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Nitrogen Use Efficiency of Maize Hybrids under Contrasting Nitrogen Levels in Post-Rice Field Conditions

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Abstract

Growing maize under both high and low nitrogen conditions in post-rice fields is essential for understanding the factors influencing nitrogen fertilizer efficiency. This study aimed to identify maize hybrids with high nitrogen use efficiency (NUE) and stable performance across different nitrogen levels for potential use in low-input systems and breeding programs. A field experiment was conducted during the dry season of 2023/24 to assess six maize hybrid varieties. The experiment followed a randomized complete block design with two factors, including maize variety and nitrogen fertilizer level, with three replications. Data were collected on yield, yield components, and agronomic traits to assess the effects of nitrogen fertilizer, variety, and their interaction. Among the tested hybrids, Pac789, CP639, P4163, and DK9979C recorded the highest average yields. Under nitrogen-deficient conditions, P4546 exhibited strong tolerance, maintaining stable yield levels with minimal reduction. Under sufficient nitrogen conditions, CP639, P4163, Pac789, and DK9979C demonstrated high NUE values. Across nitrogen treatments, Pac789 displayed both a high shelling percentage and dark green foliage, indicating broad adaptability. Yield under high nitrogen conditions was positively correlated with NUE, while under low nitrogen conditions, yield was closely associated with the low nitrogen tolerance index and the nitrogen deficiency index. P4546 stood out as the most tolerant hybrid under nitrogen-limited conditions, showing only a slight yield reduction. These findings provide valuable insights for farmers selecting hybrids suited to varying soil fertility and nitrogen availability. Moreover, the results offer practical guidance for breeding programs aiming to develop maize varieties with improved NUE, contributing to more productive and sustainable maize cultivation in post-rice agroecosystems.

Keywords: *correlation; low nitrogen tolerance index; nitrogen deficiency index; nitrogen fertilizer*

1. Introduction

Maize (*Zea mays* L.) plays a crucial role in Thailand's agricultural sector, serving as a key crop for both domestic consumption and the livestock feed industry (Yu et al., 2025). Its adaptability, relatively short growing cycle, and high yield potential have made it a central component in crop rotation systems, particularly following rice cultivation (Ghosh et al., 2021). In many maize-growing regions, especially in the central and northeastern plains, maize is widely grown in post-rice paddy fields as part of a double-cropping strategy aimed at maximizing land productivity throughout the year. However, these post-rice fields often suffer from low residual soil fertility, which stem from several compounding factors. Continuous cultivation, minimal crop residue retention, and heavy dependence on chemical inputs have led to the depletion of organic matter and the degradation of soil structure (Fukai & Mitchell, 2024). As a result, nutrient availability, particularly nitrogen (N), is often insufficient to support optimal maize growth without significant external inputs. The situation is further complicated by the rising costs of N fertilizers, which place considerable economic pressure on smallholder farmers. Given that N is one of the most critical and limiting nutrients for maize productivity (Yue et al., 2021), its efficient use has become increasingly important in the context of sustainable agriculture. Excessive or inefficient application of N not only reduces profitability but also contributes to environmental issues such as nitrate leaching and greenhouse gas emissions (Wang et al., 2021).

Nitrogen use efficiency (NUE) in maize represents the grain yield produced per unit of nitrogen available in the soil, including both native and applied nitrogen (Moll et al., 1982). It consists of two main components: Nitrogen uptake efficiency (NUpE) or the ability of plants to extract N from the soil and nitrogen utilization efficiency (NUtE), or the capacity of plants to convert absorbed nitrogen into grain yield (Congreves et al., 2021). Genetic, agronomic, and environmental factors may influence NUE (Ali et al., 2025). High-yielding hybrids often require higher N input, yet excessive fertilization can lead to environmental pollution and economic inefficiencies. Genotypic differences in root architecture, biomass allocation, and phenology contribute to variation in NUE (Sharma et al., 2021). However, NUE remains relatively low in conventional systems, especially under post-rice field conditions where nutrient leaching and suboptimal soil structure can further limit plant uptake (Reddy et al., 2024). These issues are more pronounced during the dry season, when water scarcity can constrain nutrient availability and root development, compounding the problem of inefficient fertilizer use.

Improving NUE in maize is critical for enhancing agricultural sustainability, reducing production costs, and minimizing environmental impact. Furthermore, identifying hybrids with stable performance under varying N levels can support breeding programs aimed at developing varieties adapted to low-input systems. Despite the importance of NUE, few studies have assessed field maize hybrid performance under low nitrogen conditions during the dry season in post-rice field environments. Moreover, little is known about the interaction between maize genotype and nitrogen input levels in these specific agroecological conditions in Thailand. This gap limits the availability of data needed to guide the selection of hybrids suited to low-input environments.

This study aims to evaluate the performance of selected maize hybrids grown in post-rice field conditions during the dry season under both high and low nitrogen levels. The primary objective is to identify hybrids with superior grain yield and NUE traits, thereby contributing to the development of more resource-efficient maize production systems in Thailand. We hypothesize that maize hybrid varieties differ significantly in their nitrogen use efficiency and tolerance to nitrogen deficiency, and that certain varieties may offer high yields under both high and low nitrogen conditions.

2. Objectives

To evaluate NUE and low nitrogen tolerance of six maize hybrids under post-rice field conditions during the dry season.

