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Research article

Implementing a soil ammonium N fertilizer management for synchronizing potato N demands

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ABSTRACT

Potatoes, as a high-nitrogen (N)-demand crop, are strongly influenced by both the quantity and form of N supply. Previous studies have demonstrated that applying nitrate N prior to tuber formation and ammonium N post-tuber formation can substantially enhance potato yields and improve N fertilizer use efficiency. However, the ammonium N introduced into the soil undergoes nitrification, creating challenges in aligning the N supply form with the needs of potatoes. This study explored novel N regulation strategies aimed at augmenting potato yields and improving N fertilizer use efficiency. Two field experiments were conducted from 2020 to 2022. Experiment 1 involved four N gradients, namely no N, 150 kg N ha^{-1}, 300 kg N ha^{-1}, and 450 kg N ha^{-1}. Soil samples were collected regularly to determine the transformation patterns of soil ammonium N during potato growth. Experiment 2 included three N management practices: farmer practice (Con), "nitrate followed by ammonium" with nitrification inhibitor (N–NI), and optimization (the soil ammonium N transformation-based split application of N fertilizer, Opt). The potato yield and N fertilizer use efficiency were compared to assess the performance of the optimized strategy. The results showed that 90 % of the ammonium N transformed 20 days after the basal dressing of N. When N fertilizer was applied as top dressing during the tuber formation and bulking stages, more than 90 % of ammonium N was transformed after 10 days. The optimized strategy resulted in a 20 % increase in potato yield, a 20 % increase in N fertilizer partial factor productivity, and a 12–20 % reduction in residual inorganic N in the 0–60 cm soil layer. This suggests that ammonium N applied as base fertilizer exhibits a relatively slow transformation rate, while applying ammonium N as top dressing during the tuber formation and bulking stages accelerates the transformation rate. The split application of ammonium N based on soil ammonium N transformation patterns can improve the alignment between the N supply form with the specific demands of potatoes.

1. Introduction

Potatoes, which are renowned for their adaptability, play a crucial role in ensuring food security and are cultivated in more than

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150 countries worldwide [1,2]. In China, Inner Mongolia stands out as a significant hub for both potato seed production and commercial potato cultivation, with its planting area and total production ranking among the top in the country [3]. The region's sustained increase in potato production in recent years has been achieved through a continuous surge in production inputs, especially in chemical fertilizer input. This has led to reduced resource utilization efficiency and the escalation of environmental risks. The nitrogen (N) fertilizer partial factor productivity (PFP_N) for potatoes in Inner Mongolia is approximately 84 kg ha^{-1}, lower than that in many other provinces in China, less than potato producing countries such as Germany, the United States and the Netherlands [4]. There is an urgent need for optimize N fertilizer management to achieve a sustainable potato production in Inner Mongolia.

Nitrate (NO_3^-) and ammonium (NH_4^+) are two forms of N taken up by plants. Preferences for either form depend on the crop species [5,6]. Aligning the N supply with crop requirements can significantly increase crop yield and quality [7] and improve N fertilizer utilization efficiency [8]. Research on the N form required by potatoes dates back to the 1960s and 1970s [9,10], and further studies have revealed differences in N requirements during different growth stages [11]. Our previous pot experiments indicate that supplying nitrate N before tuber formation and ammonium N with nitrification inhibitor after tuber formation can substantially enhance the quantity and weight of potato tubers [12]. This implies that adopting an appropriate "ammonium after nitrate" N fertilizer management approach in Inner Mongolia's may harmonize the alignment between N supply and the needs of potatoes, ultimately enhancing N fertilizer utilization efficiency.

Ammonium N supplied in the soil is prone to nitrification, which transforms it into nitrate N. This poses a challenge to the "ammonium after nitrate" N fertilizer management approach. Consequently, the nitrification of soil ammonium N represents a bottleneck in potato N fertilizer management. The nitrification of soil ammonium N is influenced by numerous factors, mainly including the soil texture, temperature, moisture content, pH, and microbes [13–16]. The primary potato-producing region in Inner Mongolia is characterized by cold temperatures in early spring, a short summer duration, significant day–night temperature variations, high soil pH, and loose soil texture [17–20]. These specific conditions introduce complexities into the nitrification of soil ammonium N, leading to distinct and unique patterns. Therefore, gaining a comprehensive understanding of the dynamics governing soil ammonium N transformation is essential for effectively managing N forms during potato production.

