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Effects of nitrogen application on potato (*Solanum tuberosum* L.) yield and soil nitrate dynamics in a sandy loam soil

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Abstract

Nitrogen (N) is a crucial nutrient for potato (Solanum tuberosum L.) production, but excessive application can lead to environmental degradation and reduced nitrogen use efficiency (NUE). This study evaluated the effects of different nitrogen application rates (0, 60, 120, 150, 180, 210, and 240 kg N/ha) on tuber yield, nitrogen uptake, and soil nitrate accumulation over two growing seasons. The results showed that the highest tuber yield (20.8 t/ha) was obtained at 150 kg N/ha, beyond which further increases in nitrogen application did not result in significant yield improvements ($P<0.05$). Nitrogen uptake increased with application rates but reached a saturation point beyond 150 kg N/ha, leading to declining NUE. Soil nitrate levels significantly increased at higher N rates, particularly in deeper soil layers (40–60 cm), posing a potential risk of nitrate leaching. Apparent nitrogen balance calculations indicated substantial nitrogen surpluses at rates above 180 kg N/ha, further emphasizing the risk of nitrogen losses to the environment. These findings suggest that applying nitrogen at 150 kg/ha optimizes potato yield while minimizing environmental risks. Precision nitrogen management strategies, including split applications and slow-release fertilizers, should be adopted to enhance NUE and reduce nitrate leaching. Further long-term studies are needed to refine nitrogen recommendations under varying soil and climatic conditions to ensure sustainable potato production.

Keywords: Nitrogen fertilization, Tuber yield, Soil nitrogen dynamics, NUE, Sandy loam soil, Fertilizer management.

Introduction

Potato (*Solanum tuberosum* L.) is one of the most widely cultivated and consumed crops worldwide, playing a crucial role in global food security and economic development. It is ranked as the fourth most important staple crop after wheat, rice, and maize, with its adaptability to diverse agro-ecological zones and high nutritional value contributing to its global significance (Birch et al., 2012; Kloosterman et al., 2013; Drewnowski and Rehm, 2013; Tokbergenova et al., 2017; Alimkhanov et al., 2021; Liu et al., 2021; Budanov, et al., 2023; Adilbayeva et al., 2024). However, achieving sustainable potato production is increasingly challenged by soil fertility constraints and inefficient nutrient management, particularly for nitrogen (N), a critical macronutrient for plant growth (Davenport et al., 2005; Koch et al., 2020).

Nitrogen is essential for the physiological and biochemical processes in potatoes, including photosynthesis, enzymatic activity, and protein synthesis (Ye at al., 2022). Optimal nitrogen management not only enhances tuber yield but also improves quality parameters such as starch content and dry matter (Sawicka et al., 2018; 2020). Conversely, suboptimal nitrogen application—whether excessive or insufficient—can lead to

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various agronomic and environmental challenges. Over-application of nitrogen often results in nitrate (NO_3-N) leaching, leading to groundwater contamination, greenhouse gas emissions, and soil acidification (Anas et al., 2010). On the other hand, nitrogen deficiency limits tuber growth and reduces marketable yield, affecting economic returns for farmers (Wilkinson et al., 2020).

Recent studies have underscored the importance of precise nitrogen management in potato cultivation. Solano et al. (2018) and Sawicka et al. (2020) highlighted that the apparent nitrogen balance—the difference between nitrogen inputs and crop uptake—is a critical metric for assessing nitrogen use efficiency (NUE). Positive nitrogen balances, indicative of excessive nitrogen application, are strongly associated with nitrate accumulation in the soil profile and increased risks of leaching (Bibi et al., 2016, Awaad and Deshesh, 2019). Moreover, the spatial distribution of nitrate within the soil profile is influenced by nitrogen application rates, soil type, and irrigation practices, necessitating site-specific management strategies to optimize nitrogen use (Barraclough et al., 1992; Bellido et al., 2013).

The relationship between nitrogen rates and potato yield is well-documented, with numerous studies demonstrating that yields increase with nitrogen application up to a certain threshold, beyond which no further benefits are observed (Tadesse et al., 2001; Jiao et al., 2013; Wang et al., 2020). Excess nitrogen often promotes excessive vegetative growth at the expense of tuber development, reducing NUE and leading to economic inefficiencies. This phenomenon underscores the need for determining optimal nitrogen rates that balance yield maximization with environmental sustainability.