3. Materials and Methods

3.1 Plant Materials and Experimental Design

Six maize F1 hybrids- DK9979C, P4163, P4546, Pac789, CP639, and Nakhon Sawan 5-were evaluated under rice field conditions in Khaen Dong District, Buriram Province, Thailand. The experiment was conducted during the dry-cool season (November 2023 to April 2024) at a site located at 15.16°N latitude, 103.10°E longitude, and 130 meters above sea level. A randomized complete block design (RCBD) with a factorial arrangement and three replications was employed. The independent variables were maize hybrid variety (6 levels) and nitrogen fertilizer level (2 levels). The dependent variables included yield, agronomic traits, nitrogen content, and calculated indices. The high-N treatment involved the application of 250 kg N per ha, while the low-N treatment received 31.25 kg N per ha. Each plot consisted of four rows, each 6 meters long, with a plant spacing of 75 × 20 cm.

3.2 Crop Management

To prepare the soil for planting, we first plowed the field using three plows, followed by levelling the soil with seven shovels to ensure an even surface. We took several steps to condition the soil to have a low level of nitrogen. First, we planted the experimental field with the Nakhon Sawan 5 maize hybrid. During the growth period, no fertilizer was applied to the plot. At 40 days after planting, we cut and removed the maize from the plot. This step helped to eliminate nutrients, particularly nitrogen, thus adjusting the soil conditions to a low nitrogen level while maintaining a similar nutrient balance (Barrios et al., 1998). Once the soil was conditioned, soil samples were collected from different plots before conducting the experiment. Ten points per plot were sampled at a depth of 0–30 cm and mixed before being preserved in plastic bags.

The soil was analyzed for chemical properties, including soil pH by pH meter (Peech, 1965), organic matter (OM) by Walkley & Black method (Walkley & Black, 1934), total Nitrogen by Kjeldahl method, available Phosphorus by Bray II and molybdenum-blue method (Bray & Kurtz, 1945), and exchangeable Potassium by ammonium acetate method (Schollenberger & Simon, 1945). The soil texture was analyzed using hydrometer method (Mozaffari et al., 2024).

For the high nitrogen (N) treatment, the soil in the plot received an additional 250 kg of N per ha. Initially, a base fertilizer was applied before planting, consisting of 31.25 kg of the 46-0-0 formula (N), 62.5 kg of the 0-46-0 formula (P), and 62.5 kg of the 0-0-60 formula (K), all per ha. After that, a top-dressing fertilizer using the 46-0-0 formula was applied at a rate of 218.75 kg of N per ha when the maize plants were 20 to 25 days old. This top-dressing should be sprinkled alongside the row, and the soil should be tilled to cover it.

For the low nitrogen treatment, no additional top-dressing N fertilizer was added. Instead, only the base fertilizer was applied prior to planting, which included 31.25 kg of the 46-0-0 formula (N), along with 62.5 kg of the 0-46-0 formula (P) and 62.5 kg of the 0-0-60 formula (K), all per ha.

In both treatments, two maize seeds were planted per hole. After 14 days, thinning was performed to leave only one plant per hole. Agronomic practices followed the recommendations of the Department of Agriculture (2020). Maize was harvested once 90 percent of the leaves had turned brown across the entire plot.

3.3 Data Collection

The data collected included several parameters: plant height (cm), ear height (cm), days to 50% anthesis, days to 50% silking, stay green (measured in SPAD unit), leaf nitrogen (N) content (%), shelling percentage (%), and grain yield (ton per ha). Stay green was assessed using a chlorophyll meter (SPAD 502). To eliminate bias, sampling was conducted using maize plants located in the middle two rows of the plot. For the analysis of leaf N content, approximately 10 leaves from below the first emerged ear were collected at the silk emergence stage (70 days after planting). Samples were then prepared for N analysis using the Kjeldahl method.

The yield parameter was used to calculate the indices of nitrogen deficiency (Shirinzadeh et al., 2010), as follows:

Nitrogen Deficiency Index (NDI)

$$NDI = (Y_s / Y_p) / (\bar{x}_s / \bar{x}_p)$$

Relative Yield Reduction (RYR)

$$RYR = 1 - (\bar{x}_s / \bar{x}_p)$$

Low Nitrogen Tolerance Index (LNTI)

$$LNTI = (Y_p \times Y_s) / X_p^2$$

Low Nitrogen Susceptible Index (LNSI)

$$LNSI = (1 - (Ys / Yp)) / (1 - (\bar{x}_s / \bar{x}_p))$$

where $\bar{x}_s$ and $\bar{x}_p$ are the average of the yield from all maize genotypes under low and high nitrogen conditions, respectively. Y_s and Y_p are the yield of each genotype under low and high nitrogen conditions, respectively.

The average yield and nitrogen content in leaves were used to calculate the efficiency indices, following Moll et al. (1982):

Nitrogen Use Efficiency (NUE)

$$NUE = NUpE \times NUtE$$

$$NUE = (Y_iHN - Y_iLN) / (FHN - FLN)$$

Nitrogen Uptake Efficiency (NUpE)

$$NUpE = (P_iHN - P_iLN) / (FHN - FLN)$$

Nitrogen Utilization Efficiency (NUtE)

$$NUtE = (Y_iHN - Y_iLN) / (P_iHN - P_iLN)$$

where Y_i HN and Y_i LN are the yield of each genotype under high and low nitrogen conditions, respectively. P_i HN and P_i LN are the nitrogen content in the leaves of each genotype under high and low nitrogen conditions, respectively. FHN and FLN are fertilizer rates under high and low nitrogen conditions, respectively.

3.4 Statistical Data Analysis

The data obtained from the experiment underwent analysis of variance (ANOVA). If the treatment was determined to be significant, the mean differences among the treatments for significant traits were analyzed using the Least Significant Difference (LSD) test at a 95 percent confidence level. Additionally, the linear correlation coefficient among the observed traits was calculated using Pearson's linear correlation analysis.

