain yield, a trend also supported by our results. Similarly, Dawadi and Sah (2012) linked nitrogen availability to increases in plant height, leaf number, and stover yield, which parallels our findings.

Finally, our results reaffirm those of Marahatta (2022), who reported the highest grain yield advantage with PCU over conventional basal nitrogen application, followed by UDP. This trend is clearly reflected in our data, further validating the efficiency of controlled-release and deep placement nitrogen strategies

4.3 Soil parameters

The non-significant effect of nitrogen sources and management practices on soil organic matter (OM) was likely due to the limited influence of inorganic fertilizers on OM dynamics. This is supported by Moran et al. (2005), who found no preferential transformation of mineral N over residue-derived N into soil organic matter. The observed reduction in soil pH in N-treated plots is attributed to the depletion of basic cations (Lucas et al., 2011; Tian & Niu, 2015) and the deposition of H^+ ions released during ammonium (NH_4^+) uptake by plant roots (Ge et al., 2018). UDP-treated plots showed higher nitrogen content in the soil, likely due to minimized N losses and prolonged N availability (Yao et al., 2018), while higher residual N in PCU-treated soils can be attributed to delayed nitrification (Ashraf et al., 2019) and gradual release of N via diffusion (Ye et al., 2013). Interestingly, the highest phosphorus (P) and potassium (K) levels were recorded in the N-check treatment, suggesting greater uptake of these nutrients in N-treated plots. This pattern is consistent with previous findings that adequate nitrogen enhances nutrient absorption (Hoffmann et al., 1994) and that P and K uptake increase with rising N levels (Ray et al., 2019).

These findings suggest that while advanced N management practices may not significantly improve soil OM in the short term, they can influence nutrient dynamics and soil acidity, factors that are critical for maintaining soil fertility and guiding sustainable fertilization strategies.

4.4 Nitrogen uptake

In our study, treatments with split N application (N at 3 splits), PCU, NCU, and UDP resulted in significantly higher nitrogen uptake compared to the N all-at-basal application. These treatments also extended the duration of active nitrogen uptake, suggesting improved synchronization of nitrogen availability with crop demand. This is evident from the higher residual nitrogen levels and improved nitrogen use efficiency (NUE) observed in these treatments.

These findings align with Fageria and Baligar (2005), who emphasized the importance of synchronizing nitrogen availability with plant demand to maximize uptake and minimize losses. The delayed nitrification and extended nitrogen availability observed in PCU and NCU treatments support the findings of Ashraf et al. (2019), who reported a 30-day delay in nitrification due to coated urea, increasing the plant-available nitrogen pool. Similarly, Ye et al. (2013) described how coating urea forms a diffusion barrier that slows nitrogen release, reduces losses, and enhances NUE. In the case of UDP, our results are consistent with Eldridge et al. (2022) and Yao et al. (2018), who found that deep placement of urea briquettes reduces nitrogen losses and increases plant uptake. Additionally, Du et al. (2019) demonstrated that split N applications prolong the period of rapid nitrogen absorption, which aligns with our observation of extended nitrogen uptake phases in the split application treatments.

4.5 Nitrogen use efficiency

In our study (Figures 7 and 8), LCC (critical value 4.5) recorded the highest agronomic efficiency at 23.19 kg grain/kg N applied (54.19% more compared to basal application), which can be attributed to its lower total nitrogen application while still achieving substantial yield. This supports the findings of Jat et al. (2012), who reported higher NUE with lower LCC thresholds. Similarly, Subedi et al. (2018) observed the highest agronomic efficiency with LCC-based nitrogen management. We observed statistically similar results with UDP (22.33 kg grain/kg N applied) and this aligns with the study of Dhakal et al. (2021) and Marahatta (2022), who observed high NUE with UDP and PCU.

UDP showed the highest recovery efficiency at 0.63 kg N recovered/kg N applied, which is 61.54% more compared to basal application (Figure 7 and 8), followed by PCU at 0.61 kg N recovered/kg N applied and LCC at 0.6 kg N recovered/kg N applied with no statistical difference, confirming the enhanced nitrogen uptake and minimized loss with deep placement and slow-release approaches. These results align with those of Yao et al. (2018), who reported recovery efficiency of up to 62% with UDP, and Xie et al. (2020), who demonstrated higher N recovery and yield with PCU compared to conventional urea. Liu et al. (2019) also reported superior NUE for UDP over basal N application, which supports the trend observed in our experiment.