Farmers usually follow a three-stage N fertilization regimen in which fertilizer is first applied during seeding, and subsequent fertilization occurs once during the tuber formation stage and at bulking stage with urea. Guided by both the practices of local farmers and the findings from our prior research, the objectives of this study were to observe the nitrification dynamics of ammonium N applied to soil with different application times and rates and to test the following two hypotheses. (1) The split application of ammonium built upon the understanding of the nitrification dynamics of fertilizer ammonium N in soil can align the N supply not only in terms of quantity and timing but also in terms of form with the demands of the potato crop after tuber formation. (2) Adopting the "ammonium after nitrate" N fertilizer management scheme can enhance N fertilizer utilization efficiency in the potato production system.

2. Materials and methods

2.1. Site description

The experiments were conducted from 2020 to 2022 in Kebuer, Inner Mongolia (112°36′10.41″E, 41°18′2.31″N). This region receives an average annual precipitation of approximately 300 mm, with an average temperature of 1.3 °C. The annual evaporation falls within the range of 1700–2100 mm, and the frost-free period spans approximately 100 days. The soil type in the experimental field is classified as chestnut soil. Table 1 presents the physicochemical properties of the 0–20 cm soil layer in the pre-sowing soil. Three years of meteorological data for the pilot area are shown in Fig. 1.

2.2. Experimental design

2.2.1. Experiment 1

To observe the influence of the N application time and rate on ammonium N nitrification in soil, a field experiment was conducted from 2020 to 2021 with four N application levels (Table 2). A base rate of 30 % N fertilizer was band-applied with seed potato sowing, 40 % was fertigated using a subsurface drip irrigation system during the tuber formation period, and 30 % was fertigated during the tuber bulking period. Ammonium sulfate served as the N source. The experiment was designed using a randomized block design with three replications for each treatment. Each plot occupied an area of 10.8 m × 9.44 m = 102 m^2, with a separation distance of 1.8 m between individual plots. The preceding crop in the experimental field was wheat, and subsurface drip irrigation was used as the irrigation method. Potato rows were spaced 90 cm apart, with a plant spacing of 24 cm, resulting in a planting density of 46,300 plants ha^{-1}. In 2020, planting was performed on May 8, and the harvest was conducted on September 10. In 2021, planting was performed on

Table 1
Physicochemical properties of 0–20 cm soil in experimental fields.

Year	SOM (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	Olsen P (mg kg^{-1})	NH4OAc-exchangeable K (mg kg^{-1})	pH
2020	23.3	7.90	0.87	13.6	128.5	8.1
2021	25.4	6.91	2.68	14.3	130.3	8.0
2022	25.1	8.92	3.42	13.2	132.5	8.0

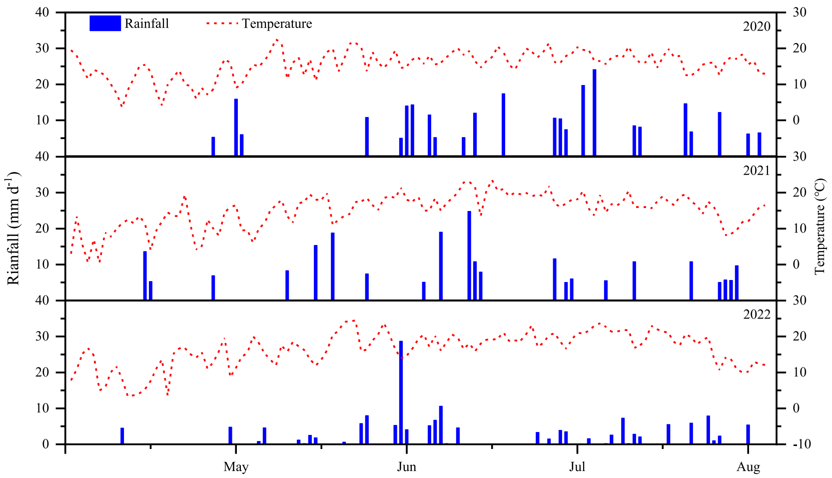

Fig. 1. Meteorological data in experimental years.

Table 2
Total nitrogen fertilizer input for each treatment from 2020 to 2021 (kg N ha^{-1}).

