

Effects of Nitrogen Rates on Nitrogen use Efficiency of Low-Nitrogen Tolerant Maize (*Zea mays* L.) Varieties

Soyinka K.O.

Department of Plant Physiology and Crop Production, College of Plant Science and Crop Production, Federal University of Agriculture, Abeokuta, Nigeria.

Corresponding author: soyinkako@funaab.edu.ng

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Abstract

Maize is a nitrogen-demanding crop whose productivity is strongly influenced by nitrogen (N) availability. However, the high cost and limited accessibility of nitrogen fertilizers necessitate the development of maize cultivars with improved nitrogen use efficiency (NUE), particularly under low-input systems. This study evaluated the effects of varying nitrogen rates on NUE indices and yield performance of low-nitrogen tolerant maize varieties. Field experiments were conducted during raining period (May to July) 2012 at the Teaching and Research Farm of the Institute of Food Security, Environmental Resources and Agricultural Research, Federal University of Agriculture, Abeokuta (Opeji), and MATKIS Farm, Eruwa, Oyo State, Nigeria. Six maize varieties (M0926-6, M0926-9, M1026-10, OBA 98, SUWAN-1-SX, and OBA SUPER 2) were evaluated under four nitrogen rates (0, 15, 30, and 45 kg N ha⁻¹) in a 6 × 4 × 2 factorial arrangement (variety × nitrogen rate × location) fitted into a randomized complete block design with three replications. Data were collected on physiological efficiency (PE), nitrogen use efficiency (NUE), nitrogen uptake efficiency (NUpE), recovery efficiency (RE), cob yield, grain yield, 100-grain weight, and stover yield. Data were analyzed using analysis of variance (ANOVA) in GenStat (12th edition), and means were separated at $p \leq 0.05$. Application of 45 kg N ha⁻¹ significantly increased NUE across varieties, while variety M1026-10 recorded the highest nitrogen uptake efficiency (60.9 kg kg⁻¹). Application of 15 kg N ha⁻¹ significantly improved physiological efficiency (228.0 kg kg⁻¹) and recovery efficiency (0.508). Nitrogen × location interaction significantly affected PE and RE, with the highest values recorded at Eruwa. Overall, application of 45 kg N ha⁻¹ enhanced nitrogen use efficiency and yield performance of low-nitrogen tolerant maize varieties under the studied environments.

Keywords: Nitrogen Fertilization, Nitrogen Uptake Efficiency, Maize Genotypes, Low-Input Agriculture, Nutrient Management.

Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated cereal crops globally and serves as a major source of food, feed, and industrial raw materials. It is grown across diverse agro-ecological environments and ranks as the world's leading cereal in terms of production volume, exceeding both wheat and rice. Owing to its versatility, maize plays a crucial role in human nutrition, livestock feeding, biofuel production, and various industrial applications, making it an essential crop for global food and livelihood security (Erenstein

et al., 2022). The crop is valued for its high productivity and nutritional composition, containing approximately 78% starch, 10% protein, 2.3-4.47% oil, 3.61% fibre, 3.0% sugar, and 3.64% ash (Imam et al, 2025). In Africa, maize was introduced in the 1500s and has since become a dominant staple food crop, contributing significantly to household food security and income generation.

Globally, maize production exceeds 700 million metric tonnes annually, with the United States, China, and Brazil accounting for the largest share of global production. The United States and China remain the world's two leading maize producers, contributing a substantial proportion of global output (Ranum et al., 2014). In Sub-Saharan Africa, maize occupies a substantial proportion of the cereal production area and is one of the most important staple crops for food security. In Ethiopia, maize remains the leading cereal crop in terms of production. According to the Ethiopian Statistics Service (ESS, 2023), during the 2022 Meher production season, maize occupied approximately 22% of the total cereal area and contributed about 32.5% of the country's total cereal production, making it the highest-producing cereal crop. Its wide adaptability, high photosynthetic efficiency, and superior capacity to convert solar radiation into biomass contribute to its high yield potential compared with most other cereal crops. Nitrogen is the most limiting nutrient in maize production systems. Nitrogen is the most limiting nutrient in maize production because of the crop's high nitrogen demand throughout its growth cycle. Studies indicate that maize requires approximately 16–18 kg of nitrogen uptake per tonne of grain produced, while continued grain harvest removes significant quantities of nitrogen from the soil (Shen, et al., 2025). Therefore, appropriate nitrogen fertilizer management is critical for maximizing grain yield, improving nitrogen use efficiency, and sustaining long-term soil productivity. Nitrogen is a vital macronutrient that constitutes amino acids, proteins, nucleic acids, and chlorophyll, thereby directly influencing photosynthetic efficiency, biomass accumulation, and grain yield in maize; consequently, nitrogen uptake is strongly associated with plant growth performance and productivity (Su et al., 2020; Wang et al., 2025). Grain yields of 9.5, 5.0, and 2.0 t ha⁻¹ have been reported with nitrogen applications of 187, 90, and 40 kg N ha⁻¹, respectively, highlighting the direct relationship between nitrogen supply and crop performance. However, the efficiency with which applied nitrogen is utilized by maize plants varies widely.