4. Results and Discussion

4.1 Soil Properties Before Applying Fertilizers

The soil was moderately acidic soil (Table 1), which is appropriate for growing maize, as the ideal pH range is between 5.5 and 7.5 (Department of Agriculture, 2020). The organic matter content in the soil was low (0.96%), suggesting limited microbial activity and reduced nutrient-holding capacity. Organic amendments could enhance soil fertility. The measured nitrogen (N) content was considered very low, well below the sufficiency range for most crops, including maize. Meanwhile, the level of available phosphorus (P) in the soil was moderate to high, implying that P availability is generally sufficient. Additionally, the exchangeable potassium (K) content in the soil was adequate, supporting good root development and plant vigor.

Table 1 Soil characteristics before conducting the experiment

Characteristic	Value
pH	5.43
OM (%)	0.96
Total N (%)	0.050
Available P (mg/kg)	46.95
Exchangeable K (mg/kg)	113.08
Sand (%)	53.15
Silt (%)	31.43
Clay (%)	15.42
Soil texture	Sandy loam

The soil texture was sandy loam. A sandy loam texture offers good drainage and root penetration but may have low nutrient- and water-holding capacity. Soil amendments, including organic matter or slow-release fertilizers, are required to improve nutrient retention and soil fertility. According to the Department of Land Development (2007), the optimal soil texture for growing maize is loam or sandy loam.

4.2 The Impacts of Different N Fertilizer Regimes, Varieties, and The Interactions Between Varieties and N Fertilizer Regimes on Agronomic Traits, Yield, and Yield Components in Maize

The effect of N fertilizer regimes (N) was highly significant on all traits measured ($P \leq 0.01$), except for days to 50% anthesis and shelling percentage (Table 2). Variety (V) also influenced all traits, showing statistical differences except for ear height, days to 50% anthesis, days to 50% silking, and nitrogen content in the leaves. Regarding the interaction between variety and N fertilizer regimes (N × V), most traits did not show statistically significant differences, except for yield.

Maize grown in high-nitrogen regimes demonstrated superior agronomic traits, yield components, and yield potential compared to maize cultivated in low-nitrogen regimes. The nitrogen requirements of maize peak approximately 30 to 45 days after planting, and nearly all the nitrogen provided is utilized by the plant. This uptake remains effective until just before flowering. Consequently, a deficiency of nitrogen during the early stages of growth can lead to reduced yields (Welutung et al., 2025; Piekielek, 1997; Kaewtaphan et al., 2024). Furthermore, varying rates of nitrogen fertilizer application significantly influenced maize yield (Sukto et al., 2017).

Table 2 Mean squares for agronomic, yield, and yield components of six maize varieties evaluated under low and high nitrogen conditions in the dry season of 2023/24

df	1	5	5	22	
Traits	Mean squares				C.V. (%)
	Nitrogen (N)	Variety (V)	N × V	Error	
Plant height (cm)	12,573.9 **	211.50 *	111.30 ^{ns}	66.90	4.6
Ear height (cm)	8,661.40 **	23.26 ^{ns}	27.87 ^{ns}	38.93	7.3
Days to 50% anthesis (day)	16.00 ^{ns}	1.44 ^{ns}	0.33 ^{ns}	0.80	1.5
Days to 50% silking (day)	78.02 **	2.69 ^{ns}	0.69 ^{ns}	1.37	1.9
SCMR 70 days (spad-unit)	6,302.24 **	41.75 **	6.71 ^{ns}	5.33	5.7
Nitrogen in leaf at 70 days (%)	23.49 **	0.04 ^{ns}	0.03 ^{ns}	0.03	9.0
Shelling (%)	1.23 ^{ns}	40.93 *	9.36 ^{ns}	13.65	4.7
Grain yield (ton/rai)	4,657,928 **	55,289 **	59,213 **	13,019	12.0

ns, * and ** = non-significant, significantly different at the 0.05 and 0.01 probability levels, respectively.

Table 3 Means for yield and agronomic traits of maize varieties evaluated in low nitrogen (LN) and high nitrogen (HN) conditions in the dry season of 2023/24

Traits	N condition	Variety						Average means across varieties
		DK9979C	P4163	P4546	Pac 789	CP639	NS5	
Days to 50% anthesis (days)	HN	60	60	59	59	59	60	59.50 ^{ns}
	LN	61	61	60	61	60	61	60.67 ^{ns}
Days to 50% silking (days)	HN	62	62	61	61	61	62	61.50 ^{ns}
	LN	65	65	63	65	64	65	64.50 ^{ns}
Plant height (cm)	HN	196.23	205.5	196.00	208.20	200.93	180.46	197.89 **
	LN	160.96	161.60	164.56	158.73	162.20	154.96	160.51 ^{ns}
Ear height (cm)	HN	100.93	105.10	99.13	101.50	104.70	98.06	101.57 ^{ns}
	LN	69.33	66.26	73.10	72.66	73.53	68.40	70.55 ^{ns}
SCMR at 70 days (SPAD units)	HN	54.14	56.95	55.04	52.70	51.67	53.79	54.05 **
	LN	26.72	30.96	32.24	24.96	22.78	27.87	27.59 **
Nitrogen in leaf at 70 days (%)	HN	2.77	3.11	2.94	2.63	2.67	3.03	2.86 **
	LN	1.07	1.23	1.28	1.42	1.17	1.46	1.27 *
Shelling percentage (%)	HN	75.99	79.84	79.44	83.87	81.56	75.66	79.39 *
	LN	78.32	77.05	82.17	82.00	78.77	75.84	79.03 ^{ns}
Grain yield (ton/rai)	HN	1.35	1.44	1.08	1.42	1.44	1.09	1.30 *
	LN	0.54	0.51	0.68	0.69	0.58	0.50	0.58 *
Low nitrogen tolerant index		0.41 ^{b}	0.35 ^{b}	0.65 ^{a}	0.50 ^{ab}	0.41 ^{b}	0.46 ^{b}	0.46 **
Low nitrogen susceptible index		0.99	1.10	0.77	0.81	1.10	0.98	0.96 ^{ns}
Nitrogen Use Efficiency		23.16 ^{a}	26.65 ^{a}	11.22 ^{b}	20.83 ^{ab}	24.60 ^{a}	16.88 ^{ab}	20.56 *
Nitrogen Uptake Efficiency		0.92 ^{ab}	0.98 ^{a}	0.67 ^{b}	0.85 ^{ab}	1.04 ^{a}	0.70 ^{b}	0.86 *
Nitrogen Utilize Efficiency		24.71 ^{a}	27.42 ^{a}	16.05 ^{b}	24.16 ^{a}	23.26 ^{a}	24.34 ^{a}	23.32 **

