Influence of Applied Nitrogen on Soil Water, Soil Nitrate (NO$_3$-) Concentration and Crop Yields in a Potato Field in the Saïs Plain

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Abstract

Nitrate (NO$_3^-$) leaching is a growing global environmental concern, particularly in intensively cultivated regions. The Saïss Plain, a major agricultural area in Morocco, has experienced increased nonpoint-source pollution due to excessive nitrogen (N) fertilizer use. A field experiment was conducted at the Douyet experimental station to assess the short-term effects of different N application rates on soil water content (SWC), soil nitrate

(NO_3–N) dynamics, and potato (*Solanum tuberosum* L.) tuber yield within the 0–100 cm soil profile under irrigated conditions during the 2021 and 2022 growing seasons. The experiment was arranged in a randomized complete block design with three replications and six N fertilizer rates (0, 90, 135, 180, 225, and 275 kg N ha^{-1}). Soil samples were collected from five depth intervals (0–20, 20–40, 40–60, 60–80, and 80–100 cm). Nitrogen rates did not significantly affect SWC at any soil depth in either season. However, soil water dynamics were strongly influenced by irrigation, particularly in the 0–20 cm layer, where SWC decreased before irrigation and increased significantly afterward. In 2021, only slight temporal variations in soil NO_3–N concentrations were observed among N treatments. In contrast, in 2022, NO_3–N distribution across the 0–100 cm profile showed notable month-to-month variability, with higher nitrate levels occurring at specific crop growth stages depending on N rates. Nitrogen application rates significantly influenced potato tuber yield. These results suggest that optimizing N supply to match crop demand, adopting split N applications, and improving irrigation management (e.g., drip irrigation and uniform water distribution) can enhance potato productivity while reducing nitrate accumulation and potential leaching risks.

Keywords: Soil nitrate dynamics; Soil water contents; Sais plain; Nitrogen fertilization; Onion; Morocco

Introduction

Nitrogen (N) fertilization is essential for optimizing potato (Solanum tuberosum L.) yield and quality ((Giroux M. , 1982); (Westermann & Kleinkopf, 1985); (Lauer , 1986); (Ojala, Stark, & Kleinkopf, 1990); (Zebarth & Rosen , 2007)). However, environmental losses of N can occur as NO3 leaching (Davenport, Milburn, Rosen, & Thornton, 2005). Clear evidence of NO3- leaching under intensive potato production systems has been reported ((Milburn, et al., 1990); (Giroux I. , 1995). Such leaching to groundwater has important environmental and human health implications (Keeney & Hatfield, 2001). Consequently, N management poses a challenge to potato producers. The recovery of applied fertilizer N by the potato crop is generally low (Zvomuya, Rosen, Russelle, & Gupta, 2003). Recovery of applied mineral fertilizer N in potato tubers is commonly estimated at around 45% (Tran & Giroux, 1991). This low efficiency has been attributed to the limited and shallow root system of the crop (STALHAM & ALLEN, 2001). In addition, the potato crop is commonly grown on sandy soils and, consequently, the susceptibility to NO3 leaching is increased.

Nitrate leaching is the primary mechanism for N loss in potato production (Zebarth & Rosen , 2007) and will vary according to soil type, climatic conditions and fertilizer N management. Estimates of NO3 leaching from different potato production regions ranged from 10 to 200 kg N/ ha ((Meisinger, 1976); (Saffigna & Keeney, 1977); (Hill, 1986); (Milburn, et al., 1990); (Jensen, Sloth, Risgaard-Petersen, Rysgaard, & Revsbech, 1994); (Errebhi, Rosen, & Birong, 1998). The effectiveness of N fertilizer management is governed by several factors, such as the type and form of fertilizer, its placement, rate and timing of application, along with prevailing soil and environmental conditions (Alva, 2004); (Zebarth & Rosen , 2007). Optimized nitrogen fertilizer management contributes to minimizing nitrate (NO_3^-) leaching during the cropping season and reducing residual soil nitrate (RSN) at harvest (Maidl, Brunner, & Sticksel, 2002).

The rate of nitrogen application plays a key role in determining the environmental risk of N losses. Applying nitrogen beyond crop requirements decreases fertilizer use efficiency and enhances nitrogen losses to the environment during and after the growing season. Postponing all or part of the N fertilizer application improves crop nitrogen recovery, primarily through reduced nitrate (NO_3^-) leaching and, to a lesser extent, decreased denitrification losses (Burton, Zebarth, Gillam, & MacLeod, 2008), these patterns are frequently observed under wetter soil conditions during the early growing season. Spatial variability in soil nitrogen availability within fields is often linked to differences in drainage characteristics and soil texture. In clay soils, reduced water movement and oxygen-deficient pore spaces create favorable conditions for denitrification. (Strong & Fillery, 2002). While clayey soils usually exhibit slow water percolation, the presence of cracks and well-developed pore networks in specific soil horizons can significantly modify water flow patterns (Oostindie & Bronswijk, 1995).

Potato (*Solanum tuberosum* L.) cultivation is a dominant agricultural activity in the Sais Plain and requires substantial nitrogen fertilizer and irrigation to maximize yields, thereby increasing the vulnerability of the system to nitrate leaching (Halvorson A. D., Follett, Bartolo, & Schweissing, 2002). The research discussed in this study was conducted to determine how various rates of N fertilizers affect the vertical and temporal distribution of water and NO3-N concentrations in the soil profile (0-100cm) under potato irrigated cropping during two growing seasons (2021 and 2022); (2) assess the effect of increasing N fertilizers on potato crop yields.

Methods

The experiments were performed at the Douyet Experimental Station on irrigated plots cultivated with potato (*Solanum tuberosum* L.) during the 2021 and 2022 seasons.

To characterize the physicochemical properties of the soil, composite samples were collected prior to sowing from five successive depth layers (0–20, 20–40, 40–60, 60–80, and 80–100 cm) using a manual Eijkelkamp auger. The soil characteristics of the experimental site are reported in Table 1. The experimental field soil is characterized by a silty clay loam texture (Lahjouj et al., 2021).

Six N application rates were arranged in a randomized complete block design with three blocks. The N application rates were 0, 90, 135, 180, 225, and 270 kg/ha, and are designated N0, N1, N2, N3, N4, and N5, respectively. There are18 elementary plots (6 per each block). And all elementary plots had an area of 30m2 (6 × 5m), and were separated by 2m.