Over the past six decades, global fertilizer consumption has increased substantially, contributing to major changes in crop production and fertilizer use efficiency worldwide (Khatri et al., 2025). Continued expansion in fertilizer use has contributed significantly to increased global food production (Peñuelas, et al., 2023). Nevertheless, escalating fertilizer costs and environmental concerns related to nitrogen losses through volatilization, leaching, and denitrification necessitate improved nitrogen management strategies and enhanced nitrogen use efficiency (NUE).

Nitrogen Use Efficiency (NUE), defined as the ratio of grain yield to nitrogen supplied, varies among maize genotypes and significantly influences yield responses to nitrogen fertilization; recent field studies demonstrate that maize varieties with higher NUE produce

greater grain yields per unit of nitrogen fertilizer compared to less efficient varieties (Yang et al., 2026). Nitrogen Use Efficiency (NUE) is a complex trait that can be partitioned into components such as nitrogen Uptake Efficiency (NUpE) and Nitrogen Utilization Efficiency (NUE), reflecting the plant's ability to absorb available nitrogen and convert it into grain yield (Li et al., 2025). Under high nitrogen input systems, nitrogen uptake efficiency is often the dominant contributor to NUE, whereas under low-input systems, nitrogen utilization efficiency becomes more critical (Van Ginkel et al., 2001).

Several factors influence Nitrogen Use Efficiency (NUE), including nitrogen application rate and timing, soil properties, genotype, moisture availability, and crop rotation; for example, optimized nitrogen application patterns combined with favorable soil and moisture conditions have been shown to enhance maize NUE (Zhang et al., 2024). Crop rotation alters soil nitrogen accumulation and nitrogen use efficiency by modifying soil moisture dynamics, mineral nitrogen availability, and crop nitrogen uptake (Yang et al., 2022) and maize–soybean intercropping with appropriate nitrogen rates increases N uptake and NUE indices compared with monocropping (Nasar et al., 2023). Genetic variability among maize cultivars also significantly affects nitrogen use efficiency and yield responses under low nitrogen conditions (Ige et al., 2024). Furthermore, variations in yield and internal nitrogen partitioning among maize varieties with differing nitrogen efficiencies underscore the combined effects of environmental nitrogen availability and genetic potential on grain protein and yield traits (Yang et al., 2026).

Maize shows rapid nitrogen uptake during the mid-vegetative growth stage, and peak nitrogen accumulation occurs around silking, highlighting the importance of supplying adequate N during key development periods (Yang et al., 2026). Inadequate nitrogen availability reduces leaf area, photosynthetic performance, and ultimately grain yield (Su et al., 2020). Consequently, optimizing nitrogen application rates and enhancing the performance of low-nitrogen tolerant genotypes are essential strategies for improving maize productivity under resource-limited environments (Ige et al., 2024).

Despite extensive research on nitrogen fertilization, there remains a need to evaluate the interaction between nitrogen rates and low-nitrogen tolerant maize varieties under specific agro-ecological conditions. Identifying varieties with superior nitrogen use efficiency under moderate or reduced nitrogen inputs can reduce production costs while minimizing environmental impacts.

Therefore, this study aimed to evaluate the effects of varying nitrogen rates on nitrogen use efficiency components and yield performance of selected low-nitrogen tolerant maize varieties.

Null Hypothesis

H₀₁: Maize variety has no significant effect on nitrogen use efficiency (NUE) indices.

H₀₂: There is no significant interaction effect between nitrogen fertilizer rate and maize variety on nitrogen use efficiency (NUE) indices.