ns, * and ** = non-significant, significantly different at the 0.05 and 0.01 probability levels, respectively
Means followed by different letters within the same column are significantly different based on Least Significant Difference (LSD) at 5%.

4.3 Variety Responses to Nitrogen Fertilizer Regimes

Under high nitrogen conditions, plant height and stay green varied significantly among different varieties. The percentage of shelling and yield also showed significant differences. Maize varieties grown in high nitrogen conditions exhibited earlier days to 50% anthesis and days to 50% silking and better agronomic and yield performance than maize varieties cultivated under low nitrogen conditions (Table 3). In nitrogen-deficient conditions, there was a statistically significant difference in stay green values. Nitrogen content in the leaves and the yields was significantly different as well. Other traits did not show statistically significant differences. The LNTI values were significantly different, with the varieties P4546 and Pac789 having the highest LNTI values of 0.65 and 0.50, respectively. Conversely, the LNSI values did not show significant differences. Variety P4546 had an LNSI value of 0.77 and exhibited the earliest flowering date.

In conditions of nitrogen deficiency, the varieties Pac789, P4546, and CP639 recorded the highest average yields. Thus, Pac789 and P4546 were considered tolerant to nitrogen deficiency and demonstrated a LNSI. NUE showed significant variation among varieties. The varieties with the highest NUE values were P4163, CP639, DK9979C, Pac789, and Nakhon Sawan 5, with values of 26.65, 24.60, 23.16, 20.83, and 16.88, respectively. NUpE also displayed significant differences, with the top cultivars being CP639, P4163, DK9979C, and Pac789, which had values of 1.04, 0.98, 0.90, and 0.85, respectively. Additionally, NUtE varied significantly, with the highest NUtE values recorded for P4163, DK9979C, Nakhon Sawan 5, Pac789, and CP639, at 27.42, 24.70, 24.34, 24.16, and 23.26, respectively.

Under sufficient nitrogen conditions, CP639, P4163, Pac789, and DK9979C achieved the highest average yields. Therefore, these varieties are efficient in utilizing nitrogen fertilizer, effectively absorbing nitrogen from the soil and converting it into production, which leads to high productivity. Overall, in both nitrogen-sufficient and nitrogen-deficient conditions, Pac789, CP639, P4163, and DK9979C had the highest average yields. Consequently, Pac789 stands out as a variety that is resilient to nitrogen deficiency, demonstrates good efficiency in nitrogen fertilizer use, effectively absorbs nitrogen from the soil, and converts it into substantial yields. It is therefore considered the most effective variety.

4.4 LNTI and NUE of Six Maize Varieties Evaluated in High-Nitrogen and Low-Nitrogen Conditions

In conditions without nitrogen fertilizer, the nitrogen content in the leaves, as indicated by stay green, significantly decreased. Although the values of plant height, cob height, and shelling percentage also decreased, these changes were not statistically significant. When examining agronomic traits, it was noted that in conditions where nitrogen fertilizer was applied at a low rate, both anthesis and silking dates were delayed. Additionally, the interval between anthesis and silking was longer. The Pac789 variety exhibited the highest average shelling percentage, while the P4546 variety had the earliest flowering time (Table 3). The nitrogen deficiency index (NDI) showed no statistically significant difference (Table 4). In both nitrogen-sufficient and nitrogen-deficient conditions, the varieties Pac789, CP639, P4163, and DK9979C recorded the highest average yields.

Analyzing yield differences under various nitrogen fertilizer conditions reveals the nitrogen deficiency index. This analysis suggested that the maize varieties identified are those that do not respond well to fertilizer application and demonstrate low fertilizer use efficiency; these varieties can thrive in low nitrogen conditions without significant yield loss. The varieties P4546 and Pac789 had the highest low nitrogen tolerance index (LNTI), with values of 0.65 and 0.50, respectively. Moreover, the varieties P4163, CP639, DK9979C, Pac789, and Nakhon Sawan 5 presented the highest nitrogen use efficiency (NUE) values at 26.65, 24.60, 23.16, 20.83, and 16.88, respectively. In contrast, P4546 had the lowest NUE and low yield, indicating it did not effectively respond to fertilization. Therefore, P4546 was a maize variety that can tolerate nitrogen deficiency and was suitable for growth in low nitrogen conditions without major yield reductions.

