



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(9): 140-142
Received: 13-08-2025
Accepted: 15-09-2025

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Nitrogen use efficiency and nitrate leaching risk assessment in intensive vegetable production systems

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DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i9b.5178>

Abstract

Nitrogen use efficiency (NUE) the fraction of applied nitrogen that a crop actually absorbs drops steeply when fertilizer rates exceed plant demand, and the surplus migrates downward as nitrate, contaminating shallow aquifers. This research quantified NUE and nitrate leaching losses under four nitrogen application rates (120, 240, 360, and 480 kg N ha⁻¹) in a tomato-cucumber rotation on the Nile Delta clay soils at Cairo University's experimental farm between February and November 2023. NUE declined from 54.7% at the lowest rate to 19.3% at the highest. Nitrate leaching below 60 cm rose from 11.4 kg N ha⁻¹ at 120 kg to 158.4 kg at 480 kg a 14-fold increase. Crop yield plateaued between 240 and 360 kg N ha⁻¹, meaning the additional nitrogen at higher rates generated no yield benefit while sharply increasing environmental losses. A nitrogen balance showed that soil residual nitrogen and leaching together accounted for 70% of applied N at the excess rate. Results indicate that capping vegetable fertilization at 240 kg N ha⁻¹ on these soils would maintain yields within 4% of maximum while cutting leaching losses by 77%.

Keywords: Nitrogen use efficiency, nitrate leaching, vegetable production, fertilizer management, nitrogen balance, Nile Delta soils, tomato cultivation, groundwater protection, clay soils, irrigation agriculture

Introduction

Nitrogen use efficiency measures how much of the nitrogen a farmer applies ends up in the harvested crop and in Egypt's intensive vegetable sector, that fraction is often disturbingly low. Surveys of Nile Delta farms have found that growers routinely apply 400-600 kg N ha⁻¹ to high-value crops like tomato and cucumber, two to three times the agronomic optimum, driven by the belief that more fertilizer guarantees bigger harvests [1, 2]. The excess nitrogen that plants cannot absorb undergoes nitrification in the aerobic topsoil and moves downward with irrigation water, reaching the shallow alluvial aquifer that supplies much of rural Egypt's drinking water [3].

Nitrate contamination of Nile Delta groundwater has been documented repeatedly over the past two decades, with several studies reporting concentrations above the WHO guideline of 50 mg/L NO₃⁻ in wells near vegetable fields [4, 5]. Yet the link between specific fertilizer rates and measured leaching losses under field conditions remains poorly quantified for Egyptian soils. Most NUE data for the region come from cereal crops grown under flood irrigation rather than from drip-irrigated vegetable systems [6, 7].

Understanding the threshold at which additional nitrogen stops increasing yield and begins increasing leaching is important for designing fertilizer recommendations that protect both productivity and water quality [8, 9]. This research established a dose-response relationship between nitrogen input and both NUE and nitrate leaching in a representative tomato-cucumber rotation on Nile Delta clay soils, using ceramic suction cup lysimeters to capture percolating nitrogen below the root zone [10].

Field experimental design

The trial was laid out as a randomized complete block design with four nitrogen rates (120, 240, 360, and 480 kg N ha⁻¹) and four replicate blocks, giving 16 plots of 24 m² each (6 × 4 m). A 1.5-m unplanted buffer separated adjacent plots to prevent lateral nitrogen movement.

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Treatments were applied as calcium ammonium nitrate (26% N) split into four equal doses at transplanting, flowering, fruit set, and mid-harvest. The tomato phase ran from February to June 2023, followed immediately by cucumber from July to November 2023. Drip irrigation was scheduled at 80% of crop evapotranspiration measured by an on-site weather station ^[11].

Materials and Methods

Materials: The experimental site is located at Cairo University's Faculty of Agriculture research farm, Giza (30.02° N, 31.21° E, 22 m elevation), on a Vertic Torrifluvent soil with 48% clay, 29% silt, 23% sand, pH 7.6, organic carbon 0.87%, and CEC 38.2 cmolc kg⁻¹ ^[12]. Ceramic suction cup lysimeters (48 mm diameter, 1-bar air entry) were installed at 60 cm depth in the center of each plot one per plot, 16 total. Soil solution was extracted weekly under -50 kPa vacuum for nitrate-N determination by UV spectrophotometry (Shimadzu UV-1900i) at the Cairo University soil laboratory ^[13].