In addition to yield optimization, nitrogen management has significant implications for soil health and environmental quality. Excess nitrate accumulation in the soil, particularly in deeper layers, increases the potential for leaching into groundwater, posing risks to water quality and human health (Wang et al., 2015; Bijay-Singh and Craswell, 2021). Furthermore, inefficient nitrogen use contributes to nitrous oxide (N_2O) emissions, a potent greenhouse gas that exacerbates climate change. Sustainable nitrogen management practices, including the use of slow-release fertilizers and nitrification inhibitors, have been proposed as potential solutions to enhance NUE and mitigate environmental risks (Millar et al., 2010; Liu et al., 2021).

This study aims to investigate the effects of different nitrogen application rates on potato tuber yield, nitrogen uptake, and soil nitrate dynamics under controlled field conditions. Specifically, the objectives are to: (i) Quantify the effects of nitrogen rates on tuber yield and nitrogen uptake, (ii) evaluate the apparent nitrogen balance and its relationship with soil nitrate stocks, and (iii) assess the distribution of nitrate nitrogen within the soil profile at varying nitrogen application rates.

Material and Methods

Study Site and Environmental Conditions

The field experiments were conducted over two consecutive growing seasons (2022 and 2023) at a research station with sandy loam soils (56% sand, 18% clay, and 26% silt), characterized by low organic matter content (1.2%), a neutral pH (7.12), non-saline conditions (electrical conductivity of 0.76 dS m^{-1}), and the absence of carbonate (3.65% $CaCO_3$). The total nitrogen and nitrate nitrogen contents were 0.138% and 13.25 mg kg^{-1}, respectively. According to the Köppen-Geiger classification, the climate of the experimental site is classified as Cfa (humid subtropical), with an average annual temperature of 13.1°C and an average annual precipitation of 936 mm.

Experimental Design

A randomized complete block design (RCBD) was employed to assess the effects of different nitrogen application rates on potato yield and soil nitrate dynamics. The experiment consisted of seven nitrogen treatments, each replicated three times. Individual plots measured 30 m^2 (5 m × 6 m) and were separated by buffer zones to minimize cross-contamination between treatments. The nitrogen treatments were as follows:

- N_0: 0 kg N ha^{-1} (control)
- N_{60}: 60 kg N ha^{-1}
- N_{120}: 120 kg N ha^{-1}
- N_{150}: 150 kg N ha^{-1}
- N_{180}: 180 kg N ha^{-1}
- N_{210}: 210 kg N ha^{-1}
- N_{240}: 240 kg N ha^{-1}

Nitrogen was applied in the form of urea (46% N), a widely used and cost-effective nitrogen source. To ensure that nitrogen was the only limiting factor, phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied uniformly across all treatments at 65 kg ha^{-1} and 115 kg ha^{-1}, respectively. The phosphorus source was calcium magnesium phosphate, while potassium chloride (KCl) was used as the potassium source.

Fertilizer Application

Nitrogen was applied in three split doses to align with key physiological stages of potato growth, enhancing nitrogen use efficiency (NUE) while minimizing losses due to leaching and volatilization. Before planting, 40% of the total nitrogen dose was incorporated into the topsoil (0–20 cm) along with the full phosphorus (P_2O_5) and potassium (K_2O) applications. At the vegetative growth stage (35 days after planting, DAP), an additional 30% of nitrogen was surface-applied to support shoot and foliage development. The remaining 30% was applied at the flowering stage (60 DAP) to promote tuber bulking and maximize final yield. This split application strategy ensured optimal nitrogen availability throughout the growing season, facilitating balanced nutrient uptake while mitigating the risk of nitrate leaching.

Crop Management

Certified mid-season potato seed tubers were planted using a ridge cultivation system. The ridges were 35 cm in height and spaced 60 cm apart, facilitating proper aeration, root development, and water drainage. The planting density was set at 4.200 plants ha^{-1} to maintain uniform growth and maximize yield potential. Standard agronomic practices, including pest and disease management, were employed throughout the growing season. Drip irrigation was used to maintain soil moisture at approximately 80% of field capacity, ensuring optimal water availability for tuber formation while minimizing water loss through deep percolation.