In both nitrogen-sufficient and nitrogen-deficient conditions, Pac789, CP639, P4163, and DK9979C yielded the highest averages. Importantly, Pac789 was characterized by a high nitrogen deficiency index (NDI) and showed tolerance to nitrogen deficiency. It exhibited good nitrogen use efficiency (NUE) and was highly efficient in the uptake and conversion of nitrogen into yield. When grown in low nitrogen conditions, the Pac789 variety produced a lower yield compared to high nitrogen conditions, with a difference of 0.73 tons. Its NDI was measured at 1.01, which was consistent among all varieties. Pac789 recorded the highest LNTI value (0.50) and displayed low nitrogen susceptible index (0.81), like other varieties. Additionally, it achieved the highest NUpE value of 0.85 kg/kg N. Its highest NUtE was 24.16 kg/kg N, and the highest NUE was 20.83 kg/kg N (Table 3).

In summary, the Pac789 variety was tolerant to nitrogen-deficient conditions and exhibited the best NUpE. It also showed significant NUtE. Variability in nitrogen use efficiency among most maize varieties under high nitrogen conditions can be attributed to differences in their genetic abilities to convert nitrogen into yield. Moreover, variations in nitrogen fertilizer application result in differing genetic expressions in maize (Kamprath et al., 1982; Presterl et al., 2003; Gallais & Hirel, 2004).

Table 4 Yield and nitrogen efficiency indices of six maize varieties under high and low nitrogen conditions evaluated in the dry season of 2023/24

Varieties	YHN	YLN	YHN-YLN				NUpE	NUtE	NUE
	(ton/rai)			NDI	LNTI	LNSI	(kg/kg N)		
DK9979C	1.35 ^{a}	0.54 ^{b}	0.81 ^{a}	1.02	0.41	0.99	0.92	24.71	23.16
P4163	1.44 ^{a}	0.51 ^{b}	0.93 ^{a}	1.00	0.35	1.10	0.98	27.42	26.65
P4545	1.07 ^{b}	0.68 ^{a}	0.39 ^{b}	1.02	0.65	0.77	0.67	16.05	11.22
Pac789	1.42 ^{a}	0.69 ^{a}	0.73 ^{ab}	1.01	0.50	0.81	0.85	24.16	20.83
CP639	1.44 ^{a}	0.58 ^{ab}	0.86 ^{a}	1.03	0.41	1.1	1.04	23.26	24.60
NS5	1.08 ^{b}	0.49 ^{b}	0.59 ^{ab}	0.99	0.46	0.98	0.70	24.34	16.88
mean	1.30	0.58	0.72						

Means followed by different letters within the same row are significantly different according to DMRT at the 5% level. YHN = yield under high N, YLN = yield under low N, NDI = nitrogen deficiency index, LNTI = low nitrogen tolerant index, LNSI = low nitrogen susceptible index, NUE = nitrogen use efficiency, NUpE = nitrogen uptake efficiency, and NUtE = nitrogen utilization efficiency.

Table 5 Correlation coefficients among YHN and YLN conditions, NDI, LNTI, LNSI, NUE, NUpE and NUtE of six maize varieties in the dry season of 2023/24

Traits	YHN	YLN	YHN-YLN	NDI	LNTI	LNSI	NUpE	NUtE
YLN	0.25 ns							
YHN-YLN	0.88 **	–0.21 ns						
NDI	–0.54 ns	0.62 ns	–0.84 *					
LNTI	–0.56 ns	0.64 ns	–0.87 *	0.98 **				
LNSI	0.36 ns	–0.72 ns	0.71 ns	–0.81 *	–0.87 *			
NUpE	0.91 **	0.002 ns	0.92 **	–0.63 ns	–0.69 ns	–0.02 ns		
NUtE	0.45 ns	–0.56 ns	0.73 ns	–0.92 **	–0.89 **	0.82 *	0.42 ns	
NUE	0.88 **	–0.21 ns	1.00 **	–0.84 *	–0.87 *	0.30 ns	0.92 **	0.73 ns

ns, * and ** = non-significant, significantly different at the 0.05 and 0.01 probability levels, respectively.

4.5 Correlations Between Yield, Low-N Tolerance, and Nitrogen-Use Efficiencies

Yield under high nitrogen conditions was positively correlated with NUE ($r = 0.88^{**}$) and NUpE ($r = 0.91^{**}$) (Table 5). This suggests that maize varieties capable of producing high yields tend to exhibit good NUE and NUpE (Hirel et al., 2001). Conversely, a decrease in yield due to nitrogen deficiency was negatively correlated with the LNTI ($r = –0.87^{*}$) and the NDI ($r = –0.84^{*}$), while it had a positive correlation with NUpE ($r = 0.92^{**}$) and NUE ($r = 1.00^{**}$). This indicates that maize varieties that are not tolerant to low nitrogen conditions will have significantly lower yields when nitrogen is lacking, but these varieties can still demonstrate high NUE by achieving high yields in high nitrogen conditions.

The LNSI is considered the opposite of the NDI and does not correlate with the LNTI. Therefore, ideal maize varieties should exhibit a good LNTI, yielding higher than other varieties in both high and low nitrogen conditions while also responding positively to the application of nitrogen fertilizers.

Selecting maize varieties that yield well under high nitrogen fertilization can lead to the identification of maize varieties with good NUE. Additionally, if these varieties also produce good yields in nitrogen-deficient conditions, they demonstrate tolerance to nitrogen deficiency. However, it is important to note that testing maize varieties solely under high nitrogen levels does not reveal differences in nitrogen accumulation among plots due to the uniform nitrogen levels. The assessment of NUE relies on key components, namely the efficiency of converting nitrogen into synthetic substances, the movement of nitrogen to the cobs during the seed filling stage, and the efficiency of nitrogen uptake during stem growth (Kamprath et al., 1982; Moll et al., 1982).