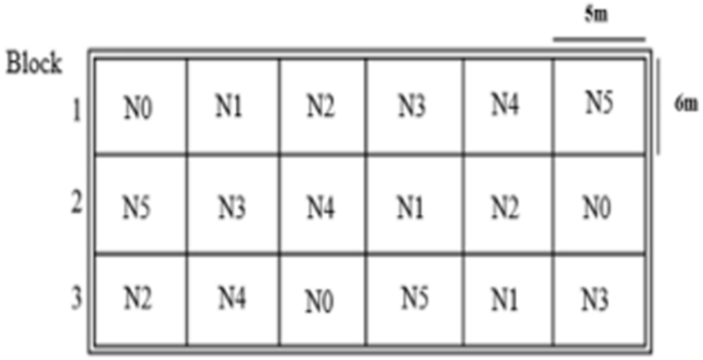


Figure 1: N fertilization scheme (block design)

Table 1: Texture and composition of the soil at study plot

Year	**2021**					**2022**				
Depth (cm)	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**
Silt %	58,83	58,1	63,44	60,28	56,2	58,83	58,1	63,44	60,28	56,2
Clay %	28,44	29,8	25,52	28	32,04	28,44	29,8	25,52	28	32,04
Sand%	13	12,3	11,53	11,81	11,92	13	12,3	11,53	11,81	11,92
pH	8,03	8,06	8,01	8,11	7,85	8,03	8,06	8,01	8,11	7,85
Organic matter %	1,36	1,20	1,18	1,22	1,27	1,6	1,8	1,3	1,2	1,7
Active limestone %	9,0	10,4	10,4	10,3	9,3	10,8	9,8	8,6	10,5	8,8
Water content %	6,16	18,67	18,03	18,88	18,60	19,37	17,65	16,85	17,71	19,52
NO_3^- (mg/kg)	36,5	38,5	42,4	52,3	50,4	35,82	29,50	23,73	19,26	23,43
P (mg/kg)	19,8	14,8	7,3	1,3	2,3	13,4	10,0	0,8	2,5	4,8
N %	0,10	0,01	0,01	0,03	0,02	0,13	0,03	0,03	0,06	0,10

Potato (*Solanum tuberosum* L.) was planted on 24 March 2021 and 22 March 2022. Nitrogen fertilization was applied in three splits: the first third as ammonium sulfate (21% N) incorporated into the top 10 cm of soil prior to planting, the second third as ammonium nitrate (33.5% N) at the vegetative growth stage before irrigation, and the final third at the tuber formation stage. Phosphorus and potassium were applied at planting.

Harvesting occurred at physiological maturity on 13 July 2021 and 22 July 2022. Prior to analysis, all data were checked for normality using the Shapiro–Wilk's test (Shapiro and Wilk, 1965).

Statistical analyses, including one-way ANOVA and Tukey's HSD test at P = 0.05, were carried out in R (Version 4.1.1) to evaluate the influence of nitrogen application rates on soil nitrate distribution and potato yields during the 2021 and 2022 growing seasons. (Ihaka & Gentleman, 1996). Repeated-measures analysis was applied to evaluate soil nitrate differences across N application rates at each depth. Additionally, two-way ANOVA was conducted to test for significant seasonal variations in soil water content (SWC), nitrate (NO_3–N), and potato yields.

Figure 2: A: Potato plantation; B: Soil sampling at the experiment field using a soil auger

Results

Soil water content (SWC)

Figures 2 and 3 illustrate the soil water content (SWC) under six nitrogen (N) application treatments, measured before and after irrigation throughout the potato growth cycle during the 2021 and 2022 growing seasons. In both seasons, SWC exhibited comparable temporal patterns across all N treatments. However, in 2022, the treatment receiving 180 kg N ha^{-1} deviated from this general trend, displaying a distinct temporal and vertical distribution of soil water levels.

During the first growing season, no pronounced differences in soil water content (SWC) were observed between pre- and post-irrigation measurements in the control treatment or in plots receiving N rates of 90, 135, and 275 kg N ha^{-1}. In contrast, significant differences between pre- and post-irrigation water levels were recorded for the 180 and 225 kg N ha^{-1} treatments, particularly within the surface soil layer (0–20 cm). SWC reached its lowest values in February (approximately 18%) prior to irrigation and increased during the subsequent months following irrigation events. Furthermore, no clear vertical variation in SWC distribution was observed during this season.

The second growing season did not display the same temporal SWC patterns as the first. Pre-irrigation soil water contents were markedly lower (approximately 10%) than post-irrigation values across all N treatments, with the exception of the 180 kg N ha^{-1} treatment. This difference was most pronounced at soil depths between 40 and 100 cm. In the control plots, SWC distribution was influenced by soil depth, with slight variations in water content over time observed at depths of 60–100 cm.

As summarized in Table 2, nitrogen application rates did not have a significant effect on SWC. However, a significant seasonal effect was detected, with overall soil water contents being lower during the second cropping season compared to the first across all N treatments.

Table 2: Soil water concentrations (SWC) at soil layers under different Nitrogen fertilizer application rates