Soil and Plant Sampling

To evaluate soil nitrogen dynamics and crop response, soil and plant sampling was systematically conducted at critical growth stages. Soil samples were collected from three depth intervals (0–20 cm, 20–40 cm, and 40–60 cm) at planting, mid-season (vegetative stage), and harvest to monitor temporal variations in nitrate availability. Bulk density measurements were taken to facilitate the calculation of soil nitrate stocks. Additionally, soil samples were extracted using 2M KCl and analyzed for nitrate nitrogen (NO_3-N) using the Kjeldahl distillation method (Jones, 2001).

At harvest, plant biomass was separated into tubers and straw to assess yield and nutrient uptake. Tuber yield was determined by weighing the harvested tubers from each plot. Straw samples were initially dried at 105°C for 2 hours, followed by further drying at 85°C until a constant weight was achieved. The dried plant material was then ground using a micro-plant grinding machine and passed through a 0.5-mm mesh sieve for subsequent chemical analysis (Jones, 2001).

Measurements and Calculations

Tuber yield was determined by measuring both marketable (>30 mm diameter) and unmarketable tubers, with marketable yield expressed in tons per hectare (t ha^{-1}). To evaluate nitrogen uptake, the micro-Kjeldahl method was used to analyze nitrogen content in both tubers and straw. Apparent nitrogen uptake (N_{uptake}) was calculated using the equation 1:

$$N_{uptake} = N_{tuber} \times Y_{tuber} + N_{straw} \times Y_{straw} \times 0.001 \quad (1)$$

where N_{tuber} and N_{straw} represent the nitrogen content (g kg^{-1}) in tubers and straw, respectively, and Y_{tuber} and Y_{straw} correspond to the biomass yields (kg ha^{-1}) of these plant components.

Soil nitrate stocks were estimated to assess nitrogen dynamics in the soil. The nitrate nitrogen stock (NNS) was calculated using the equation 2:

$$NNS = NNC \times BD \times D \times 10 \quad (2)$$

where NNC represents the nitrate nitrogen content (mg kg^{-1}), BDB is the soil bulk density (g cm^{-3}), and DDD is the soil depth (cm). The total nitrate stock in the 0–60 cm soil profile was determined by summing the stocks at three depth intervals (0–20 cm, 20–40 cm, and 40–60 cm).

To evaluate nitrogen balance within the system, the apparent nitrogen balance ($N_{balance}$) was calculated as the difference between nitrogen input from fertilizers (N_{input}) and nitrogen uptake by the crop (N_{uptake}), following the equation 3:

$$N_{balance} = N_{input} - N_{uptake} \quad (3)$$

where $N_{balance}$ represents the nitrogen balance (kg ha^{-1}), N_{input} is the total nitrogen applied as fertilizer (kg ha^{-1}), and N_{uptake} is the total nitrogen absorbed by the plant. These calculations provided a comprehensive understanding of nitrogen efficiency, soil nitrate retention, and the potential for nitrogen losses in the experimental system.

Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) to assess the effects of nitrogen treatments on tuber yield, nitrogen uptake, and soil nitrate stocks. Mean comparisons were performed using the least significant difference (LSD) test at a 5% significance level. Regression analysis was conducted to evaluate relationships between nitrogen application rates, apparent nitrogen balance, and soil nitrate dynamics.

Results and Discussion

Tuber yield response to nitrogen application

Nitrogen application significantly affected potato tuber yield across both growing seasons (Table 1). The lowest yield was observed in the control (N0) treatment, averaging 12.4 t ha^{-1} across both years. Yield increased significantly ($P<0.05$) with nitrogen rates up to 150 kg ha^{-1}, reaching a maximum of 20.8 t ha^{-1}. However, further increases in nitrogen application beyond this threshold did not result in significant yield improvements.

Table 1. Effect of nitrogen rates on tuber yield (t/ha) with standard deviations and statistical groupings.

Nitrogen Rate (kg/ha)	2022 Yield (t/ha)	2023 Yield (t/ha)	Mean Yield (t/ha)
N_0	12.1 ± 0.5 c	12.6 ± 0.4 c	12.4 ± 0.45 c
N_{60}	15.8 ± 0.6 b	16.3 ± 0.7 b	16.1 ± 0.65 b
N_{120}	19.2 ± 0.8 ab	19.8 ± 0.9 a	19.5 ± 0.85 a
N_{150}	20.4 ± 0.7 a	21.2 ± 0.8 a	20.8 ± 0.75 a
N_{180}	20.3 ± 0.7 a	21.0 ± 0.8 a	20.7 ± 0.75 a
N_{210}	19.9 ± 0.6 a	20.4 ± 0.7 a	20.2 ± 0.65 a
N_{240}	19.5 ± 0.6 a	20.0 ± 0.7 a	19.8 ± 0.65 a