To summarize, the primary objective of this study was to compare split application, slow-release approaches and precision tools with conventional method of N management and identify the most effective approach of nutrient management in maize farming. The results demonstrated that slow-release urea and split N applications significantly enhanced maize performance and nitrogen use efficiency (NUE) compared to conventional urea. Among the treatments, PCU produced the highest grain yield and N uptake, while LCC and UDP recorded the highest agronomic and recovery efficiencies, respectively. NCU and N applied in 3 splits also outperformed the all at basal application.

These findings suggest that slow-release N sources and precision tools offer clear advantages over conventional practices in terms of both productivity and sustainability. However, adjustments to LCC and SPAD threshold values may further improve their accuracy in assessing crop N requirements. Further research is recommended to evaluate the performance of these tools under varying threshold settings and environmental conditions.

Conclusion

This study demonstrated that improved nitrogen management strategies significantly enhance maize yield and nitrogen use efficiency. Among the treatments, PCU resulted in the highest grain yield and nitrogen uptake, while UDP and LCC showed notable improvements in agronomic and recovery efficiencies. Overall, the findings highlight the potential of slow-release fertilizers and precision tools over conventional nitrogen application for promoting productivity and sustainability in maize farming. Regarding performance PCU was best recommended, while regarding convenience and cost-effectiveness, UDP is more accessible and affordable for smallholder farmers due to its lower material cost compared to coated urea, LCC and SPAD and simpler application process (once at plantation time) compared to splits application.

Acknowledgement

This is to sincerely express our profound gratitude to the Department of Soil Science and Agri-Engineering, Agriculture and Forestry University, for providing all the farm equipment and implements used for the research and analysis. The authors also acknowledge all the helping hands for their assistance in the fieldwork.

References

Adhikari, P., Baral, B. R., & Shrestha, J. (2016). Maize response to time of nitrogen application and planting seasons. *Journalof Maize Research and Development*, *2*(1), 83–93. https://doi.org/10.3126/jmrd.v2i1.16218

Ashraf, M. N., Aziz, T., Maqsood, M. A., Bilal, H. M., Raza, S., Zia, M., & Wang, Y. S. (2019). Evaluating organic materials coating on urea as potential nitrification inhibitors for enhanced nitrogen recovery and growth of maize *(Zea mays L.). International Journal of Agriculture and Biology*, *22*(5), 1102–1108.

Ashraf, U., Salım, M. N., Sher, A., Sabir, S.-U.-R., Khan, A., Pan, S., & Tang, X. (2016). Maize growth, yield formation and water-nitrogen usage in response to varied irrigation and nitrogen supply under semi-arid climate. *Turkish Journal of Field Crops, 21*(1), 88–96.

Azeem, B., KuShaari, K., Man, Z. B., Basit, A., & Thanh, T. H. (2014). Review on materials & methods to produce controlled release coated urea fertilizer. *Journal of Controlled Release, 181*, 11–21. https://doi.org/10.1016/j.jconrel.2014.02.020

Bathla, S., Jaidka, M., & Kaur, R. (2019). Nutritive value. In A. Hossain (Ed.), *Maize – Production and use.* Intech Open. https://doi.org/10.5772/intechopen.88963

Beshir, A., Pradhan, B., Choudhary, D., & Rusinamhodzi, L. (2019, June 3). Slow-release nitrogen fertilizers measure up: Briquetted urea and polymer-coated urea more efficient as maize fertilizers than regular urea, researchers in Nepal find. *International Maize and Wheat Improvement Center (CIMMYT).* https://www.cimmyt.

org/news/slow-release-nitrogen-fertilizers-measure-up/

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis: Part 1. Physical and mineralogical methods* (2nd ed., Agronomy Monograph No. 9, pp. 363–375). American Society of Agronomy; Soil Science Society of America.

Chang-Ai, Z., Shurong, X., & Yan, L. (2016). Nitrogen release of controlled release coated urea in soil [Retracted article]. In *2016 International Conference on Smart City and Systems Engineering (ICSCSE)* (pp. 122–127). IEEE. https://doi.org/10.1109/ICSCSE.2016.0043

Cheetham, H., Millner, J., & Hardacre, A. (2006). The effect of nitrogen fertilisation on maize grain quality and yield. *Agronomy New Zealand, 36*, 71–84.