Depth (cm)	**Year**	**N rates (kg/ha)**					
		0	**90**	**135**	**180**	**225**	**275**
0-20	**2021**	22.17 ± 2.02ab	21.63 ± 2.59c	21.89 ± 2.29bc	22.35 ± 3.19ab	22.87 ± 2.17a	22.52 ± 1.66ab
20-40		20.10 ± 1.66ab	20.24 ± 0.96c	20.57 ± 2.26bc	20.91 ± 1.57ab	21.36 ± 2.89a	20.60 ± 1.45ab
40-60		18.97 ± 2.51c	19.73 ± 1.48bc	20.51 ± 1.62bc	20.29 ± 1.31bc	21.51 ± 2.54a	20.71 ± 1.64ab
60-80		20.67 ± 1.57bc	19.83 ± 2.53c	21.51 ± 1.27ab	20.29 ± 1.94bc	23.08 ± 1.12a	21.82 ± 0.95ab
80-100		22.13 ± 2.12ab	20.26 ± 2.75c	22.35 ± 0.83ab	20.36 ± 2.45bc	22.89 ± 1.76ab	23.16 ± 1.03a
0-20	**2022**	20.15 ± 1.32a	18.78 ± 3.05a	19.69 ± 2.17a	18.26 ± 3.43a	19.47 ± 2.61a	18.43 ± 4.34a
20-40		16.82 ± 2.96a	19.18 ± 2.22a	17.80 ± 4.21a	16.48 ± 2.67a	16.49 ± 3.40a	17.86 ± 4.43a
40-60		16.22 ± 3.46a	16.43 ± 3.76a	17.43 ± 4.47a	15.86 ± 2.44a	16.30 ± 3.29a	15.08 ± 2.81a
60-80		15.20 ± 4.48a	16.77 ± 2.93a	17.83 ± 5.06a	14.12 ± 2.11a	15.70 ± 3.37a	15.40 ± 4.24a
80-100		18.22 ± 5.19a	17.98 ± 3.35a	17.60 ± 5.17a	14.27 ± 3.26a	16.04 ± 3.73a	17.57 ± 6.25a

Mean values in each N rate for same depth in same year followed by the same letter are not significantly different at the 0.05 level.

Table 3: ANOVA results for soil water concentrations (SWC)

	Sum of Squares	**df**	**F**	**p**
N rates	103.6	5	2.3711	**0.038318 ***
Season	2217.3	1	253.6782	< **2.2e-16** ***
N rates / Season	153.3	5	3.5084	**0.003969** **
Residuals	4449.0	509		

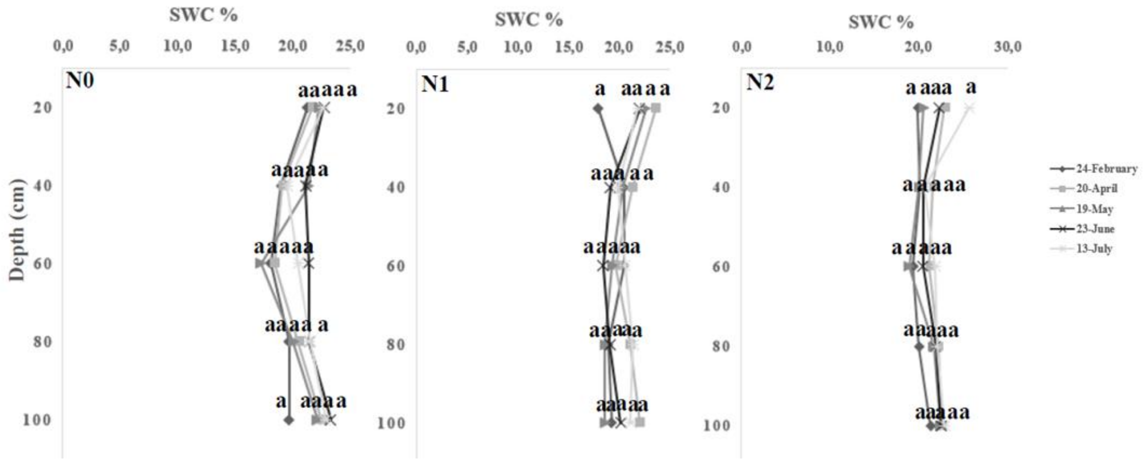
*Signif. codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

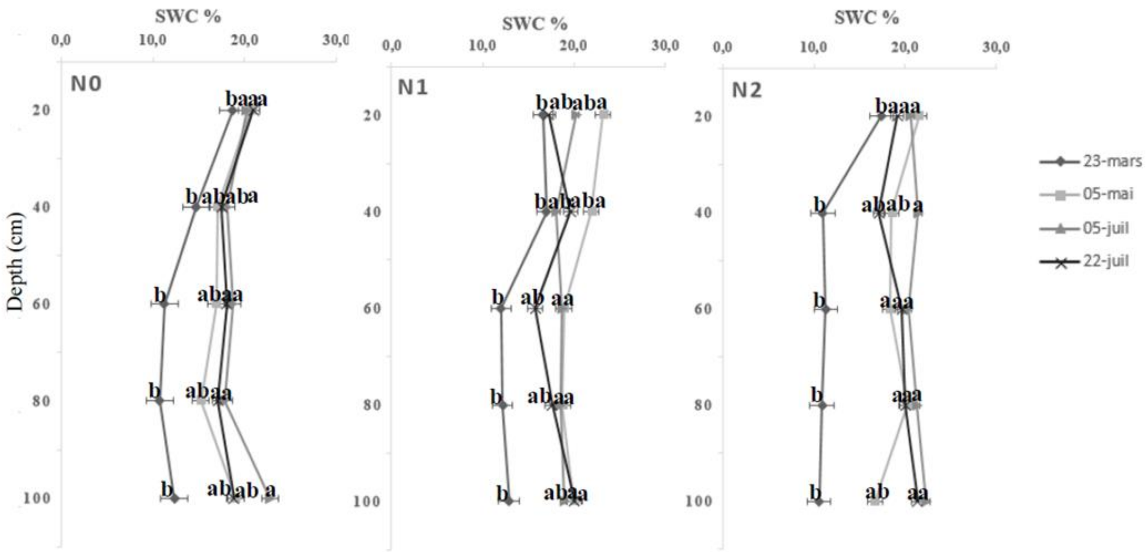
Table 4: Soil water concentrations (SWC) mean in two seasons under different Nitrogen fertilizer application rates

	Seasons	
N rates (kg/ha)	**S1**	**S2**
0	20.90 ± 2.25a	17.32 ± 3.94b
90	20.34 ± 2.20a	17.84 ± 3.11b
135	21.37 ± 1.82a	18.08 ± 4.21b
180	20.87 ± 2.26a	15.78 ± 3.11b
225	22.33 ± 2.22a	16.82 ± 3.40b
275	21.78 ± 1.65a	16.87 ± 4.52b

Mean values in each season for same N rate followed by different letters are significantly different at the 0.05 level.