Overall, the relationship between yield, LNTI, and NUE suggests that desirable maize varieties should have a high LNTI and higher NUE and yield than other varieties in both normal and nitrogen-deficient conditions. Therefore, selecting varieties that excel in both high and low nitrogen conditions is essential for breeding programs aimed at developing plants with effective NUE and LNTI.

4.6 Correlations Between Agronomic Traits with Low-N Tolerance and Nitrogen-Use Efficiencies

Under high nitrogen (N) conditions, the LNTI showed a negative relationship with all traits observed (Table 6). Conversely, the LNSI was positively associated with all traits except plant height. NUpE demonstrated a significantly positive relationship with ear height ($r = 0.92^{**}$). NUtE was positively associated with all traits, although its correlation with shelling percentage was not statistically significant. NUE exhibited a significant positive relationship with ear height ($r = 0.83^{*}$) and positive, through non-significant, associations with all other traits, except for stay green and leaf nitrogen content.

Table 6 Correlation coefficients among yield components and LNTI and NUE of six maize varieties evaluated in the dry season of 2023/24

Traits	LNTI	LNSI	NUpE	NUtE	NUE
Days to 50% anthesis (day) in high N	–0.59 ns	0.50 ns	0.04 ns	0.62 ns	0.32 ns
Days to 50% silking (day) in high N	–0.59 ns	0.50 ns	0.04 ns	0.62 ns	0.32 ns
Plant height (cm) in high N	–0.16 ns	–0.01 ns	0.59 ns	0.17 ns	0.49 ns
Ear height (cm) in high N	–0.65 ns	0.65 ns	0.92 **	0.50 ns	0.83 *
SCMR at 70 days (spad-unit) in high N	–0.07 ns	0.06 ns	–0.15 ns	0.10 ns	–0.007 ns
Nitrogen in leaf at 70 days (%) in high N	–0.58 ns	0.24 ns	–0.33 ns	0.08 ns	–0.16 ns
Shelling (%) in high N	–0.68 ns	0.49 ns	0.33 ns	–0.05 ns	0.19 ns
Days to 50% anthesis (day) in low N	–0.49 ns	0.12 ns	0.02 ns	0.74 ns	0.36 ns
Days to 50% silking (day) in low N	–0.73 ns	0.39 ns	0.31 ns	0.91 **	0.61 ns
Plant height (cm) in low N	0.27 ns	–0.08 ns	0.24 ns	–0.49 ns	–0.03 ns
Ear height (cm) in low N	0.61 ns	–0.50 ns	–0.09 ns	–0.67 ns	–0.38 ns
SCMR at 70 days (spad-unit) in low N	0.37 ns	–0.28 ns	–0.52 ns	–0.33 ns	–0.45 ns
Nitrogen in leaf at 70 days (%) in low N	0.06 ns	–0.29 ns	–0.61 ns	–0.06 ns	–0.45 ns
Shelling (%) in low N	0.75 ns	–0.81 *	–0.23 ns	–0.66 ns	–0.43 ns

ns, * and ** = non-significant, significantly different at the 0.05 and 0.01 probability levels, respectively.

Under low nitrogen conditions, LNTI showed a positive but non-significant correlation with all traits, except anthesis and silking dates. LNSI demonstrated a significant negative relationship with shelling percentage (r = –0.81*) and non-significant associations with other traits, excluding anthesis and silking dates. NUpE had a negative but non-significant relationship with all traits, except anthesis date and plant height. Similarly, NUtE showed a non-significant negative correlation with all traits except silking date, which showed a significant positive correlation (r = 0.91**). Lastly, NUE was negatively correlated with all traits under low N conditions, although none of these associations were statistically significant except for those related to anthesis and silking dates.

4.7 Future Outlook

As the global demand for sustainable agriculture intensifies, breeding programs are prioritizing resource use efficiency, particularly NUE, in maize. Since NUE is a complex trait influenced by both genetic and environmental factors, the integration of NUE traits into mainstream maize breeding pipelines presents both challenges and opportunities. On one hand, the polygenic nature of NUE complicates selection, especially under fluctuating field conditions (Govindasamy et al., 2023). On the other hand, advances in high-throughput phenotyping, genomic selection, and trait-based modeling offer powerful tools for accelerating the development of nitrogen-efficient cultivars (Ndlovu et al., 2022). Future breeding efforts should focus on dissecting the physiological and genetic bases of NUE and incorporating these insights into predictive breeding frameworks.

This study underscores the indispensable role of multi-environment trials (METs) in capturing the full spectrum of genotype × environment (G × E) interactions that influence maize performance. METs not only allow for the identification of broadly adapted genotypes but also facilitate the recognition of specifically adapted lines for targeted environments (Yue et al., 2022). Understanding G × E is particularly important for NUE, as nitrogen availability and crop response vary widely across different agroecological zones, seasons, and management practices.

Harnessing MET data through statistical models such as AMMI (Additive Main Effects and Multiplicative Interaction), GGE biplots, or machine learning-based G × E predictions will be vital in uncovering stability patterns and context-dependent performance (Ma et al., 2024). Furthermore, integrating environmental covariates (e.g., soil nitrogen dynamics, rainfall patterns, temperature) with genomic data can enable breeders to design environment-specific ideotypes with enhanced NUE (Fritsche-Neto et al., 2021). Therefore, future maize breeding programs should adopt a holistic approach that combines NUE-focused selection with robust multi-environmental evaluation. This dual strategy will not only increase the resilience and sustainability of maize production systems but also ensure that improved cultivars meet the productivity demands of diverse and evolving agricultural landscapes.