Chen, Y., Peng, J., Wang, J., Fu, P., Hou, Y., Zhang, C., … Huang, J. (2015). Crop management based on multi-split top-dressing enhances grain yield and nitrogen use efficiency in irrigated rice in China. *Field Crops Research, 184*, 50–57. https://doi.org/10.1016/j.fcr.2015.09.006

Dawadi, D. R., & Sah, S. K. (2012). Growth and yield of hybrid maize (*Zea mays* L.) in relation to planting density and nitrogen levels during the winter season in Nepal. *Tropical Agricultural Research, 23*(3), 218–227. https://doi.org/10.4038/tar.v23i3.4659

Devkota, K. P., McDonald, A. J., Khadka, L., Khadka, A., Paudel, G., & Devkota, M. (2016). Fertilizers, hybrids, and the sustainable intensification of maize systems in the rain-fed mid-hills of Nepal. *European Journal of Agronomy, 80*, 154-167. https://doi.org/10.1016/j.eja.2016.08.003

Dhakal, K., Baral, B. R., Pokhrel, K. R., Pandit, N. R., Gaihre, Y. K., & Vista, S. P. (2021). Optimizing N fertilization for increasing yield and profits of rainfed maize grown under sandy loam soil. *Nitrogen, 2*(3), 359–377. https://doi.org/10.3390/nitrogen2030025

Dhakal, K., Baral, B. R., Pokhrel, K. R., Pandit, N. R., Thapa, S. B., Gaihre, Y. K., & Vista, S. P. (2020). Deep placement of briquette urea increases agronomic and economic efficiency of maize in sandy loam soil. *AGRIVITA Journal of Agricultural Science, 42*(3), 499–508. https://doi.org/10.17503/agrivita.v42i3.2766

Dobermann, A. (2007). *Nutrient use efficiency—measurement and management.* In A. Krauss, K. Isherwood, & P. Heffer (Eds.), *Fertilizer Best Management Practices: General principles, strategy for their adoption and voluntary initiatives versus regulations* (pp. 1–28). International Fertilizer Industry Association.

Du, X., Xi, M., & Kong, L. (2019). Split application of reduced nitrogen rate improves nitrogen uptake and use efficiency in sweetpotato. *Scientific Reports, 9*(1), 14058. https://doi.org/10.1038/s41598-019-50532-2

Eldridge, S. M., Pandey, A., Weatherley, A., Willett, I. R., Myint, A. K., Oo, A. N., Ngwe, K., Mang, Z. T., Singh, U., & Chen, D. (2022). Recovery of nitrogen fertilizer can be doubled by urea-briquette deep placement in rice paddies. *European Journal of Agronomy, 140*, 126605. https://doi.org/10.1016/j.eja.2022.126605

Fageria, N. K., & Baligar, V. C. (2005). Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy, 88*, 97–185. https://doi.org/10.1016/S0065-2113(05)88004-6

Fugice, J., Dimkpa, C. O., & Johnson, L. (2018). Slow and steady: The effects of different coatings on nitrogen release in soil. *Fertilizer Focus, 35*(5), 12–13. https://ifdc.org/wp-content/uploads/2018/10/Fertilizer-Focus-Slow-and-Steady-Sept-Oct-2018.pdf

Gagnon, B., Ziadi, N., & Grant, C. (2012). Urea fertilizer forms affect grain corn yield and nitrogen use efficiency. *Canadian Journal of Soil Science, 92*(2), 341–351. https://doi.org/10.4141/cjss2011-074

Gee, G. W., & Bauder, J. W. (1986). Particle-size analysis. In A. Klute (Ed.), *Methods of soil analysis: Part 1. Physical and mineralogical methods* (2nd ed., pp. 383–411). American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c15.

Ge, S., Zhu, Z., & Jiang, Y. (2018). Long-term impact of fertilization on soil pH and fertility in an apple production system. *Journal of Soil Science and Plant Nutrition, 18*(1), 282–293. https://doi.org/10.4067/S0718-95162018005001002

Hergert, G. R., Ferguson, C., Wortmann, C., Shapiro, C., & Shaver, T. (2011). Enhanced efficiency fertilizers: Will they enhance my fertilizer efficiency? In *Proceedings of the 3rd Annual Crop Production Clinics.* University of Nebraska–Lincoln Extension.