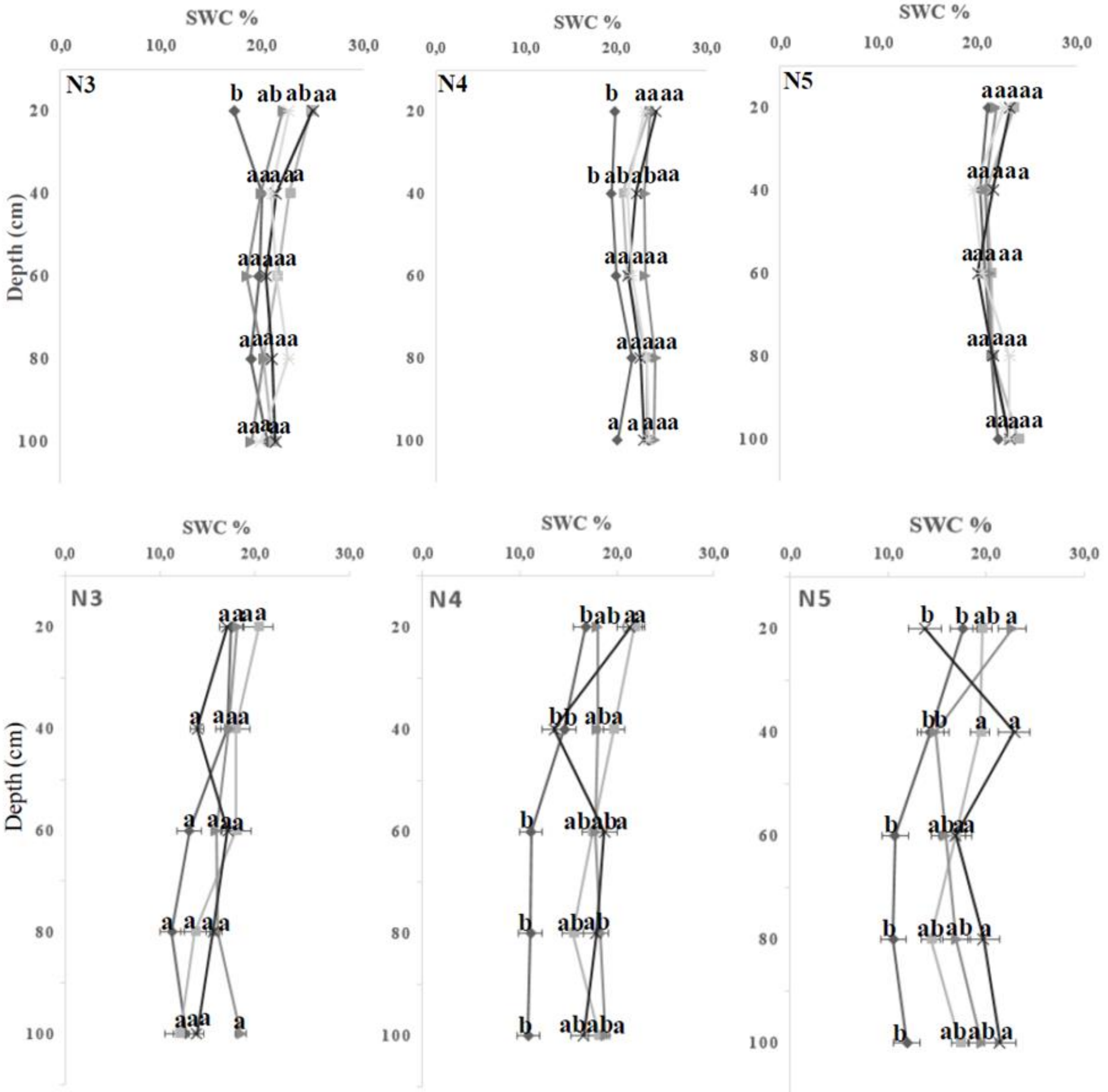
Figure 3: Soil water concentration (SWC) at different soil depths as affected by nitrogen fertilization application rates (2021)





Mean values in each N rate for same depth in different time followed by the same letter are not significantly different at the 0.05 level.

Figure 4: Soil water concentration (SWC) at different soil depths as affected by nitrogen fertilization application rates (2022)



Mean values in each N rate for same depth in different time followed by the same letter are not significantly different at the 0.05 level.

Soil nitrate concentration (SNC)

The distribution of NO3-N in the 0-100 cm soil profile under different nitrogen (N) fertilizer rates is shown in Figures 3 and 4 for the 2021 and 2022 cropping seasons. In 2021, soil NO3-N levels across all N treatments ranged from 8,9 mg. kg^{-1} to 90,5 mg. kg^{-1}, while in 2022, nitrate levels ranged from 6,9 mg. kg^{-1} to 141,8 mg. kg^{-1}.

In the first cropping season, soil nitrate concentrations generally decreased over time in response to crop N demands, particularly in the control subplot, where the trend was consistent across all soil layers. Similar temporal distribution was noticed in the N rate 135 Kg N / ha at 40-100cm, but at shallow depth 0-40cm, soil NO3- decreased over the period February-May and increased in June (57 DAP) compared to the previous period. Similarly in the elementary plot under the N treatments 90 and 180 Kg N / ha soil NO3- increased in June at 0-20cm and exceed initial nitrate levels (about 70 mg. kg^{-1}). For the treatments receiving 225 Kg N / ha, soil NO3- distribution was different between shallow and deeper soil horizons. In fact, at 0-40cm, nitrate contents increased (about 60 mg. kg^{-1}) after the first in application (28 DAP), and decreased in May. After this period, soil NO3- increased slightly compared to the previous month. In contrast, at 40-100cm, nitrate contents decreased over months. Moreover, for the subplot receiving the higher N rate 275 kg N / ha, soil nitrate distribution was not similar to other N treatments. In fact, at shallow depth 0-40cm, nitrate levels were higher (approximatively 60 mg. kg^{-1}) at harvest stage (111 DAP) and lower at 60-100cm. Generally, soil nitrate tended to decrease vertically from 20 to 100cm and temporally over months with lower levels at harvest stage for all N rates.