5. Conclusion

This study evaluated nitrogen use efficiency (NUE) across six maize varieties grown under post-rice field conditions. Among them, P4546 was the earliest to flower and maintained relatively high grain yield under low nitrogen (N) input, despite its low NUE. Its performance suggests a degree of tolerance to N deficiency, making it a viable option for low-input systems where yield stability is prioritized over NUE. In contrast, Pac789 consistently outperformed all other varieties across both N levels. It exhibited high NUE, nitrogen uptake efficiency, and nitrogen utilization efficiency, coupled with strong tolerance to N stress. These traits contributed to its superior yield performance, identifying Pac789 as the most promising variety for cultivation under varying N regimes and as a potential candidate for breeding programs targeting improved NUE.

6. Abbreviations

Abbreviation	Full Term
NUE	Nitrogen Use Efficiency
NUpE	Nitrogen Uptake Efficiency
NUtE	Nitrogen Utilization Efficiency
LNTI	Low Nitrogen Tolerance Index
LNSI	Low Nitrogen Susceptible Index
NDI	Nitrogen Deficiency Index
YHN	Yield under High Nitrogen
YLN	Yield under Low Nitrogen
HN	High Nitrogen
LN	Low Nitrogen
G × E	Genotype × Environment Interaction

7. CRediT Statement

Sirigul Bunphok: Validation, Statistical analysis, Investigation, Data Curation, Writing - Original Draft, Funding Acquisition.
Wanpen Chalorcharoenying: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Visualization, Project Administration.

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9. References

Ali, A., Jabeen, N., Farruhbek, R., Chachar, Z., Laghari, A. A., Chachar, S., ... & Yang, Z. (2025). Enhancing nitrogen use efficiency in agriculture by integrating agronomic practices and genetic advances. *Frontiers in Plant Science*, *16*, Article 1543714. https://doi.org/10.3389/fpls.2025.1543714

Barrios, E., Kwesiga, F., Buresh, R. J., Coe, R., & Sprent, J. I. (1998). Relating preseason soil nitrogen to maize yield in tree legume-maize rotations. *Soil Science Society of America Journal*, *62*(6), 1604-1609. https://doi.org/10.2136/sssaj1998.03615995006200060018x

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, *59*(1), 39-46. https://doi.org/10.1097/00010694-194501000-00006

Congreves, K. A., Otchere, O., Ferland, D., Farzadfar, S., Williams, S., & Arcand, M. M. (2021). Nitrogen use efficiency definitions of today and tomorrow. *Frontiers in Plant Science*, *12*, Article 637108. https://doi.org/10.3389/fpls.2021.637108

Department of Agriculture. (2020). Guidebook: *Maize production technology*. Institute of Agronomy and renewable energy, Ministry of Agriculture and Cooperatives, Thailand. https://pubhtml5.com/iytc/cjgc/

Department of Land Development. (2007). *Soil management with organic fertilizer to increase maize yield*. Ministry of Agriculture and Cooperatives, Thailand. Retrieved form http://www1.ldd.go.th/menu_Dataonline/G2/G2_09.pdf

Fritsche-Neto, R., Galli, G., Borges, K. L. R., Costa-Neto, G., Alves, F. C., Sabadin, F., ... & Crossa, J. (2021). Optimizing genomic-enabled prediction in small-scale maize hybrid breeding programs: A roadmap review. *Frontiers in Plant Science*, *12*, Article 658267. https://doi.org/10.3389/fpls.2021.658267

Fukai, S., & Mitchell, J. (2024). Crop diversification in rainfed lowland rice ecosystems in tropical Asia. *Advances in Agronomy*, *188*, 207-246. https://doi.org/10.1016/bs.agron.2024.06.002

Gallais, A., & Hirel, B. (2004). An approach to the genetics of nitrogen use efficiency in maize.

Journal of Experimental Botany, *55*(396), 295-306. https://doi.org/10.1093/jxb/erh006

Ghosh, D., Brahmachari, K., Das, A., Hassan, M. M., Mukherjee, P. K., Sarkar, S., ... & Hossain, A. (2021). Assessment of energy budgeting and its indicator for sustainable nutrient and weed management in a rice-maize-green gram cropping system. *Agronomy*, *11*(1), Article 166. https://doi.org/10.3390/agronomy11010166

Govindasamy, P., Muthusamy, S. K., Bagavathiannan, M., Mowrer, J., Jagannadham, P. T. K., Maity, A., ... & Tiwari, G. (2023). Nitrogen use efficiency a key to enhance crop productivity under a changing climate. *Frontiers in Plant Science*, *14*, Article 1121073. https://doi.org/10.3389/fpls.2023.1121073

Hirel, B., Bertin, P., Quilleré, I., Bourdoncle, W., Attagnant, C., Dellay, C., ... & Gallais, A. (2001). Towards a better understanding of the genetic and physiological basis for nitrogen use efficiency in maize. *Plant Physiology*, *125*(3), 1258-1270. https://doi.org/10.1104/pp.125.3.1258

Kamprath, E. J., Moll, R. H., & Rodriguez, N. (1982). Effects of nitrogen fertilization and recurrent selection on performance of hybrid populations of corn 1. *Agronomy Journal*, *74*(6), 955-958. https://doi.org/10.2134/agronj1982.00021962007400060007x

Kaewtaphan, P., Maniin, P., Nilkong, P., Aninbon, C., & Teamkao, P. (2024). Effect of organic fertilizer quantity on yield and seed qualities of rice. *International Journal of Agricultural Technology*, *20*(3), 1067–1074.