Treatment	Total N	Seeding	Potato tuber formation	Potato tuber bulking
N0	0			
N1	150	45	60	45
N2	300	90	120	90
N3	450	135	180	135

May 5, and the harvest was conducted on September 3. The potato variety used was 'Kexin-1'. Phosphorus fertilizer (79 kg P ha^{-1}) and potassium fertilizer (224 kg K ha^{-1}) were both applied as base fertilizers.

2.2.2. *Experiment 2*

To develop a potato N management system based on the dynamics of soil ammonium N nitrification, an experiment was conducted in 2022 and involved three N fertilizer management modes: The first management mode is conventional farmer mode (Con), where a total of 300 kg N ha^{-1} with urea as the N source was used. A base rate of 30 % total N was applied with seed potato sowing, 40 % N was applied at 20 days after emergence (DAE), and the remaining 30 % N was used at 40 DAE. The second management mode is "ammonium after nitrate" + nitrification inhibitor (N–NI), in which nitrate N was applied as a base dose and ammonium N was drip-fertigated with nitrification inhibitor (dicyandiamide at 5 % of the N rate) at 20 DAE and 40 DAE. The N application time and rate were the same as those described in the first management mode. The third management mode is optimization (Opt), in which nitrate N as a base dose was applied as described in the second management mode, and after tuber formation, ammonium N was split drip-fertigated depending on the ammonium N nitrification dynamics. The N application frequency was determined according to when 90 % of the applied ammonium N was nitrified; that is, N was applied after 90 % of the preceding applied N had been nitrified. The ammonium N rates during the tuber formation and bulking stages were the same as those described in the second mode, according to the conclusion of experiment 1 that "When N fertilizer was applied as top dressing during the tuber formation and bulking stages, more than 90 % of ammonium N was transformed after 10 days", opt practice applied fertilizer at 10 d intervals during tuber formation and tuber bulking, and the total fertilizer rate was the same as that of the previous two modes, as shown in Table 3. In the first and second modes, calcium nitrate served as the source of nitrate N, and ammonium sulfate served as the source of ammonium N. Phosphorus fertilizer (79 kg P ha^{-1}) and potassium fertilizer (224 kg K ha^{-1}) were both applied as base fertilizers. The experiment was designed using a randomized

Table 3
Nitrogen fertilizer input and management practices for each treatment in 2022.

Treatment	N basal dressing		N drip fertigation				
	Rate (kg ha^{-1})	Form	Rate (kg ha^{-1})				Form
			20 DAE	30 DAE	40 DAE	50 DAE	
Con	90	$CO(NH_2)_2$	120		90		$CO(NH_2)_2$
N–NI	90	NO_3^-	120		90		NH_4^+
Opt	90	NO_3^-	60	60	45	45	NH_4^+

DAE: days after emergence.

block design with three replications for each treatment. Each plot occupied an area of 10.8 m × 9.44 m = 102 m^2, with a separation distance of 1.8 m between individual plots. Potato planting took place on May 7, and the harvest occurred on September 3. The potato variety used for the experiment was 'Kexin 1', and all other management practices were the same as those previously described in Section 2.2.1.

2.3. Sampling and measurements

2.3.1. Soil sampling

Following each N fertilizer application, soil samples were systematically collected at intervals of 1, 3, 5, 7, and 10 days, with three sampling points in each plot randomly selected each time. Subsequently, three samples in each plot were taken every 10 days until the next N application. These samples were collected at the midpoint between potato plants within a row. After harvest, three soil samples in each plot were randomly collected. At each sampling time, Soil samples were collected from 0 to 60 cm and divided into three layers according to 0–20 cm, 20–40 cm and 40–60 cm. All the soil samples were used for the determination of soil moisture content, soil ammonium N, and nitrate N.

2.3.2. Soil testing

Soil ammonium N and nitrate N were extracted using 2 mol L^{-1} KCl solution, and the nitrate and ammonium concentration in the solution were determined spectrophotometrically using the Continuous Flow Analyzer System (SKALAR SAN++, Netherlands). The soil total N was analyzed using H_2SO_4–H_2O_2 digestion and Kjeldahl N determination (K1100, Hanon, China). The soil available phosphorus was measured using 0.5 mol L^{-1} Na HCO_3 extraction and spectrophotometric determination (Alpha1500, LASPEC, China). The soil available potassium was analyzed using 1 mol L^{-1} NH_4OAc extraction and flame photometric determination (Sherwood, UK). The soil organic matter was measured following the method of Bao [21].