Literature Review

Nitrogen (N) is the most yield-limiting nutrient in maize production because it is required in large quantities for chlorophyll formation, photosynthesis, protein synthesis, and grain development. However, maize typically recovers less than 50% of the nitrogen fertilizer applied under field conditions, while the remaining nitrogen is lost through leaching, denitrification, volatilization, and surface runoff. Consequently, improving nitrogen use efficiency (NUE) has become a major objective of sustainable maize production, particularly in Sub-Saharan Africa, where nitrogen deficiency and low fertilizer use continue to constrain maize productivity (Asibi et al., 2019).

Nitrogen use efficiency is affected by several interacting factors, including nitrogen application rate, fertilizer source, timing and placement of fertilizer, soil characteristics, climatic conditions, and maize genotype. Among these factors, nitrogen application rate is considered the most influential because it directly determines crop nitrogen uptake, biomass accumulation, and grain yield. Increasing nitrogen rates generally enhances grain yield and nitrogen uptake until an optimum level is reached. Beyond this point, additional nitrogen results in diminishing yield responses while reducing agronomic efficiency, recovery efficiency, and partial factor productivity because nitrogen losses increase substantially (Pasley et al., 2020).

Pasley et al. (2020) evaluated maize response to four nitrogen fertilizer rates (0, 40, 80, and 160 kg N ha⁻¹) across several locations in Kenya and Zimbabwe. The study showed that grain yield and total nitrogen uptake increased significantly with increasing nitrogen rate. However, nitrogen recovery efficiency declined at the highest fertilizer rates because crop demand was exceeded, leaving larger amounts of residual soil nitrogen susceptible to environmental losses. The authors concluded that optimum nitrogen recommendations should maximize nitrogen recovery while minimizing residual soil nitrogen accumulation. Recent reviews have emphasized that nitrogen use efficiency depends not only on fertilizer application but also on the synchronization of nitrogen supply with crop demand throughout the growing season. Asibi et al. (2019) reported that improved synchronization between nitrogen availability and maize growth stages enhances nitrogen uptake, photosynthetic activity, biomass production, and grain filling while reducing nitrogen losses. The review further noted that integrating improved maize varieties with efficient nitrogen management practices offers significant opportunities for increasing productivity while minimizing environmental impacts.

More recent studies have expanded the concept of nitrogen use efficiency by emphasizing effective nitrogen use rather than simply increasing fertilizer recovery. Ciampitti and Lemaire (2022) argued that modern maize breeding has substantially improved grain yield but has also increased crop dependence on nitrogen fertilizer. They recommended breeding and management strategies that improve intrinsic nitrogen uptake capacity and overall nitrogen utilization rather than relying solely on increased fertilizer application.

A comprehensive review of nutrient use efficiency in Sub-Saharan Africa by Zingore et al. (2022) further demonstrated that maize response to nitrogen fertilizer varies considerably

across environments because of differences in soil fertility, rainfall, genotype, and management practices. The authors recommended site-specific nutrient management strategies instead of blanket fertilizer recommendations to improve nitrogen use efficiency and enhance fertilizer profitability for smallholder farmers.

Global analyses also indicate that nitrogen management should be integrated with other agronomic practices. Appropriate planting density, improved hybrids, split nitrogen application, and balanced nutrient management enhance nitrogen uptake, fertilizer recovery, and grain yield compared with excessive nitrogen application alone. These integrated management practices improve nitrogen use efficiency while reducing environmental nitrogen losses.

Overall, post-2019 research consistently demonstrates that optimizing nitrogen fertilizer rate is fundamental to improving maize nitrogen use efficiency. Moderate and site-specific nitrogen application rates, combined with improved maize varieties and complementary crop management practices, increase grain yield, agronomic efficiency, recovery efficiency, and fertilizer productivity while minimizing nitrogen losses to the environment. These findings provide a strong scientific basis for evaluating the effects of different nitrogen fertilizer rates on nitrogen use efficiency indices of maize varieties under local agroecological conditions (Pasley et al., 2020; Zingore et al., 2022).

Materials and Methods

Experimental Sites

Field experiments were conducted during the 2012 cropping season at two locations in Southwestern Nigeria: The first location was at the Teaching and Research Farm of the Institute of Food Security, Environmental Resources and Agricultural Research (IFSERAR), Federal University of Agriculture, Abeokuta (FUNAAB), located at Opeji (rainforest–transition agro-ecological zone) while the second location was at MATKIS Farm, Lanlate, Oyo State, located within the rainforest agro-ecological zone.