Hoffmann, C., Ladewig, E., Claassen, N., & Jungk, A. (1994). Phosphorus uptake of maize as affected by ammonium and nitrate nitrogen: Measurements and model calculations. *Zeitschrift für Pflanzenernährung und Bodenkunde, 157*(3), 225–232. https://doi.org/10.1002/jpln.19941570310

Jat, S. L., Parihar, C. M., Singh, A. K., Kumar, A., & Meena, H. N. (2012). Resource conserving techniques and nitrogen use efficiency in different cropping systems. *Compendium of Deliverables of the Conservation Agriculture Course 2012,* 5.

Joshi, A. G. J. K., Gupta, J. K., Choudhary, S. K., & Paliwal, D. K. (2014). Efficiency of different nitrogen source, doses and split application on growth and yield of maize (Zea mays L.) in the Malwa region of Madhya Pradesh. *IOSR Journal of Agriculture and Veterinary Science, 7*(2), 39–42. https://doi.org/10.9790/2380-07213942

Karthik, R., Dhaker, D., & Raising, L. P. (2022). Performance of cereals under need-based nitrogen management strategies: A review. *Agricultural Reviews, 43*(3), 320–326. https://doi.org/10.18805/ag.R-2312

Koirala, K. B., Rijal, T. R., KC, G., Khan, S., Mahato, D. N., Manandhar, S., Subedi, S., & Tripathi, M. P. (2020). Evaluation of maize hybrids in Terai and inner Terai ecological belt of Nepal. *Journal of Agriculture and Forestry University, 4*(1), 109–116. https://doi.org/10.3126/jafu.v4i1.47055

Li, P., Lu, J., Hou, W., Pan, Y., Wang, Y., Khan, M. R., Ren, T., Cong, R., & Li, X. (2017). Reducing nitrogen losses through ammonia volatilization and surface runoff to improve apparent nitrogen recovery of double cropping of late rice using controlled release urea. *Environmental Science and Pollution Research, 24,* 11722–11733. https://doi.org/10.1007/s11356-017-8825-8

Liu, W., Xiong, Y., Xu, X., Xu, F., Hussain, S., Xiong, H., & Yuan, J. (2019). Deep placement of controlled-release urea effectively enhanced nitrogen use efficiency and fresh ear yield of sweet corn in fluvo-aquic soil. *Scientific Reports, 9*(1), 20307. https://doi.org/10.1038/s41598-019-56912-y

Lucas, R. W., Klaminder, J., Futter, M. N., Bishop, K. H., Egnell, G., Laudon, H., & Högberg, P. (2011). A meta-analysis of the effects of nitrogen additions on base cations: Implications for plants, soils, and streams. *Forest Ecology and Management, 262*(2), 95–104. https://doi.org/10.1016/j.foreco.2011.03.018

Maharjan, B., Ferguson, R. B., & Slater, G. P. (2016). Polymer-coated urea improved corn response compared to urea-ammonium-nitrate when applied on a coarse-textured soil. *Agronomy Journal, 108*(2), 509–518. https://doi.org/10.2134/agronj2015.0356

Marahatta, S. (2022). Effects of coated and briquette urea on yield and nitrogen use efficiency of rice at Rampur, Chitwan, Nepal. *Journal of Agriculture and Forestry University*, *5*(1), 219–227. https://doi.org/10.3126/jafu.v5i1.48468

Moran, K. K., Six, J., Horwath, W. R., & van Kessel, C. (2005). Role of mineral-nitrogen in residue decomposition and stable soil organic matter formation. *Soil Science Society of America Journal*, *69*(6), 1730–1736. https://doi.org/10.2136/sssaj2004.0301

Nelson, D. W., & Sommers, L. E. (1980). Total nitrogen analysis of soil and plant tissues. *Journal of the Association of Official Analytical Chemists*, *63*(4), 770–778. https://doi.org/10.1093/jaoac/63.4.770

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (USDA Circular No. 939). U.S. Department of Agriculture.

Pratt, P. F. (1965). Potassium. In C. A. Black (Ed.), *Methods of soil analysis: Part II* (pp. 1022–1030). American Society of Agronomy.