In the second cropping season, soil nitrate distribution did not show similar patterns for all N treatments. In the control subplot, significant differences were observed between NO3-N concentrations measured in the soil profile before and after planting. Nitrate levels were higher in March (50 mg. kg^{-1}) and decreased by June and July (85 and 116 DAP) to around 10 mg.kg^{-1}. For the 90 kg N/ha treatment, NO3-N concentrations in the 0-20 cm layer dropped from 40 mg/kg in March to 141 mg/kg by July, while concentrations at 40-100 cm soil NO3- decreased over months, and then increased in July (at harvest stage). Similarly, NO3-N concentrations decreased over months for the 135 kg N/ha treatment, with slightly higher initial soil NO3- in the top 0-20cm layer (about 50 mg. kg^{-1}). For the 225 kg N/ha treatment, NO3-N levels increased significantly after the first N application (38 DAP) at all soil layers, then decreased significantly over months. The 275 kg N/ha treatments exhibited higher soil NO3-N levels (90 mg. kg^{-}1) in response to the first N application particularly at shallow depth 0-20cm. In contrast, no remarkable variation in soil NO-3 was observed temporally and vertically at 40-100cm.

Results from one-way ANOVA indicated that the differences in soil NO3-N concentrations between N treatments were not statistically significant ($p > 0.05$) (Table 2). Furthermore, the temporal variations in NO3-N were significantly different over months with lower soil NO3- at harvest stage.

As shown in the tables 3 and 4, there was a significant effect of cropping season on soil NO3-N concentrations. The mean NO3-N concentrations were higher in the first season, ranging from 33.55 ± 18.99 mg. kg^{-1} (control) to 40.62 ± 21.24 mg. kg^{-1} (275 kg N/ha). In contrast, the second season showed lower mean NO3-N concentrations, ranging from 22.00 ± 17.18 mg. kg^{-1} (control) to 24.11 ± 18.68 mg. kg^{-1} mg/kg (275 kg N/ha).

Table 5: Soil nitrate concentrations (SNC) at soil layers under different Nitrogen fertilizer application rates

Depth (cm)	**Year**	**N rates (kg/ha)**					
		0	**90**	**135**	**180**	**225**	**275**
0-20	**2021**	32.27 ± 15.52a	44.36 ± 19.99a	32.29 ± 13.02a	40.88 ± 11.40a	38.98 ± 15.65a	47.87 ± 22.35a
20-40		24.73 ± 13.67a	33.39 ± 16.03a	31.16 ± 13.01a	38.46 ± 25.53a	31.45 ± 17.09a	35.03 ± 15.11a
40-60		20.73 ± 22.61a	25.31 ± 21.18a	38.49 ± 21.64a	32.12 ± 22.74a	25.82 ± 12.15a	31.79 ± 14.55a
60-80		37.10 ± 20.42a	30.62 ± 18.55a	33.90 ± 20.46a	32.66 ± 27.92a	33.84 ± 19.35a	47.51 ± 26.93a
80-100		36.30 ± 22.53a	39.07 ± 12.19a	30.29 ± 12.58a	35.21 ± 12.88a	30.64 ± 15.96a	41.50 ± 24.61a
0-20	**2022**	29.48 ± 10.54a	57.00 ± 38.04a	40.44 ± 7.50a	39.85 ± 18.28a	38.49 ± 21.13a	42.83 ± 24.29a
20-40		19.34 ± 13.90a	39.06 ± 11.88a	26.33 ± 10.28a	35.03 ± 28.77a	27.31 ± 12.43a	25.32 ± 12.81a
40-60		15.34 ± 17.27a	22.61 ± 20.39a	23.64 ± 15.56a	28.58 ± 23.08a	24.71 ± 28.91a	24.80 ± 16.10a
60-80		24.69 ± 26.05a	25.38 ± 21.82a	19.19 ± 10.86a	24.20 ± 23.92a	22.84 ± 19.31a	12.20 ± 9.17a
80-100		15.56 ± 13.92a	22.47 ± 14.93a	21.42 ± 17.34a	24.56 ± 10.28a	27.99 ± 21.50a	20.39 ± 19.56a

Mean values in each N rate for same depth in same year followed by the same letter are not significantly different at the 0.05 level.

Table 6 : ANOVA results for soil nitrate concentrations (SNC)

	Sum of Squares	**df**	**F**	**p**
N rates	2514	5	1.3627	0.2370
Season	7881	1	21.3581	**0.000004918 *****
N rates / Season	2745	5	1.4880	0.1922
Residuals	174892	474		

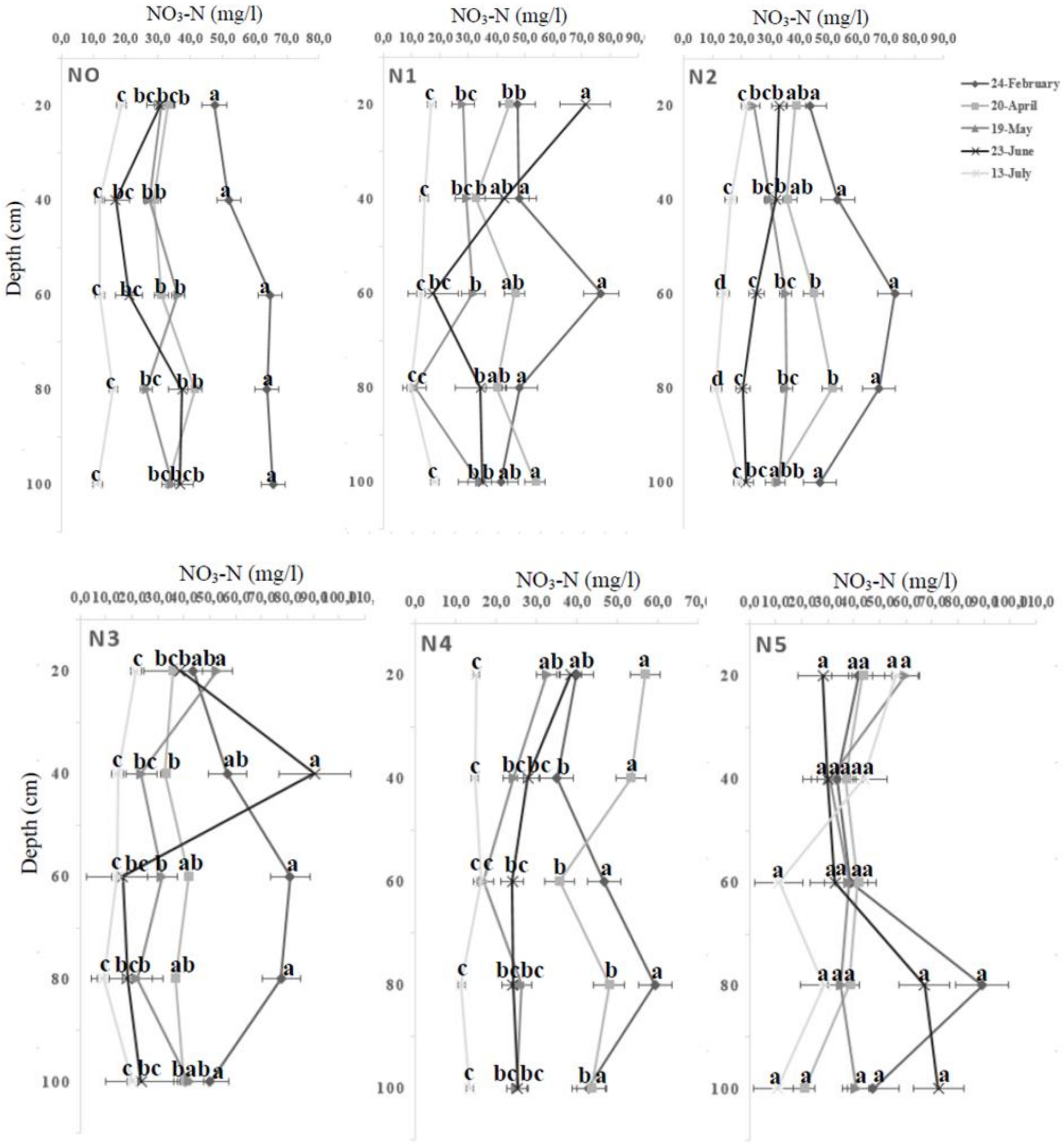
Signif. codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 7: Soil nitrate concentrations (SNC) mean in two seasons under different Nitrogen fertilizer application rates