Both sites are characterized by a bimodal rainfall pattern, with a long rainy season beginning in late March and a short rainy season extending from September to early November, separated by a brief dry spell in August. The experiments were established on previously cultivated, degraded soils at both locations.

Land Preparation

Conventional tillage operations were carried out prior to planting. The fields were ploughed and harrowed to achieve a fine tilth suitable for maize establishment and to enhance soil aeration and nutrient availability.

Experimental Design and Field Layout

The experiment was arranged in a $6 \times 4 \times 2$ factorial combination (variety $\times$ nitrogen rate $\times$ location) fitted into a randomized complete block design (RCBD) with three replications at each site.

The total experimental area measured 14 m × 83.5 m (1,169 m²). Each plot measured 4 m × 3 m (12 m²). Maize was planted at a spacing of 0.75 m between rows and 0.25 m within rows. The central 2 m × 3 m area of each plot was designated as the net plot for data collection to minimize border effects.

Treatments

Maize Varieties: Six maize varieties evaluated in the experiment were Mog26-6, Mog26-9, M1026-10, OBA 98, SUWAN-1-SX and OBA SUPER 2 (hybrid). The first four varieties were obtained from the International Institute of Tropical Agriculture (IITA), while SUWAN-1-SX and OBA SUPER 2 were sourced from the Ogun State Agro-Service Centre.

Nitrogen Fertilizer Application: Nitrogen was applied as urea (46% N) at four rates which were 0 kg N ha⁻¹, 15 kg N ha⁻¹, 30 kg N ha⁻¹ and 45 kg N ha⁻¹. The fertilizer rates were determined based on soil test results and recommendations from the Manual of Soil Fertility Assessment (Association of Nigeria Soil Scientists, 2004). Nitrogen was applied according to standard agronomic practices for maize production.

Data Collection

Stand Count: Stand count was taken at three weeks after planting (3 WAP) by counting the number of emerged plants per plot.

Percentage emergence was calculated as
$$\frac{\text{Number of plant emerge/plot} \times 100}{\text{Total number of plant expected}}$$

Plant Height: Plant height was measured at two-week intervals from five randomly selected plants within the net plot. Measurements were taken from the soil surface to the tip of the longest leaf using a measuring tape, and mean values were computed.

Determination of Nitrogen Use Efficiency Indices: At physiological maturity, five representative plants were randomly harvested from the net plot of each treatment. Plants were separated into leaves, stems, tassels, ears, cobs, and grains. Samples were oven-dried to constant weight and weighed. Sub-samples were ground to pass through a 1-mm sieve and analyzed for total nitrogen concentration using an automated dry combustion method (gas chromatograph).

The following nitrogen efficiency indices were computed:

Nitrogen Use Efficiency (NUE): NUE was determined at maturity by harvesting a sample of five plants randomly selected in each net plot, separating into the leaves, stem, tassel, ear, cob, grain. Each component was dried and weighed; sub sample of each of the components was taken and grinded to enable to pass through 1mm sieve. Total N concentration of each of the sample was determined by automated dry combustion-gas chromatograph in the laboratory.

$$NUE = \frac{Y_N - Y_0}{Y_a}$$

$$\text{Nitrogen Uptake Efficiency} = \frac{\text{Total plant nitrogen}}{\text{Applied N} + \text{Soil N}} \times 100$$

$$\text{Nitrogen Utilization Efficiency} = \frac{\text{Grain Nitrogen}}{\text{Total Plant Nitrogen}} \times 100$$

Internal utilization efficiency (IE) (kg/kg)

$$IE = \frac{Y}{U}$$

$$\text{Recovery Efficiency (RE)} = \frac{U_N - U_o}{N_a}$$

Where:

- U_N = Total nitrogen uptake by the fertilized crop (kg N ha⁻¹)
- U_o = Total nitrogen uptake by the unfertilized (control) crop (kg N ha⁻¹)
- N_a = Nitrogen fertilizer applied (kg N ha⁻¹)

Physiology efficiency (PE) (kg/kg): This was calculated using this formula:

$$PE = \frac{Y_f - Y_o}{U_f - U_o}$$

Where:

1. **PE** = Physiological Efficiency (kg grain per kg additional N uptake)
2. **Y_f** = Grain yield in the fertilized treatment (kg ha⁻¹)
3. **Y_o** = Grain yield in the unfertilized (control) treatment (kg ha⁻¹)
4. **U_f** = Total nitrogen uptake in the fertilized treatment (kg N ha⁻¹)
5. **U** = Total nitrogen uptake in the unfertilized (control) treatment (kg N ha⁻¹)

Statistical Analysis

Data collected from both locations were subjected to combined analysis of variance (ANOVA) appropriate for a factorial experiment using GenStat (12th Edition). Treatment means were separated using the Standard Error of Difference (SED) at a significance level of $p \leq 0.05$.

Results

Effects of Fertilizer Rate, Variety, Location, and Their Interactions on Nitrogen Efficiency Parameters of Low-Nitrogen Tolerant Maize Varieties

Nitrogen Use Efficiency (NUE)

Nitrogen use efficiency (NUE) was significantly influenced by location and nitrogen application rate (Table 1). Location had no significant effect ($p \leq 0.05$) on NUE, with Eruwa recording a higher mean value (44.81 kg kg⁻¹) compared with Opeji (41.10 kg kg⁻¹).

Nitrogen rate also significantly affected NUE ($p \leq 0.05$). The highest NUE (61.40 kg kg⁻¹) was obtained at the application rate of 45 kg N ha⁻¹, whereas the control treatment (0 kg N ha⁻¹) recorded the lowest value. This indicates that increasing nitrogen rate up to 45 kg N ha⁻¹ enhanced nitrogen utilization efficiency across the evaluated maize varieties.

Nitrogen Uptake Efficiency (NUpE)

Nitrogen uptake efficiency was significantly influenced by nitrogen rate and location (Table 1). The application of 15 kg N ha⁻¹ resulted in the highest NUpE value (58.20 kg kg⁻¹), which was significantly different ($p \leq 0.05$) from other nitrogen levels.

Variety had no significant effect on NUpE, however M1026-10 recorded the highest NUpE. Location exerted a highly significant effect ($p \leq 0.05$) on NUpE. Eruwa recorded a markedly higher uptake efficiency (68.70 kg kg⁻¹) compared with Opeji (45.10 kg kg⁻¹). This suggests improved nitrogen acquisition under the environmental conditions prevailing at Eruwa.

Physiological Efficiency (PE)

Variety had no significant effect ($p \leq 0.05$) on physiological efficiency (PE) of the low-nitrogen tolerant maize varieties (Table 1). However, nitrogen rate significantly influenced PE ($p \leq 0.05$).

The highest physiological efficiency (228.00 kg kg⁻¹) was recorded at the application rate of 15 kg N ha⁻¹. Increasing nitrogen rates beyond this level resulted in comparatively lower PE values.

Recovery Efficiency

From table 1, it was also observed that Nitrogen rate had a highly significant effect on recovery efficiency. Application rate of 15 kg N ha⁻¹ recorded the highest (0.508) RE while control recorded the lowest (0.000). no significant effect of variety was observed. Location was also observed to have a highly significant effect on RE with crops planted at Eruwa recording the highest RE (0.528).

Internal Utilization Efficiency

Nitrogen rates and variety did not show any significant effect on the Internal Utilization Efficiency (Table 1). OBA SUPER 2 and Control plot recorded the highest IUE (1067.00 kg kg⁻¹) and (662.00 kg kg⁻¹) respectively. However, location was observed to be highly significant for IUE. Opeji recorded the highest IUE of 715.00 kg kg⁻¹

Table 1 Effects of nitrogen rate, variety and location on nitrogen efficiency indices of maize

Factor	Treatment	NUE	NUpE	PE	RE	IUE
Nitrogen rate (kg N ha ⁻¹)						
	0	0.00c	33.30c	0.00b	0.000c	662.00
	15	51.10b	58.20a	228.00a	0.508a	264.00
	30	59.20a	55.20ab	184.00a	0.391ab	485.00
	45	61.40a	51.00b	167.00a	0.309b	395.00
	SED ($p \leq 0.05$)	2.93*	4.39**	49.30**	0.088**	ns
Variety						
	M0926-6	43.40	53.90	133.00	0.440	255.00