Ray, K., Banerjee, H., Dutta, S., Hazra, A. K., & Majumdar, K. (2019). Macronutrients influence yield and oil quality of hybrid maize (*Zea mays* L.). *PLoS ONE*, *14*(5), e0216939. https://doi.org/10.1371/journal.pone.0216939

Sapkota, M., Joshi, N. P., Kattel, R. R., & Bajracharya, M. (2017). Determinants of maize seed income and adoption of foundation seed production: Evidence from Palpa District of Nepal. *Agriculture & Food Security*, *6*(1), 41. https://doi.org/10.1186/s40066-017-0119-3

Shapiro, C., Attia, A., Ulloa, S., & Mainz, M. (2016). Use of five nitrogen source and placement systems for improved nitrogen management of irrigated corn. *Soil Science Society of America Journal*, *80*(6), 1663–1674. https://doi.org/10.2136/sssaj2015.10.0363

Shrestha, J. (2015). *Growth and productivity of winter maize (Zea mays L.) under different levels of nitrogen and plant population.* Universal-Publishers.

Singh, V., Bhatnagar, A., & Singh, A. P. (2016). Evaluation of leaf-colour chart for need-based nitrogen management in maize (*Zea mays*) grown under irrigated conditions of Mollisols. *Indian Journal of Agronomy*, *61*(1), 64–69.

Subedi, P., Sah, S. K., Marahattha, S., Panta, S., & Shrestha, J. (2018). Nitrogen use efficiency in dry direct seeded rice under LCC based nitrogen management. *ORYZA: An International Journal on Rice*, *55*(4), 590–595. https://doi.org/10.5958/2249-5266.2018.00069.3

Thakur, D. R., Prakash, O., Kharwara, P. C., & Bhalla, S. K. (1998). Effect of nitrogen and plant spacing on yield, nitrogen uptake and economics in baby corn (*Zea mays*). *Indian Journal of Agronomy*, *43*(4), 668–671.

Tian, D., & Niu, S. (2015). A global analysis of soil acidification caused by nitrogen addition. *Environmental Research Letters*, *10*(2), 024019. https://doi.org/10.1088/1748-9326/10/2/024019

Umesha, C., Sridhara, C. J., & Kumarnaik, A. H. (2017). Recent forms of fertilizers and their use to improve nutrient use efficiency and to minimize environmental impacts. *International Journal of Pure and Applied Bioscience*, *5*(2), 858–863. https://doi.org/10.18782/2320-7051.2739

Varadachari, C., & Goertz, H. M. (2010). Slow-release and controlled-release nitrogen fertilizers. In B. Singh (Ed.), *ING bulletins on regional assessment of reactive nitrogen* (Bulletin No. 11, pp. i–iv & 1–42). SCON-ING.

Walkley, A. J., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37*(1), 29–38. https://doi.org/10.1097/00010694-193401000-00003

Xie, Y., Tang, L., Han, Y., Yang, L., Xie, G., Peng, J., Tian, C., Zhou, X., Liu, Q., Rong, X., & Zhang, Y. (2019). Reduction in nitrogen fertilizer applications by the use of polymer-coated urea: Effect on maize yields and environmental impacts of nitrogen losses. *Journal of the Science of Food and Agriculture, 99*(5), 2259–2266. https://doi.org/10.1002/jsfa.9421

Xie, Y., Tang, L., Yang, L., Zhang, Y., Song, H., Tian, C., Rong, X., & Han, Y. (2020). Polymer-coated urea effects on maize yield and nitrogen losses for hilly land of southern China. *Nutrient Cycling in Agroecosystems, 116*(2), 299–312. https://doi.org/10.1007/s10705-019-10038-9

Yang, J.-G., Chen, X.-P., Cheng, L.-L., Cui, Z.-L., & Zhang, F.-S. (2011). Reducing nitrogen losses in winter wheat grown in the North China Plain by top-dressing with different nitrogen fertilizers. *International Journal of Agricultural Research, 6,* 562–572. https://doi.org/10.3923/ijar.2011.562.572

Yao, Y., Zhang, M., Tian, Y., Zhao, M., Zhang, B., Zhao, M., Zeng, K., & Yin, B. (2018). Urea deep placement for minimizing NH_3 loss in an intensive rice cropping system. *Field Crops Research, 218,* 254–266. https://doi.org/10.1016/j.fcr.2017.03.013

Ye, Y., Liang, X., Chen, Y., Liu, J., Gu, J., Guo, R., & Li, L. (2013). Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice: Effects on dry matter accumulation, yield, water and nitrogen use. *Field Crops Research, 144,* 212–224. https://doi.org/10.1016/j.fcr.2012.12.003