	Seasons	
N rates (kg/ha)	**S1**	**S2**
0	33.55 ± 18.99a	22.00 ± 17.18 a
90	35.91 ± 17.85a	33.30 ± 25.22b
135	33.39 ± 16.36a	25.21 ± 14.17a
180	35.56 ± 20.84a	29.98 ± 21.17b
225	32.03 ± 16.11a	28.14 ± 20.93a
275	40.62 ± 21.24a	24.11 ± 18.68b

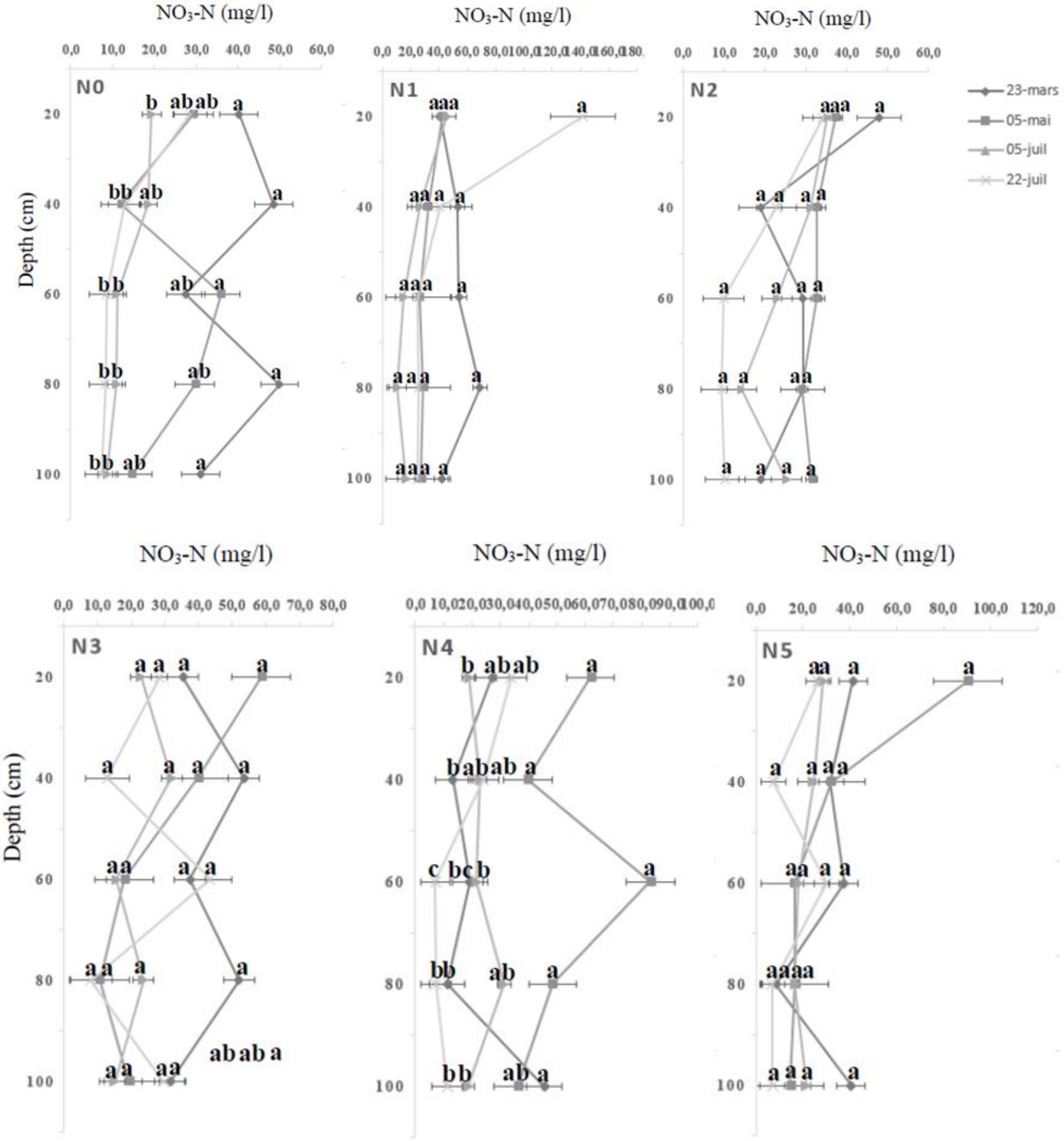
Mean values in each season for same N rate followed by different letters are significantly different at the 0.05 Level.