Factor	Treatment	NUE	NU _p E	PE	RE	IUE
	Mog26-9	45.00	49.80	115.00	0.263	334.00
	M1026-10	41.80	60.90	239.00	0.312	351.00
	OBA 98	38.90	60.70	140.00	0.213	331.00
	SUWAN-1-SX	43.60	60.40	124.00	0.382	372.00
	OBA SUPER 2	45.10	55.90	120.00	0.203	1067.00
	SED ($p \leq 0.05$)	ns	ns	ns	ns	ns
Location						
	Opeji	41.10	45.10	108.00	0.076	715.00
	Eruwa	44.80	68.70	182.00	0.528	188.00
	SED ($p \leq 0.05$)	ns	3.10**	34.90*	0.062**	186.90**

Interaction Effects of Nitrogen Rate, Variety, and Location on Nitrogen Use Efficiency

The interaction among nitrogen rate, variety, and location had a significant effect ($p \leq 0.05$) on nitrogen use efficiency (NUE) (Table 2). At Opeji, the highest NUE (74.00 kg kg⁻¹) was recorded in OBA SUPER 2 when 45 kg N ha⁻¹ was applied. Similarly, relatively high NUE values were observed for most varieties at 45 kg N ha⁻¹, except for Mog26-6, which recorded the lowest NUE (37.90 kg kg⁻¹) at the same nitrogen rate.

The Location × Nitrogen rate × Variety interaction was significant (SED = 10.14, $p \leq 0.05$), indicating that the effect of nitrogen fertilizer on Nitrogen use efficiency differed among maize varieties and between locations. At Opeji, OBA SUPER 2 and SUWAN-1-SX recorded the highest values at 45 kg N ha⁻¹, while at Eruwa, Mog26-6 at 45 kg N ha⁻¹ and Mog26-9 at 30 kg N ha⁻¹ produced the highest values. The control treatments (0 kg N ha⁻¹) consistently recorded the lowest values at both locations.

Table 2. Interaction effects of nitrogen rates × maize variety × location on nitrogen use efficiency (NUE) of low-nitrogen tolerant maize.

Location	Nitrogen rate (kg N ha ⁻¹)	Mog26-6	Mog26-9	M1026-10	OBA 98	SUWAN-1-SX	OBA SUPER 2
Opeji							
	0	0.00g	0.00g	0.00g	0.00g	0.00g	0.00g
	15	51.00a-f	57.40a-f	37.40ef	25.40ef	36.30f	45.90b-f
	30	67.10ab	56.30a-f	61.70a-e	42.70b-f	41.70c-f	71.20a
	45	37.90d-f	63.80a-c	67.30ab	65.70a-c	73.30a	74.00a
Eruwa							
	0	0.00g	0.00g	0.00g	0.00g	0.00g	0.00g
	15	61.20a-e	54.90a-f	54.50a-f	52.20a-f	63.80a-c	63.80a-c
	30	56.60a-f	71.30a	56.50a-f	56.40a-f	66.80ab	65.50a-d

Location	Nitrogen rate (kg N ha ⁻¹)	Mog26- 6	Mog26- 9	M1026- 10	OBA 98	SUWAN-1- SX	OBA SUPER 2
	45	73.10a	56.60a-f	57.10a-f	58.60a-f	66.50a-c	43.00b-f
	SED (p ≤ 0.05)						10.14*

Interaction of Nitrogen Rate and Location on Physiological Efficiency

The interaction between nitrogen rate and location significantly influenced physiological efficiency (PE) ($p \leq 0.05$) (Table 3). At Eruwa, the application of 15 kg N ha⁻¹ resulted in the highest PE value (325 kg kg⁻¹), which was substantially greater than the corresponding value recorded at Opeji (132 kg kg⁻¹) at the same nitrogen rate.

This result suggests that moderate nitrogen application enhanced physiological nitrogen utilization more effectively under the environmental conditions at Eruwa than at Opeji.

Table 3. Interaction effects of nitrogen rates × location on physiological efficiency of low-nitrogen tolerant maize.

Location	0 kg N ha ⁻¹	15 kg N ha ⁻¹	30 kg N ha ⁻¹	45 kg N ha ⁻¹
Opeji	0.00d	132.00b-d	212.00a-c	89.00bc
Eruwa	0.00d	325.00a	157.00bc	246.00ab
SED (p ≤ 0.05)				69.80*

Internal Utilization Efficiency (IUE)

Nitrogen rate and variety had no significant effect ($p > 0.05$) on internal utilization efficiency (IUE) (Table 1). However, location exerted a highly significant effect ($p \leq 0.05$).