Comparing the two years, yields were slightly higher in 2023 across all nitrogen treatments. For instance, the N_{150} treatment resulted in yields of 20.4 t ha^{-1} in 2022 and 21.2 t ha^{-1} in 2023. This slight variation may be attributed to differences in climatic conditions, particularly temperature and rainfall distribution, which influence nitrogen availability and uptake. Statistical analysis (LSD test, $P<0.05$) revealed significant differences among treatments. While nitrogen application up to 150 kg/ha led to statistically higher yields than the control, increasing nitrogen rates to 210 or 240 kg ha^{-1} did not result in further significant gains. Excess nitrogen at these levels likely promoted vegetative growth at the expense of tuber formation, a phenomenon commonly observed in potato cultivation under high nitrogen supply (Koch et al., 2020). Furthermore, when comparing treatments against one another, the yield at N_{180} (20.7 t ha^{-1}) was statistically similar to N_{150}, indicating no additional benefit from increasing nitrogen beyond 150 kg ha^{-1}. These results suggest that excessive nitrogen input does not translate into higher yield but may instead contribute to inefficiencies in nitrogen use.

The results of this study align with previous findings that demonstrate a diminishing return in yield response at high nitrogen application rates (Sawicka et al., 2018; Wang et al., 2020; Liu et al., 2021). The increase in yield with nitrogen application up to 150 kg/ha highlights the importance of adequate nitrogen availability for optimizing tuber formation. However, beyond this level, the lack of further yield increases suggests that the crop reaches a physiological limit where additional nitrogen does not enhance productivity.

From an agronomic perspective, these findings emphasize the need for optimizing nitrogen fertilization to balance productivity and environmental sustainability. Excessive nitrogen application not only leads to economic inefficiencies but also poses environmental risks such as nitrate leaching and increased greenhouse gas emissions (Wick et al., 2012; Bijay-Singh and Craswell, 2021). Therefore, precision nitrogen management strategies, such as split applications and the use of slow-release fertilizers, should be considered to maximize nitrogen use efficiency (NUE) while minimizing environmental impact.

In addition, inter-annual variations in yield response underscore the role of climatic conditions in nitrogen dynamics. Slightly higher yields in 2023 suggest that favorable weather conditions may have enhanced nitrogen uptake and utilization. Future research should consider long-term trials incorporating different climatic scenarios to develop more robust nitrogen management recommendations. Overall, the results support the recommendation of 150 kg ha^{-1} as the optimal nitrogen application rate for maximizing potato tuber yield in sandy loam soils while ensuring economic and environmental sustainability.

Nitrogen uptake and its efficiency across different application rates

Nitrogen uptake by potato plants exhibited a strong positive response to increasing nitrogen application rates across both years (Table 2). The lowest nitrogen uptake was recorded in the control (N_0) treatment, averaging 47.2 kg ha^{-1} across the two growing seasons. Uptake increased significantly ($P<0.05$) with nitrogen application up to 240 kg ha^{-1}, reaching a maximum value of 118.2 kg ha^{-1}. However, despite higher uptake at elevated nitrogen levels, nitrogen use efficiency (NUE) declined significantly beyond 150 kg ha^{-1}.

Table 2. Effect of nitrogen rates on nitrogen uptake (kg ha^{-1}) with standard deviations and statistical groupings

Nitrogen Rate (kg ha^{-1})	2022 Uptake (kg ha^{-1})	2023 Uptake (kg ha^{-1})	Mean Uptake (kg ha^{-1})
N_0	46.2 ± 3.2 d	48.1 ± 3.1 d	47.2 ± 3.15 d
N_{60}	78.5 ± 4.1 c	80.2 ± 4.2 c	79.4 ± 4.15 c
N_{120}	101.7 ± 5.2 b	103.5 ± 5.3 b	102.6 ± 5.25 b
N_{150}	118.3 ± 5.6 a	120.2 ± 5.8 a	119.2 ± 5.70 a
N_{180}	119.6 ± 5.7 a	121.4 ± 5.6 a	120.5 ± 5.65 a
N_{210}	118.9 ± 5.5 a	120.1 ± 5.4 a	119.5 ± 5.45 a
N_{240}	117.8 ± 5.3 a	118.5 ± 5.2 a	118.2 ± 5.25 a

Yearly comparisons indicate that nitrogen uptake was slightly higher in 2023 than in 2022 across all treatments. For instance, in the N_{150} treatment, uptake values were recorded as 118.3 kg ha^{-1} in 2022 and 120.2 kg ha^{-1} in 2023. This variation could be attributed to differences in soil moisture and mineralization rates, which affect nitrogen availability.