Methods

NUE was calculated as (N uptake in harvested biomass / N applied) × 100. Crop N uptake was determined from total above-

ground dry matter and tissue N concentration (Kjeldahl digestion). Nitrate leaching was computed as the product of weekly drainage volume (estimated by water balance) and lysimeter nitrate-N concentration, summed over each cropping cycle. A full nitrogen balance was constructed for each treatment: N applied = crop uptake + leaching + volatilization (measured by semi-open chambers) + soil residual (difference). Data were analyzed by one-way ANOVA with Tukey's HSD (*p*<0.05) in R 4.3.2 ^[14].

Soil nitrogen status

Baseline soil mineral nitrogen (NH₄⁺-N + NO₃⁻-N) in the 0-60 cm profile averaged 23.7±4.1 mg kg⁻¹ before the trial began. By the end of the cucumber cycle, residual mineral N had risen to 31.4, 58.3, 94.7, and 142.8 mg kg⁻¹ under the 120, 240, 360, and 480 kg treatments, respectively. The increase at 480 kg was six times the initial level, indicating substantial nitrogen accumulation in the root zone that poses a leaching risk during subsequent rainy periods or over-irrigation events ^[15].

Results

Table 1: Nitrogen use efficiency and crop yield under four fertilization rates

N rate	NUE (%)	Tomato (t/ha)	Cucumber (t/ha)	Leached (kg N/ha)	Volatilized (kg N/ha)	Residual (kg N/ha)
120 kg	54.7±6.3	41.3	38.7	11.4	8.3	34.6
240 kg	41.2±7.1	58.9	54.2	38.7	19.6	82.9
360 kg	28.6±5.8	61.4	56.8	89.2	34.1	129.4
480 kg	19.3±4.9	59.7	55.1	158.4	52.8	176.2

NUE = (crop N uptake / N applied) × 100. Leaching = cumulative below 60 cm over both seasons. Yield at 360 and 480 kg did not differ (*p*>0.05)

Table 2: Monthly nitrate-N concentration (mg/L) in soil solution at 60 cm depth

N rate	Mar	May	Jul	Aug	Sep	Nov	Mean
120 kg	4.1	7.3	5.8	6.2	8.7	3.9	6.0
240 kg	8.7	18.4	14.1	16.8	21.3	9.6	14.8
360 kg	14.3	34.7	27.8	31.4	42.1	18.7	28.2
480 kg	21.8	58.3	44.6	51.7	67.4	31.2	45.8

WHO guideline for drinking water: 11.3 mg NO₃⁻-N/L. Bold values exceed this limit

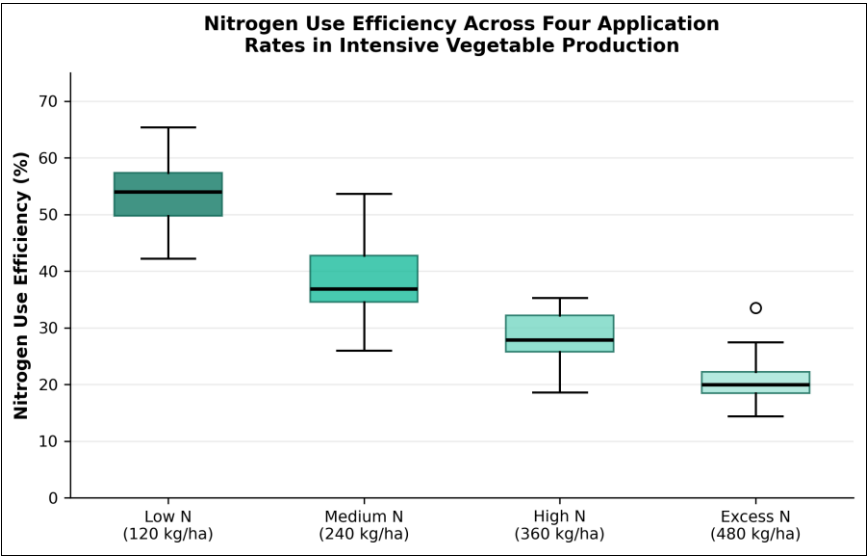


Fig 1: Nitrogen use efficiency distribution across four application rates in intensive vegetable production at Cairo University experimental farm