Opeji recorded a significantly higher IUE value (715 kg kg⁻¹) compared with Eruwa (188 kg kg⁻¹). This indicates that nitrogen conversion to grain yield per unit of plant nitrogen uptake differed markedly between locations.

Recovery Efficiency (RE)

The interaction between nitrogen rate and location significantly affected recovery efficiency (RE) ($p \leq 0.05$) (Table 4). At Eruwa, the application of 15 kg N ha⁻¹ produced the highest recovery efficiency (0.907), whereas the corresponding value at Opeji was substantially lower (0.110).

These findings demonstrate that nitrogen recovery by maize plants was more efficient at Eruwa, particularly at moderate nitrogen application rates.

Table 4. Interaction effects of nitrogen rates × location on recovery efficiency of low-nitrogen tolerant maize.

Location	0 kg N ha ⁻¹	15 kg N ha ⁻¹	30 kg N ha ⁻¹	45 kg N ha ⁻¹
Opeji	0.00c	0.110c	0.157c	0.036c

Location	0 kg N ha ⁻¹	15 kg N ha ⁻¹	30 kg N ha ⁻¹	45 kg N ha ⁻¹
Eruwa	0.00c	0.907a	0.624b	0.580b
SED (p ≤0.05)				0.1246 **

Discussion

Nitrogen use efficiency (NUE) and its component traits were significantly influenced by nitrogen rate, location, and their interactions, highlighting the complex nature of nitrogen dynamics in maize production systems. The significant effect of location on NUE, with higher values recorded at Eruwa than at Opeji, underscores the importance of environmental conditions in determining nitrogen availability and utilization. Environmental factors such as rainfall distribution, soil texture, organic matter content, and inherent soil fertility strongly influence nitrogen mineralization, mobility, and plant uptake (Halvorson & Wienhold, 2001). The superior NUE observed at Eruwa may therefore be attributed to more favorable soil and climatic conditions that enhanced nitrogen acquisition and assimilation.

Nitrogen rate significantly influenced NUE, with the highest value recorded at 45 kg N ha⁻¹. This suggests that increasing nitrogen supply up to a moderate threshold enhanced the conversion of applied nitrogen into grain yield. Similar findings have been reported in recent studies where moderate nitrogen rates improved nitrogen uptake and grain productivity in maize (Dawar et al., 2024). Long-term field experiments also indicate that optimizing nitrogen application enhances yield and NUE, while excessive nitrogen supply leads to reduced efficiency due to soil nitrogen accumulation and increased losses (Zhang et al., 2025). Furthermore, increasing nitrogen application beyond the optimal level often results in minimal yield improvement and declining NUE due to diminishing returns (Chen et al., 2022). These findings support the observation that moderate nitrogen application rates are critical for maximizing nitrogen use efficiency in maize production; Fageria & Baligar, 2005), the nitrogen rates used in this study were relatively low. Thus, the observed increase in NUE at 45 kg N ha⁻¹ likely reflects improved nitrogen availability without reaching levels that promote substantial losses through leaching or volatilization. Similar findings have been reported where moderate nitrogen application improved maize yield and nitrogen efficiency under low-input systems (Van Ginkel et al., 2001).

Nitrogen uptake efficiency (NUpE) was highest at 15 kg N ha⁻¹, indicating that lower nitrogen rates enhanced the plant’s ability to acquire available nitrogen. This agrees with the findings of Moll et al. (1982), who demonstrated that nitrogen uptake efficiency tends to be higher under limited nitrogen supply as plants increase root proliferation and nutrient scavenging capacity. The significantly higher NUpE observed at Eruwa further supports the influence of site-specific environmental conditions on nutrient acquisition. Soil moisture availability, in particular, plays a crucial role in facilitating nitrogen diffusion and mass flow toward plant roots (Halvorson & Wienhold, 2001).