Ma, C., Liu, C., & Ye, Z. (2024). Influence of genotype × environment interaction on yield stability of maize hybrids with AMMI Model and GGE Biplot. *Agronomy*, *14*(5), Article 1000. https://doi.org/10.3390/agronomy14051000

Moll, R. H., Kamprath, E. J., & Jackson, W. A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization 1. *Agronomy Journal*, *74*(3), 562-564. https://doi.org/10.2134/agronj1982.00021962007400030037x

Mozaffari, H., Moosavi, A. A., Baghernejad, M., & Cornelis, W. (2024). Revisiting soil texture analysis: Introducing a rapid single-reading hydrometer approach. *Measurement*, *228*, Article 114330. https://doi.org/10.1016/j.measurement.2024.114330

Ndlovu, N., Spillane, C., McKeown, P. C., Cairns, J. E., Das, B., & Gowda, M. (2022). Genome-wide association studies of grain yield and quality traits under optimum and low-nitrogen stress in tropical maize (*Zea mays* L.). *Theoretical and Applied Genetics*, *135*(12), 4351-4370. https://doi.org/10.1007/s00122-022-04224-7

Peech, M. (1965). *Hydrogen-ion activity. Methods of Soil Analysis. CA Black, ed., Part 2-Chemical and Microbiological Properties*. Washington DC, US: American Society of Agronomy, Inc. https://doi.org/10.2134/agronmonogr9.2.c9

Piekielek, W. (1997). *The early season chlorophyll meter test for maize*. The Pennsylvania State University. USA. Retrieved from https://www.specmeters.com/info/4.html

Presterl, T., Seitz, G., Landbeck, M., Thiemt, E. M., Schmidt, W., & Geiger, H. H. (2003). Improving nitrogen-use efficiency in European maize: Estimation of quantitative genetic parameters. *Crop Science*, *43*(4), 1259-1265. https://doi.org/10.2135/cropsci2003.1259

Reddy, M. B., Sravani, P., Kumar, S., Rajawat, M. V. S., Jaiswal, D. K., Dhar, S., ... & Kumar, S. (2025). Nitrogen use efficiency reimagined: Advancements in agronomic, ecophysiological, and molecular strategies. *Journal of Plant Nutrition*, *48*(9), 1577-1603. https://doi.org/10.1080/01904167.2024.2447840

Schollenberger, C. J., & Simon, R. H. (1945). Determination of exchange capacity and exchangeable bases in soil ammonium acetate method. *Soil Science*, *59*(1), 13-24. https://doi.org/10.1097/00010694-194501000-00004

Sharma, N., Sinha, V. B., Prem Kumar, N. A., Subrahmanyam, D., Neeraja, C. N., Kuchi, S., ... & Raghuram, N. (2021). Nitrogen use efficiency phenotype and associated genes: Roles of germination, flowering, root/shoot length and biomass. *Frontiers in Plant Science*, *11*, Article 587464. https://doi.org/10.3389/fpls.2020.587464

Shirinzadeh, A., Zarghami, R., Azghandi, A. V., Shiri, M. R., & Mirabdulbaghi, M. (2010). Evaluation of drought tolerance in mid and late mature corn hybrids using stress tolerance indices. *Asian Journal of Plant Sciences*, *9*(2), 67-73. https://doi.org/10.3923/ajps.2010.67.73

Sukto, S., Nolapuat, W., Luanmanee, S., Thiansirirerk, A., Saipan, P., & Duangkaew, S. (2017). *Study of response to nitrogen fertilizer of maize variety NSX042022 in the clay loam soil group, sandy-loamy silt, Uthai Thani province*. Ministry of Agriculture and Cooperatives, Thailand. Retrieved from https://info.doa.go.th/research/frontend/download.php?id=4869

Walkley, A., & 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

Wang, X., Bai, J., Xie, T., Wang, W., Zhang, G., Yin, S., & Wang, D. (2021). Effects of biological nitrification inhibitors on nitrogen use efficiency and greenhouse gas emissions in agricultural soils: A review. *Ecotoxicology and Environmental Safety*, *220*, Article 112338. https://doi.org/10.1016/j.ecoenv.2021.112338

Welutung, P., Pengthamkeerati, P., Kachenchart, B., & Tawornpruek, S. (2025). Effects of nitrogen fertilizer rate with urease and nitrification inhibitors on certain morphological traits and quality of sugarcane (*Saccharum officinarum* L.). *Current Applied Science and Technology*, *25*(3), Article e0261218

Yu, Q., Nguyen, T. P. L., Shrestha, R. P., & Nitivattananon, V. (2025). Impacts and implications of agronomic efficiency on rice and maize productivity among small-scale farmers in Chiang Mai, Thailand. *Cogent Food & Agriculture*, *11*(1), Article 2496697. https://doi.org/10.1080/23311932.2025.2496697

Yue, H., Olivoto, T., Bu, J., Li, J., Wei, J., Xie, J., ... & Jiang, X. (2022). Multi-trait selection for mean performance and stability of maize hybrids in mega-environments delineated using envirotyping techniques. *Frontiers in Plant Science*, *13*, Article 1030521. https://doi.org/10.3389/fpls.2022.1030521

Yue, K., Li, L., Xie, J., Fudjoe, S. K., Zhang, R., Luo, Z., & Anwar, S. (2021). Nitrogen supply affects grain yield by regulating antioxidant enzyme activity and photosynthetic capacity of maize plant in the loess plateau. *Agronomy*, *11*(6), Article 1094. https://doi.org/10.3390/agronomy11061094