Statistical analysis (LSD test, $P<0.05$) showed significant differences among nitrogen treatments, particularly between low (N_0 and N_{60}) and high (N_{150}–N_{240}) nitrogen applications. However, uptake at N_{180}, N_{210}, and N_{240} was statistically similar, indicating that plants reached a nitrogen saturation threshold beyond which additional nitrogen did not significantly improve uptake efficiency. This is consistent with findings from Khangura et al. (2023), who observed that excessive nitrogen applications often lead to diminishing returns in nitrogen uptake.

While nitrogen uptake continued to increase with higher nitrogen rates, NUE decreased beyond 150 kg ha^{-1}, suggesting that plants were unable to fully utilize excess nitrogen. This highlights the importance of optimizing nitrogen inputs to maximize uptake efficiency while avoiding potential nitrogen losses through leaching or volatilization.

The results demonstrate that nitrogen uptake efficiency plays a critical role in determining the effectiveness of nitrogen fertilization strategies. While uptake increased with nitrogen rates, the declining NUE beyond 150 kg ha^{-1} suggests that excess nitrogen may not contribute to higher yield or efficiency, but rather lead to increased environmental losses. This is in agreement with previous studies highlighting the risks of excessive nitrogen fertilization (Wick et al., 2012; Bijay-Singh and Craswell, 2021).

From an agronomic perspective, applying nitrogen at rates beyond 150 kg ha^{-1} may not be economically viable due to diminishing uptake efficiency. Instead, targeted nitrogen management practices, such as split applications and the use of controlled-release fertilizers, could enhance NUE and minimize nitrogen losses. Additionally, integrating precision agriculture techniques, such as real-time nitrogen monitoring, could further improve nitrogen uptake efficiency. Inter-annual variations in nitrogen uptake emphasize the need for flexible fertilization strategies that account for climatic variability. Future research should focus on understanding the interactions between nitrogen application rates, soil properties, and weather conditions to develop site-specific fertilization recommendations. Overall, these findings highlight the necessity of balancing nitrogen inputs with plant uptake capacity to improve nitrogen use efficiency, optimize crop performance, and minimize environmental risks.

Soil nitrate accumulation and nitrogen balance under different application rates

Soil nitrate nitrogen accumulation exhibited a strong positive correlation with increasing nitrogen application rates (Table 3). The control (N_0) treatment had the lowest total nitrate stock, averaging 25.8 kg ha^{-1} in 2022 and 27.0 kg ha^{-1} in 2023. In contrast, the highest nitrogen treatment (N_{240}) resulted in significantly higher nitrate accumulation, exceeding 215 kg ha^{-1} in 2022 and 220 kg ha^{-1} in 2023.

Yearly comparisons indicate that soil nitrate levels were generally higher in 2023, likely due to increased soil moisture conditions facilitating nitrate retention. The LSD test ($P<0.05$) confirmed significant differences among treatments, particularly in deeper soil layers (40–60 cm), where nitrate accumulation increased at higher nitrogen rates.

At nitrogen application rates above 180 kg ha^{-1}, apparent nitrogen balance calculations revealed a substantial surplus of over 100 kg ha^{-1}, suggesting a high potential for nitrate leaching. This finding raises environmental concerns, as excessive nitrogen applications can contribute to groundwater contamination (Salo and Turtola, 2006). Therefore, optimizing nitrogen application rates is crucial for reducing the risks associated with nitrate leaching while maintaining high potato yields. These results underscore the necessity of adopting precision nitrogen management strategies, including split applications and controlled-release fertilizers, to mitigate nitrogen losses and enhance environmental sustainability.

Table 3. Soil nitrate stocks (kg ha^{-1}) at harvest with standard deviations and statistical groupings.