Physiological efficiency (PE) was highest at 15 kg N ha⁻¹, suggesting that moderate nitrogen application enhanced the efficiency with which absorbed nitrogen was converted into grain yield. At higher nitrogen rates, PE declined, likely due to luxury consumption or inefficient

partitioning of nitrogen into economic yield. Similar trends have been reported by Fageria and Baligar (2005), who noted that physiological efficiency often decreases at higher nitrogen levels when plant uptake exceeds optimal metabolic requirements. The absence of significant varietal differences in PE indicates that the tested low-nitrogen tolerant genotypes exhibited comparable nitrogen utilization capacity under the conditions of this study.

The significant interaction among nitrogen rate, variety, and location for NUE indicates differential genotypic responses across environments. At Opeji, OBA SUPER 2 exhibited superior NUE at 45 kg N ha⁻¹, while at Eruwa, varieties such as Mog26-6 and SUWAN-1-SX performed optimally at the same nitrogen rate. This genotype × environment interaction aligns with previous findings that nitrogen use efficiency is strongly influenced by both genetic factors and environmental conditions (Van Ginkel et al., 2001). Eastin and Sullivan (1984) emphasized that plant traits associated with efficient nutrient uptake and utilization are heritable and can vary significantly across agro-ecological zones. The differential varietal performance observed in this study highlights the importance of location-specific variety recommendations.

The interaction between nitrogen rate and location on physiological efficiency further emphasizes the role of environmental conditions in nitrogen metabolism. At Eruwa, 15 kg N ha⁻¹ produced the highest PE, substantially exceeding the value recorded at Opeji. This suggests that moderate nitrogen supply under favorable environmental conditions optimizes nitrogen assimilation and remobilization to grain. Below et al. (2000) reported that nitrogen assimilation and kernel development are closely linked to environmental factors affecting carbon–nitrogen balance during reproductive stages.

Internal utilization efficiency (IUE) was significantly influenced by location but not by nitrogen rate or variety. The higher IUE recorded at Opeji indicates more efficient conversion of plant nitrogen into grain yield at that location. Differences in temperature regimes, radiation interception, or soil nutrient balance may have enhanced nitrogen remobilization efficiency at Opeji. According to Gooding and Davies (1997), environmental variability significantly affects grain formation and nutrient partitioning, thereby influencing nitrogen utilization efficiency.

Recovery efficiency (RE) was highest at Eruwa under 15 kg N ha⁻¹, demonstrating that moderate nitrogen application improved the proportion of applied nitrogen recovered in plant biomass. High recovery efficiency at lower nitrogen rates is consistent with findings by Moll et al. (1982), who reported that recovery efficiency typically declines at excessive nitrogen application due to increased losses. The substantial difference in RE between locations further confirms that nitrogen recovery is strongly influenced by environmental and soil factors.

Conclusion

This study demonstrated that nitrogen application rate significantly influenced nitrogen use efficiency and its component traits in low-nitrogen tolerant maize varieties. Application

of 45 kg N ha⁻¹ improved NUE and grain productivity across locations, while moderate nitrogen levels enhanced physiological and recovery efficiencies. Environmental conditions also played a major role in determining nitrogen uptake and utilization. These findings highlight the importance of optimizing nitrogen management and selecting efficient maize genotypes to improve productivity under low-input production systems.

Recommendations

- i. A nitrogen application rate of 45 kg N ha⁻¹ is recommended for improving overall nitrogen use efficiency (NUE) and grain productivity of low-nitrogen tolerant maize varieties under conditions similar to the study locations. This rate provided the highest NUE without evidence of excessive nitrogen losses associated with higher fertilizer applications.
- ii. For environments with soil and climatic conditions similar to **Eruwa**, a lower nitrogen rate of 15 kg N ha⁻¹ may be adopted where the objective is to maximize nitrogen uptake efficiency (NUpE), physiological efficiency (PE), and recovery efficiency (RE), particularly in low-input production systems where fertilizer availability is limited.
- iii. Variety selection should be location-specific because significant genotype × environment interactions were observed. OBA SUPER 2 is recommended for cultivation at Opeji, where it exhibited superior nitrogen use efficiency at 45 kg N ha⁻¹. At Eruwa, Mog26-6 and SUWAN-1-SX are recommended because of their superior performance under the same nitrogen rate.
- iv. Site-specific nitrogen management strategies should be promoted rather than adopting a uniform fertilizer recommendation across locations. The significant influence of environmental conditions on nitrogen use efficiency components indicates that fertilizer recommendations should consider soil characteristics, rainfall patterns, and local growing conditions.

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