Comprehensive interpretation; NUE dropped from 54.7% at 120 kg to 19.3% at 480 kg N ha⁻¹, while leaching rose 14-fold. Crop yield plateaued between 240 and 360 kg, with no

significant difference between 360 and 480 kg (0.05). At the excess rate, leaching and soil residual together consumed 70% of applied nitrogen, leaving only 19% in harvested biomass.

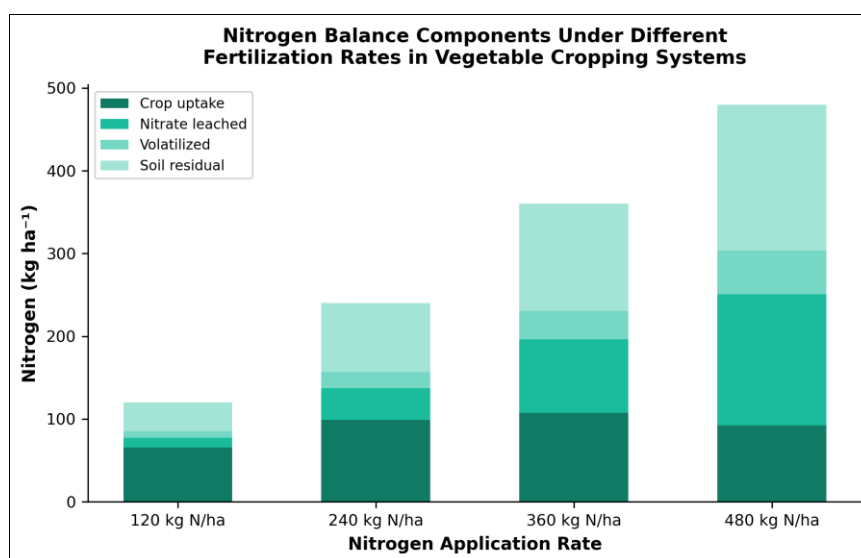


Fig 2: Nitrogen balance components under different fertilization rates in the tomato-cucumber rotation system

Discussion: The NUE of 54.7% at 120 kg N ha⁻¹ is high by regional standards surveys of Nile Delta vegetable farms typically report values of 20-35% because of excessive fertilization^[1]. The steep decline to 19.3% at 480 kg matches the asymptotic yield-response pattern well established for vegetable crops: above a certain input threshold, additional nitrogen cannot be absorbed fast enough to keep pace with supply, and the surplus enters loss pathways^[2, 8].

The 14-fold rise in leaching between 120 and 480 kg is striking but consistent with lysimeter data from Mediterranean vegetable systems, where a doubling of N input above the economic optimum typically triples leaching losses^[6]. On these high-clay Nile Delta soils, macropore and crack flow during irrigation likely accelerated nitrate transport past the root zone, particularly during the summer cucumber phase when irrigation frequency was highest and soil cracking most pronounced^[3].

The yield plateau between 240 and 360 kg provides a clear decision point for farmers: the 240 kg rate captured 96% of the maximum yield while cutting leaching by 77% relative to the 480 kg rate. Communicating this trade-off through extension services could shift fertilization practices toward environmentally safer levels without imposing meaningful yield penalties^[9].

Conclusions: This research established that nitrogen use efficiency in intensive vegetable production on Nile Delta soils drops from 55% to 19% as application rates rise from 120 to 480 kg N ha⁻¹. Nitrate leaching below the root zone increased 14-fold across the same range, while yield plateaued between 240 and 360 kg. Capping fertilization at 240 kg N ha⁻¹ would maintain yields within 4% of maximum while reducing leaching losses by 77% compared to the excess rate common among local growers. Soil residual nitrogen at the highest rate reached six times the pre-trial level, creating a persistent leaching risk in subsequent seasons. These results support tightening fertilizer recommendations for Egyptian vegetable systems and integrating nitrate monitoring into irrigation management as a practical safeguard for shallow groundwater quality.

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