Year	Nitrogen Rate (kg ha^{-1})	mg NO_3-N kg^{-1} 0–20 cm	20–40 cm	40–60 cm	Total Nitrate Stock kg NO_3-N ha^{-1}
2022	N_0	12.4 ± 1.2 g	8.3 ± 1.1 g	5.1 ± 0.9 g	25.8 ± 1.5 g
	N_{60}	28.1 ± 2.5 f	17.6 ± 2.1 f	10.4 ± 1.7 f	56.1 ± 3.0 f
	N_{120}	47.3 ± 3.8 e	30.2 ± 3.2 e	19.7 ± 2.8 e	97.2 ± 4.5 e
	N_{150}	56.2 ± 4.0 d	37.9 ± 3.9 d	24.5 ± 3.2 d	118.6 ± 5.0 d
	N_{180}	68.3 ± 4.3 c	45.7 ± 4.2 c	30.1 ± 3.7 c	144.1 ± 5.3 c
	N_{210}	89.1 ± 4.7 b	59.4 ± 4.5 b	37.2 ± 4.0 b	185.7 ± 5.7 b
	N_{240}	102.4 ± 5.1 a	68.3 ± 4.8 a	45.1 ± 4.5 a	215.8 ± 6.0 a
2023	N_0	13.2 ± 1.3 d	9.5 ± 1.8 f	4.3 ± 0.8 e	27.0 ± 1.6 g
	N_{60}	29.0 ± 2.4 c	18.7 ± 2.3 e	10.3 ± 0.9 d	58.0 ± 3.1 f
	N_{120}	48.5 ± 3.9 b	32.5 ± 2.9 d	19.0 ± 1.9 c	100.0 ± 4.6 e
	N_{150}	57.0 ± 4.1 a	49.4 ± 4.2 c	13.6 ± 1.2 d	120.0 ± 5.1 d
	N_{180}	69.5 ± 4.4 a	61.4 ± 4.4 bc	17.1 ± 2.5 c	148.0 ± 5.4 c
	N_{210}	90.0 ± 4.8 a	65.8 ± 4.9 b	34.2 ± 3.2 b	190.0 ± 5.8 b
	N_{240}	104.0 ± 5.2 a	71.2 ± 5.6 a	44.8 ± 3.9 a	220.0 ± 6.1 a

Optimizing Nitrogen Management for Sustainable Potato Production

The findings of this study emphasize the importance of nitrogen management strategies that balance yield maximization with environmental sustainability. Applying nitrogen at 150 kg ha^{-1} was found to be the most effective rate for achieving high potato yields while minimizing the risks of nitrogen losses and nitrate accumulation in the soil.

Precision nitrogen management, including split applications and the use of slow-release fertilizers, should be considered to enhance nitrogen use efficiency (NUE). Additionally, incorporating real-time nitrogen monitoring techniques can help adjust fertilization rates according to plant demand, reducing excessive nitrogen application and environmental risks.

Future research should explore the integration of alternative nitrogen sources, such as nitrification inhibitors and organic amendments, to improve nitrogen retention in the soil while maintaining crop productivity. Moreover, long-term field studies under varying climatic conditions will be valuable for refining nitrogen management recommendations. Overall, this study underscores the necessity of a balanced nitrogen application approach to ensure sustainable potato production while mitigating environmental impacts. Policymakers and farmers should work together to implement best management practices that optimize nitrogen use, reduce nutrient losses, and promote agricultural sustainability.

Conclusion

This study provides valuable insights into the effects of nitrogen application rates on potato yield, nitrogen uptake, and soil nitrate accumulation. The results demonstrate that applying nitrogen at 150 kg ha^{-1} optimizes tuber yield while preventing excessive nitrogen surpluses. Although higher nitrogen rates (above 180 kg ha^{-1}) enhanced nitrogen uptake, the efficiency of nitrogen use declined, and nitrate accumulation in deeper soil layers increased significantly. The substantial nitrogen surpluses at excessive application rates raise concerns regarding nitrate leaching, which could pose environmental risks, especially in irrigated farming systems. These findings emphasize the need for efficient nitrogen management to sustain both crop productivity and environmental health.

Balancing nitrogen application rates is crucial for ensuring sustainable potato production. The implementation of split nitrogen applications and slow-release fertilizers can improve nitrogen use efficiency and reduce nitrogen losses. Moreover, integrating advanced fertilization techniques, such as nitrification inhibitors and organic amendments, can further enhance nitrogen retention and limit environmental risks. Long-term field experiments under varying soil types and climatic conditions are necessary to develop site-specific nitrogen management strategies. A holistic approach that incorporates precision nitrogen application, real-time monitoring, and sustainable soil fertility practices will be essential to achieving both high agricultural yields and environmental sustainability in potato farming.

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