2.3.3. Tuber yield

At the end of the experiment, a randomly selected area of 36 m^2 within each plot (borders and end rows were not considered) was harvested to determine the fresh tuber weight, from which the hectare yield was subsequently calculated.

2.4. Number equations and statistical analysis

2.4.1. Number equations

$$\text{Marketable tuber rate }(\%) = \frac{\text{Weight of tubers} > 150\text{ g}}{\text{Total tuber weight}} \times 100\%$$

$$\textit{Nitrogen fertilizer partial factor productivity }(PFP_N)\left(kg\ kg^{-1}\right) = \frac{\textit{Tuber yield}}{\textit{Amount of nitrogen fertilizer applied}}$$

$$\text{Accumulated inorganic nitrogen in soil}\left(\text{kg}\ \ \text{ha}^{-1}\right) = \text{Accumulated ammonium nitrogen} + \text{Accumulated nitrate} - \text{nitrogen in soil}$$

$$\text{Nitrification rate }\left(\text{mg kg}^{-1}\ \text{d}^{-1}\right) = \frac{\left[NO_3^-\right]_{\Delta t} - \left[NO_3^-\right]_1}{\Delta t}$$

where $[NO_3^-]_1$ is the nitrate-nitrogen concentration on the first day after fertilizer application, $[NO_3^-]_{\Delta t}$ is the nitrate-nitrogen concentration on day t after fertilizer application, and Δt is the interval time.

2.4.2. Statistical analysis

All experimental data were categorized, recorded, and processed using Excel 2010. One-way analysis of variance (ANOVA) and regression analysis were performed using SPSS 25.0 software (IBM SPSS version 25.0, Chicago, IL, USA), and a least significant difference test was used for multiple comparisons [22]. Graphs and figures were generated using Origin Pro 2019 software (Origin Lab Corporation, Northampton, MA, USA) and Microsoft Excel 2010 software. For the regression analysis of the relationship between the ammonium N concentration and the days after fertilization, quadratic, linear, linear plateau response, and logarithmic models were used to fit the data. The final model was determined by comparing their R^2 values. The model with the highest R^2 value was used to describe the relationship between variables.

3. Results

3.1. Dynamics of soil ammonium nitrification

3.1.1. Dynamics of soil ammonium after the basal dressing of nitrogen

Regression analysis of the soil ammonium concentration (SAC) and the days after fertilization showed are presented in Figs. 2–4. Fig. 2 shows the changes in SAC after. Following the application of ammonium N fertilizer, the SAC in the N1, N2, and N3 treatments showed a linear decreasing trend, and 20 days after basal dressing, the SAC in the N1, N2, and N3 treatments had decreased by 84–91 %. Thereafter, the SAC in the N1, N2, and N3 treatments maintained relatively stable up to 3 mg kg^{-1}, after which it didn't change.

The amount of ammonium N supply had a significant effect on the nitrification rate before the SAC reached a critical threshold (Fig. 2, Table 4). The SAC increased with a higher N supply, leading to accelerated nitrification rates. On average over 2 years, the nitrification rates for the N1, N2, and N3 treatments were 0.68, 0.96, and 1.27 mg $(kg\ d)^{-1}$, respectively (Table 4).

3.1.2. Dynamics of soil ammonium after the top dressing of nitrogen at the tuber formation stage

The changes in the SAC after the top dressing of N during the potato tuber formation stage are shown in Fig. 3. After the top dressing of ammonium N fertilizer during the tuber formation period, the SAC in the N1, N2, and N3 treatments exhibited a linear decreasing trend, and once it reached a certain threshold, the SAC remained relatively stable. Five days after fertilization, the ammonium N in the N1, N2, and N3 treatments had decreased by 80–82 %. After 10 days of fertilizer top dressing, the ammonium N in the N1, N2, and N3 treatments had decreased by 95–98 %.

The amount of ammonium N supply also had a significant effect on the SAC. The SAC increased with the increase in the N supply amount, leading to accelerated ammonium nitrification rates. On average over 2 years, the ammonium nitrification rates for the N1, N2, and N3 treatments were 1.26, 2.46, and 3.07 mg $(kg\ d)^{-1}$, respectively (Table 4).