Figure 5: Soil nitrate concentration (SNC) at different soil depths as affected by nitrogen fertilization application rates (2021)



Mean values in each N rate for same depth in different time followed by the same letter are not significantly different at the 0.05 level.

Figure 6: Soil nitrate concentration (SNC) at different soil depths as affected by nitrogen fertilization application rates (2022)



Mean values in each N rate for same depth in different time followed by the same letter are not significantly different at the 0.05 level.

Yields

Yield results from the two-year field experiment demonstrate the pronounced effect of nitrogen (N) fertilization on potato tuber production (Figure 4). In both growing seasons, tuber yield increased with increasing N application rates. In 2021, yields ranged from 28.15 ± 9.98 to 47.56 ± 2.10 t ha^{-1}, whereas in 2022 they varied between 19.27 ± 0.09 and 26.61 ± 5.86 t ha^{-1}. The lowest yields were consistently observed in the control treatment (N0), where no nitrogen was applied. Nitrogen fertilization significantly enhanced tuber production, as confirmed by the statistical analysis (Table 25). The yield gap between the highest (N5) and lowest (N0) N treatments reached 40.8% in 2021 and 27.58% in 2022, with both differences being highly significant.

Minor yield fluctuations observed for the N3 treatment in 2021 were likely attributable to reduced soil water availability and/or localized soil heterogeneity in certain experimental plots.

Furthermore, as shown in Tables 6 and 7, the cropping season exerted a highly significant effect on yield (p-value = 4.683×10^{-9}), with consistently higher yields recorded during the first growing season.

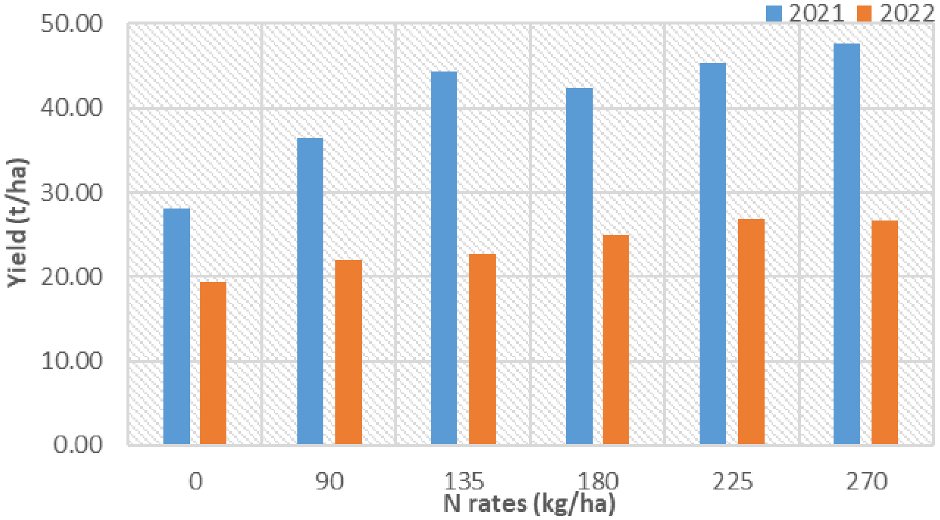


Figure 7: Average yields in t/ha for each subplot over 3 blocks for 2 years

Table 8: Crop yields(t/ha) under different nitrogen fertilizer application Rates

Year	N rates (kg/ha)					
	0	90	135	180	225	275
2021	28.15 ± 9.98b	36.52 ± 7.48ab	44.39 ± 1.12ab	42.38 ± 8.12ab	45.43 ± 6.27ab	47.56 ± 2.10a
2022	19.27 ± 0.09a	21.88 ± 3.96a	22.72 ± 2.55a	25.00 ± 6.30a	26.88 ± 4.63a	26.61 ± 5.86a

Mean values in each N rate for same year followed by different letter are significantly different at the 0.05 level.

Table 9: ANOVA results for Crop yields

	Sum of Squares	df	F	p
N rates	744.31	5	4.8682	**0.003498** **
Season	2514.41	1	82.2279	**0.000000004683** ***
N rates / Season	167.17	5	1.0934	0.390629
Residuals	703.31	23		

*Signif. codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 10: Crop yields (t/ha) mean in two seasons under different Nitrogen fertilizer application rates

	Seasons	
N rates (kg/ha)	**S1**	**S2**
0	28.15 ± 9.98a	19.27 ± 0.09b
90	36.52 ± 7.48a	21.88 ± 3.96b
135	44.39 ± 1.12a	22.72 ± 2.55b
180	42.38 ± 8.12a	25.00 ± 6.30b
225	45.43 ± 6.27a	26.88 ± 4.63b
275	47.56 ± 2.10a	26.61 ± 5.86b

Mean values in each season for same N rate followed by different letters are significantly different at the 0.05 Level.

Discussion

In the present study, nitrogen (N) application rates did not exert significant effects on soil water content (SWC) across the different soil layers, which is consistent with the findings reported by Lahjouj (2021). In contrast, SWC was significantly affected by irrigation inputs during both cropping seasons. In 2021, soil water content was notably lower prior to irrigation in the surface layer (0–20 cm) for the treatments receiving 180 and 225 kg N ha^{-1}. During the 2022 season, significant differences in SWC between pre- and post-irrigation measurements were observed at depths of 40–100 cm for the control and all N treatments, except for the 180 kg N ha^{-1} treatment. Vertical variation in SWC distribution was generally not evident across N rates, except in the control plots, where a slight increase in SWC was recorded at 80–100 cm, particularly in July. Overall, SWC was significantly higher during the first cropping season (2021). Comparable trends were observed in the onion experiments conducted at the same experimental station, suggesting that similar site-specific and seasonal factors may explain the interannual differences.