3.1.3. Dynamics of soil ammonium after the top dressing of nitrogen at the tuber bulking stage

The soil ammonium concentration dynamics after the top dressing of N at the tuber bulking stage were quite similar to those at the tuber formation stage (Figs. 3 and 4). Five days after the top dressing of N during the tuber bulking period, the ammonium N in the N1, N2, and N3 treatments had decreased by 76–78 %. Ten days after re-fertilization, the ammonium N in the N1, N2, and N3 treatments had decreased by 92–94 %.

The effect of the ammonium N supply on the SAC followed the same pattern observed during the tuber formation period regarding the top dressing of N. On average over 2 years, the ammonium nitrification rates for the N1, N2, and N3 treatments were 1.09, 1.73 and 2.11 mg $(kg\ d)^{-1}$, respectively (Table 4).

3.1.4. Potato yield under different nitrogen application rates

As shown in Table 5, all N fertilizer treatments achieved higher potato yields and marketable tuber rates than the treatment without N fertilization in both years, and the yield and marketable rate were higher under N2.

3.2. Nitrogen fertilizer management based on soil ammonium nitrogen nitrification dynamics

3.2.1. Variations in the potato yield and marketable tuber rate among treatments

Based on the soil ammonium N nitrification patterns, the optimized N management mode (Opt) was designed as shown in Table 6, with the farmer conventional mode (Con) and "ammonium after nitrate + nitrification inhibitor" (N–NI) used for comparison. The results of the experiment in 2022 indicated that optimized fertilization led to a significantly increased potato yield. In comparison to the Con method, the Opt method practice resulted in a 20.13 % increase in yield, while the yield difference between Opt and N–Ni was not significant. Additionally, optimized fertilization significantly improved the rate of marketable potatoes. Compared with the Con method, the Opt method practice improved the marketable potato rate by 20.71 %, surpassing the N–NI method by 8.83 % (Table 6).

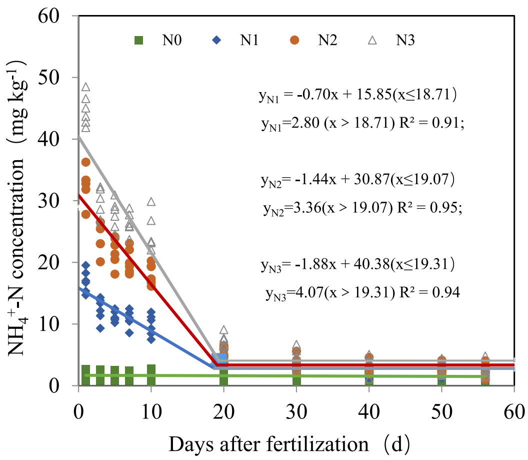

Fig. 2. Soil ammonium concentration (SAC) (mg kg^{-1}) after the basal dressing of N and regression analysis between the SAC and the days after the basal dressing of N from 2020 to 2021. N0 (no nitrogen fertilizer), N1 (150 kg N ha^{-1}), N2 (300 kg N ha^{-1}), and N3 (450 kg N ha^{-1}).

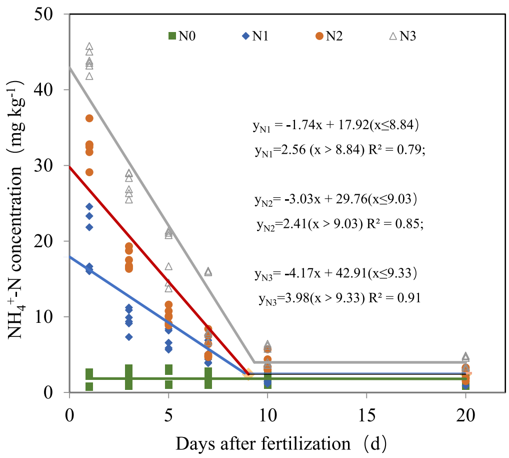

Fig. 3. Soil ammonium concentration (SAC) (mg kg^{-1}) after the top dressing of N and regression analysis between the SAC and the days after the top dressing of N during the potato tuber formation stage from 2020 to 2021. N0 (no nitrogen fertilizer), N1 (150 kg N ha^{-1}), N2 (300 kg N ha^{-1}), and N3 (450 kg N ha^{-1}).