Short-term monitoring of soil nitrate (NO_3–N) dynamics in 2021 indicated a general decline in nitrate concentrations over time, with higher levels measured before planting and lower levels at harvest. This pattern was particularly evident across all soil layers in the control plots that received no N inputs. These results are consistent with those of Guillard et al. (1995), who reported substantial nitrate accumulation in fertilized fallow soils prior to planting due to the absence of crop uptake. With increasing N application rates, temporal variations in soil nitrate were observed at depths of 60–80 cm, characterized by reduced nitrate concentrations at harvest. In 2022, higher initial nitrate contents were also detected, but only in the control plots and in treatments receiving 90 and 180 kg N ha^{-1} at depths of 40–100 cm. For treatments receiving 225 and 275 kg N ha^{-1}, soil NO_3–N concentrations increased following the first N application, particularly within the 0–80 cm and 0–20 cm layers, respectively. Across both seasons, nitrate concentrations in the control plots declined over time, reflecting crop nitrogen uptake and the role of phosphorus (P) and potassium (K) in enhancing nitrogen use efficiency (Benbi et al., 1991).

With respect to spatial monitoring, soil NO_3–N distribution across soil layers exhibited significant temporal variability over the months and visually differed among N application rates in both years. In 2021, initial soil nitrate concentrations increased with depth across all N treatments. As the cropping season progressed, NO_3–N concentrations declined over time and throughout the soil profile, reaching their lowest levels at harvest. This trend was observed for all N treatments except the highest rate (275 kg N ha^{-1}), for which nitrate accumulation was more pronounced in the upper soil layers (0–40 cm), while lower concentrations were recorded at depths of 40–100 cm. Similar patterns are consistent with the findings of Zebarth et al. (2003), who observed higher nitrate concentrations near the soil surface than at greater depths, likely due to shallow fertilizer band placement. This distribution may also reflect enhanced mineralization in surface layers or upward nitrate movement driven by evaporation.

In 2022, the temporal dynamics of soil NO_3–N were comparable across all N treatments. Nitrate concentrations decreased significantly from planting to harvest at all soil depths, primarily as a result of rapid crop nitrogen uptake during tuber initiation, bulking, and maturation stages. This short period of intensive N uptake likely limited nitrate leaching beyond the root zone. As noted in the onion experiments, Zebarth et al. (2003) suggested that a brief interval between planting and peak crop N demand can effectively reduce nitrate losses.

Consistent with the onion experiments, differences in soil NO_3–N concentrations among N treatments were not statistically significant in either year. Although the underlying mechanisms remain uncertain, several factors may account for this observation. Since both potato and onion trials were conducted at the same experimental station and during the same period, similar site-specific and environmental factors, as discussed in Chapter III, likely influenced the results.

A significant seasonal effect on soil NO_3–N concentrations was detected, with lower nitrate levels observed in 2022. This difference can be attributed to higher initial soil nitrate concentrations during the first season (approximately 90 mg kg^{-1}) compared with the second season, when initial NO_3–N levels were lower (around 70 mg kg^{-1}).

Regarding potato productivity, numerous studies have demonstrated that adequate nitrogen fertilization is essential for optimizing tuber yield and quality while reducing environmental N losses (Cambouris et al., 2008). Similarly, previous research has shown that nitrogen fertilization enhances onion bulb yield (Béanger et al., 2001). The present study corroborates these findings, as increasing N application rates (from 0 to 275 kg ha^{-1}) resulted in higher yields in both 2021 and 2022, with statistically significant differences between the control and the highest N treatments observed in 2021.

Finally, yields were consistently higher in 2021 than in 2022, likely due to improved nitrogen recovery by the first crop and greater initial soil NO_3–N availability, which collectively contributed to enhanced productivity during the first growing season.

Conclusions

This study aimed to assess the effects of different nitrogen (N) fertilizer application rates on potato tuber yield, soil water content (SWC), and soil nitrate (NO_3–N) dynamics. Overall, SWC patterns within the 0–100 cm soil profile were broadly similar across all N treatments throughout the potato growth cycle in each cropping season. Nitrogen application rates did not significantly influence SWC at any soil depth in either season. Nevertheless, marked temporal variations in SWC were observed between months and across seasons. In 2021, SWC remained relatively stable over time in the control plots and in treatments receiving 90, 135, and 275 kg N ha^{-1}. By contrast, irrigation events strongly influenced the temporal distribution of soil water, particularly in the surface layer (0–20 cm) under the 180 and 225 kg N ha^{-1} treatments, where lower pre-irrigation SWC was followed by a significant increase after irrigation. Similar irrigation-driven variations were observed in 2022 across all N rates and soil depths.

Short-term monitoring revealed significant interannual differences in soil NO_3–N dynamics. In 2021, nitrate concentrations generally declined over the cropping cycle at all depths (0–100 cm) in the control plots and in treatments receiving 90, 135, and 180 kg N ha^{-1}, with the lowest concentrations recorded at harvest. Temporal patterns of NO_3–N differed slightly among N rates. In heavily fertilized treatments (225 and 275 kg N ha^{-1}), nitrate dynamics at 0–40 cm deviated from this general trend. For the 225 kg N ha^{-1} treatment, nitrate levels peaked in April following the first N application and declined toward harvest, whereas for the 275 kg N ha^{-1} treatment, soil nitrate increased markedly between May and July in the 0–40 cm layer and decreased over time at deeper depths (60–100 cm).

In 2022, soil NO_3–N at depths of 0–100 cm exhibited month-to-month variability, with higher nitrate concentrations observed at specific crop stages depending on the N rate. However, temporal trends were not consistent across all treatments. In the control plots, nitrate concentrations declined significantly from March to July. Overall, the soil NO_3–N response to N fertilization was more pronounced in the upper soil layers (0–40 cm), particularly for the 90 and 275 kg N ha^{-1} treatments, where nitrate levels were higher at harvest and after the first N application, respectively. Spatial and temporal analyses indicated a general decline in soil nitrate concentrations over time and with increasing soil depth across all N treatments.

Although soil NO_3–N concentrations were not significantly affected by N application rates, potato tuber yield responded strongly to N fertilization in both years. Yield increased with increasing N inputs, with higher nitrogen use efficiency and greater initial soil nitrate availability contributing to the superior yields observed in 2021 compared with 2022.

The occurrence of variable NO_3–N peaks among N treatments highlights the influence of soil texture, water movement, and soil physicochemical properties, including potential nitrate adsorption, which together complicate the interpretation of nitrate dynamics.

Finally, further research is recommended to extend these findings by investigating additional crop species with longer growth cycles.

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