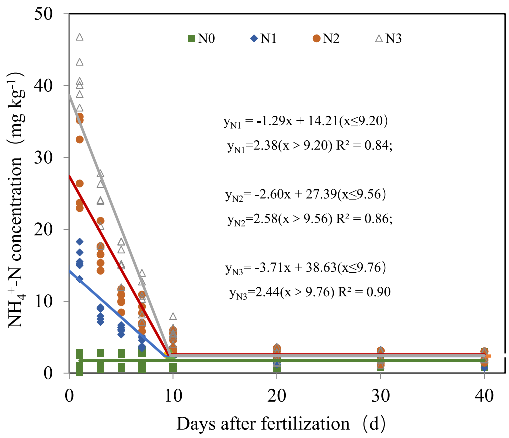

Fig. 4. Soil ammonium concentration (SAC) (mg kg^{-1}) after the top dressing of N and regression analysis between the SAC and the days after the top dressing of N during the potato tuber bulking stage from 2020 to 2021. N0 (no nitrogen fertilizer), N1 (150 kg N ha^{-1}), N2 (300 kg N ha^{-1}), and N3 (450 kg N ha^{-1}).

Table 4
Nitrification rate of soil ammonium N (mg (kg d)$^{-1}$) after the basal dressing of N, and after the top dressing of N during the potato tuber formation and bulking stages from 2020 to 2021. N1 (150 kg N ha^{-1}), N2 (300 kg N ha^{-1}), and N3 (450 kg N ha^{-1}).

Year	Treatment	Seedling	Potato tuber formation	Potato tuber bulking
		(1–20days)	(1–10days)	(1–10days)
2020	N1	0.76 ± 0.01c	1.23 ± 0.07c	1.22 ± 0.12c
	N2	0.94 ± 0.02b	2.50 ± 0.10b	1.66 ± 0.06b
	N3	1.30 ± 0.08a	2.89 ± 0.06a	1.99 ± 0.07a
2021	N1	0.60 ± 0.02c	1.28 ± 0.10c	0.96 ± 0.08c
	N2	0.97 ± 0.03b	2.29 ± 0.06b	1.44 ± 0.05b
	N3	1.25 ± 0.02a	3.26 ± 0.12a	2.22 ± 0.19a

Data with different lowercase letters indicate significant differences between treatments within a year ($p < 0.05$). All data are expressed as the mean ± SE.

Table 5
Effects of different treatments on the potato yield and marketable tuber rate from 2020 to 2021. N0 (no N), N1 (150 kg N ha^{-1}), N2 (300 kg N ha^{-1}), and N3 (450 kg N ha^{-1}).

Year	Treatment	Yield (t ha^{-1})	Marketable tuber rate (%)
2020	N0	34.52 ± 2.18c	53.34 ± 1.50c
	N1	48.55 ± 0.99b	65.07 ± 1.41b
	N2	57.96 ± 1.37a	75.97 ± 0.96a
	N3	52.65 ± 1.04b	69.49 ± 3.39b
2021	N0	42.73 ± 1.18c	53.36 ± 0.77c
	N1	49.89 ± 0.60b	64.58 ± 1.38b
	N2	55.79 ± 1.25a	73.93 ± 2.29a
	N3	51.41 ± 0.76b	65.93 ± 1.47b

Data with different lowercase letters indicate significant differences between treatments within a year ($p < 0.05$). All data are expressed as the mean ± SE.

3.2.2. Variations in potato N use efficiency as influenced by management strategies

As shown in Tables 6 and it was evident that the Opt method significantly improved the N fertilizer utilization of potatoes, which was termed PFP_N. The Opt method showed a 20.13 % increase in the PFP_N compared with the Con method, while it did not significantly outperform the N–NI method.

3.2.3. Residual inorganic nitrogen in soil

Different N management methods had a significant effect on inorganic N residues in the 0–60 cm soil layer after harvest (Fig. 6). Opt practice substantially reduced inorganic N residues. Compared to Con practice, 0–20 cm, 24–40 cm, and 40–60 cm soil layers by 15.72 %, 12.21 %, and 20.38 %, respectively.

4. Discussion

4.1. Soil nitrification intensity changes over time due to temperature in the area

Temperature is an important regulator of N nitrification in soil [23]. And low temperatures have been shown to inhibit nitrification, while rising temperatures promote ammonium N conversion [24,25], with the most optimal nitrification temperature falling within the range of 20–35 °C [26,27]. Thus, understanding the soil nitrification intensity changes over time due to temperature and the time course of soil nitrification in an area are particularly important for N management in crop production [28–30]. The results obtained in this study (Figs. 2, 3 and 5) clearly showed that it took about 20 days for 90 % of the basal N had been nitrified after its application, when the soil temperature (in the 0–20 cm soil layer) was relatively low in the area with an average of 15.1 °C over 2 years, while at the tuber formation stage of potatoes, the soil temperature in the 0–20 cm soil layer reached approximately 20.1 °C on averagely, being higher than that during seeding, this resulted in that 90 % of applied N had been nitrified after 10 days of N application. At the tuber bulking stage of potatoes, as the soil temperature was close to that at the tuber formation stage, a similar time course of soil nitrification was observed (Figs. 3–5). These findings are of important significance for matching the optimal soil N form with potato crop demands through split N fertigation. As potato emergence and subsequently seedling stage usually lasts about 50 days after sowing with basal N application in the area [31], our findings imply that NH_4–N can be used as basal N for the potato production in the area although NO_3–N is preferred by potatoes before tuber formation [12]. After tuber formation, NH_4–N benefits potatoes growth [12]. While at this time, the soil nitrification rate increases significantly (Figs. 3 and 4). Thus, a frequent NH_4–N application with less dose each time may be better for matching potato N form requirement.

4.2. Turning point of soil ammonium N nitrification

The results of the present study indicated that the nitrification process was significantly enhanced as the concentration of ammonium N increased, as shown by the fact that the nitrification rate under N3 was 1.6–2.5 times higher than N1 (Table 4). This study further confirmed previous report that the soil nitrification rate is affected by the soil ammonium concentration [32,33]. This study found that most of the applied ammonium N was converted into nitrate N within 20 days after basal dressing regardless of the N fertilization rates, after which the SAC remained at approximately 3 mg kg^{-1} (Fig. 2, Table 4). This suggests that soil nitrification in a given area may have a SAC turning point, below which nitrification will no longer occur or will occur at a negligible rate. When ammonium N was applied as top dressing at the tuber formation or bulking stage of potatoes, the SAC also stabilized at around 3 mg kg^{-1} after 10 days of N application (Figs. 3 and 4). These findings further support the argument for the existence of a SAC turning point in soil ammonium N nitrification.

4.3. Effects of nitrogen management based on soil nitrification for potato production

Plants, including potatoes, primarily use ammonium and nitrate N as their N source, and their preference for one form over the other can be influenced by various factors, including plant species, varieties, growth stages, and N source concentrations [5,6].

Table 6
Nitrogen management treatments and corresponding potato yields, marketable rates, PFP_N in 2022.

Treatment	Yield (t ha^{-1})	Marketable tuber rate (%)	PFP_N (kg kg^{-1})
Con	44.46 ± 0.83c	56.05 ± 0.64c	148.20b
N–NI	50.28 ± 0.37b	62.17 ± 0.96b	167.60a
Opt	53.41 ± 1.58a	67.66 ± 2.14a	178.03a

PFPN: nitrogen fertilizer partial factor productivity (kg kg^{-1}); Data with different lowercase letters indicate significant differences ($p < 0.05$); All data are expressed as the mean ± SE.

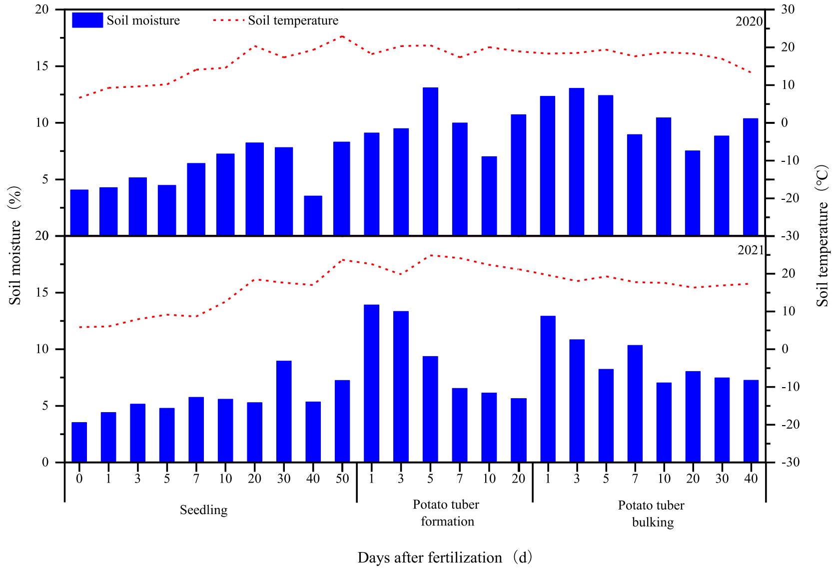

Fig. 5. Soil moisture (%) and soil temperature (°C) after basal nitrogen application, and nitrogen top dressing during the potato tuber formation and bulking stages from 2020 to 2021.

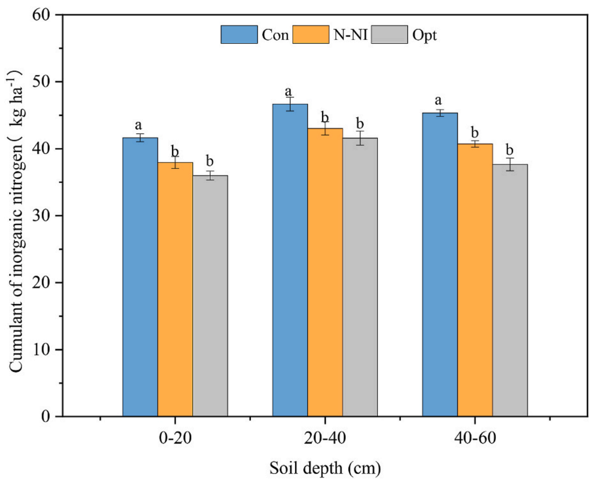

Fig. 6. Residual inorganic N in the 0–60 cm soil layer after harvest under different treatments. Farmer mode (Con), nitrate before ammonium + nitrification inhibitor (N–NI), and optimization (Opt). Vertical bars represent standard deviation.

Previous studies revealed that adopting an "ammonium after nitrate" approach significantly increased both the number and weight of potato tubers grown in pots with nitrification inhibitor [11,12]. However, the conversion of supplied ammonium N into nitrate N results in a misalignment between the N supply and the potato demand in the field. In this study, it was found that the split application of ammonium N fertilizer based on the timing of soil nitrification during the tuber formation and bulking stages of potatoes (Opt) resulted in significant increases in the potato yield, marketable tuber rate, and N fertilizer use efficiency and a significant reduction in the residual inorganic N content within the 0–60 cm soil layer. These outcomes were on par with or even outperformed the use of nitrification inhibitors (Table 6, Fig. 6). Therefore it is a promising N management for potato production, avoiding the environmental risks of using nitrification inhibitors.

In recent years, the adoption of drip irrigation has been on the rise in the potato-producing region of Inner Mongolia [20], creating favorable conditions for conducting split N fertilizer application such as Opt. Thus, supplying N precisely with the requirements of potatoes is feasible in the potato production with aid of drip irrigation system, serving as a technological blueprint for sustainable and environmentally friendly potato production.

5. Conclusions

In the primary potato-producing region in Inner Mongolia, the transformation of soil ammonium N was found to be complete about 20 days after the basal dressing of N and 10 days after the top dressing of N during the tuber formation and bulking periods. These critical days can serve as the foundation for the split application of N fertilizer. Implementing a split application of ammonium N based on soil ammonium N transformation patterns can significantly increase the potato yield, marketable tuber rate, and PFP_N and reduce the soil inorganic N residues within the 0–60 cm soil layer.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Yang Chen: Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation. **Yangyang Chen:** Writing – original draft, Investigation, Formal analysis, Data curation. **Jing Yu:** Methodology, Investigation, Funding acquisition, Conceptualization. **Xiaohua Shi:** Methodology, Investigation, Conceptualization. **Liguo Jia:** Methodology, Investigation, Conceptualization. **Mingshou Fan:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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