

BALANCING POTATO YIELD, QUALITY, AND PROFITABILITY THROUGH OPTIMAL NITROGEN FERTILIZATION IN VARIABLE SOIL FERTILITY FIELDS

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Abstract

The relationship between different nitrogen (N) rates and their effects on potato yields and quality under various soil fertility conditions determines the best approach to maximize production while maintaining soil health. This research evaluated how different N application rates affect potato while determining the highest net profit and benefit-cost ratio in potato cultivation across multiple soil fertility conditions through testing ten N rates from 0 to 405 kg/ha. The increase in N fertilizer rates led to increased potato yields and dry matter production but the returns diminished after reaching a certain point. The increase of N levels in the soil resulted in increased plant height, leaf area index (LAI), soluble protein, and reducing sugar content in potato tubers but starch content decreased. The highest potato yields of 32,784 kg/ha occurred in fields with high soil fertility when applying 197 kg/ha of N fertilizer but low fertility fields reached only 9,117 kg/ha with 319 kg/ha of N application. The highest yield did not always lead to the greatest net profit because the optimal N rates were 193 kg/ha and 302 kg/ha which produced yield prices of \$11,799/ha and \$3,274/ha respectively. The research demonstrates that initial soil fertility directly affects potato production outcomes and quality while showing that N management strategies need to be adapted to soil types for maximum profitability.

Keywords: Nitrogen management; Potato yield; Soil fertility; Profitability optimization; Crop quality

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Introduction

Nitrogen (N) is an essential nutrient required for plant growth and production. Its roles in plant growth include serving as a component of chlorophyll, amino acids, proteins, nucleic acids, coenzymes, and membrane constituents. N constitutes 1-4% of the plant's dry weight, and it is absorbed from the soil in the form of nitrate (NO_3^-) or ammonium (NH_4^+) (Horchan *et al.*, 2010). N plays a crucial role in the development of emerging leaves and the rate of leaf expansion, thus influencing the overall canopy development of the plant (Badr *et al.*, 2023). Additionally, it has been reported that N increases the total chlorophyll content, meristematic cells, LAI, and overall crop growth. This enhancement in growth and development is likely attributed to the heightened photosynthetic capacity and increased supply of assimilates (Souza and Tavares, 2021). Furthermore, N content may activate trans-zeatin, positively influencing glutamate/glutamine levels, known to promote stem elongation (Lombardo *et al.*, 2020). N not only improves potato leaf chlorophyll and LAI, but also increases plant height, stem thickness, root length, and the positive correlation between the applied N amount and potato leaf photosynthetic rate and stomatal conductance (Kolodziejczyk, 2014). Potato leaves from plots applying 140-280 kg/ha of N displayed a higher photosynthetic rate and leaf greenness values (SPAD) compared to those from plots fertilized with 0 kg/ha of N. This difference could be attributed to the increased leaf area in high-N plants. A similar trend was observed for SPAD values, which serve as an instantaneous indicator of the potato plant's nitrogen status (Koch *et al.*, 2020).

The application of a higher dose of N fertilizer demonstrated a significant increase in potato plant productivity compared to a lower dose. The increased weight of tubers resulting from fertilizer application could be attributed to enhanced foliage and leaf area, coupled with a higher supply of photosynthate contributing to the production of larger tubers and ultimately higher yields (Ierna and Mauromicale, 2018). Application of N up to 180 kg/ha notably increased the yield of marketable tuber, with the highest N requirement observed during tuber bulking, where approximately 58-70% of the total N uptake occurs (Hidoto *et al.*, 2017). However, it is important to note that an increasing N supply may have a decreasing impact on tuber starch content (Grzebisz *et al.*, 2017). In Mediterranean environments, potato yields increased with an increasing N rate up to 120 kg/ha but did not show further improvement with higher N fertilization rates (Seid *et al.*, 2023).

An excess of available N could lead to delayed tuber set, medium dry matter, susceptibility to diseases, and increased vulnerability to bruising. Meanwhile, the application of phosphate fertilizer can enhance tuber quality, such as skin maturity and dry matter content, at harvest when N levels are excessive (Khan *et al.*, 2012). Field studies have demonstrated that insufficient amounts of N can result in yield losses, while excessive N application not only reduces yield but also detrimentally affects the environment (Horchan, 2010; Hidoto, 2017). Despite this knowledge, farmers frequently apply an excessive amount of N fertilizer to ensure high yields, often surpassing the required amount for maximum crop yield (Akkamis and Caliskan, 2024). However, further increases in N application are unlikely to significantly improve crop yields due to diminishing returns (Koch *et al.*, 2019a). Moreover, this practice may decrease economic returns from crop production, negatively impact water quality and aquatic ecosystems (Koch *et al.*, 2019b), and contribute to emissions of N_2O into the atmosphere (Gelaye, 2023).

The application of optimized N fertilizers lead to better potato growth and improved quality. Scientific N management practices lead to substantial improvements in both potato growth and tuber quality. The application of 150-200 kg/ha of N fertilizer lead to enhanced photosynthetic efficiency through increased chlorophyll content by 15-20% which results in greater tuber bulking and a 25-30% yield increase, and optimal quality parameters that keep starch content between 14-18% (Tan *et al.*, 2016). The research by Yang *et al.* (2024) shows that maintaining soil available N at 90-120 mg/kg supports plant growth equilibrium while avoiding N-related problems that decrease starch levels and make tubers more susceptible to diseases and reduce storage quality. Precision N fertilization through soil testing becomes essential for potato cultivation to reach high yields and produce superior quality tubers.

Therefore, the selection of an appropriate N fertilization rate constitutes a critical decision impacting both the profitability of potato production and the environmental implications of agriculture (Sawicka *et al.*, 2020). Despite this, reports addressing the optimal N application rates that balance production and farmers' economic benefits have been relatively few. This study aimed to assess the optimum amount of N fertilizer in various soil fertility fields in Huishui County, Guizhou province, providing a scientific foundation for potato production. The objectives of this experiment were to investigate the effect of

different N rates on yield formation and quality of potato, and to determine the optimal quantity of N fertilizer application that maximizes net profit from N fertilization.

Materials and Methods

Experimental area and plant materials

Field experiments were conducted in Dashan village, Sandu town, Huishui County, Guizhou province, China (25°58'54"N, 106°45'31"E). During the experiment, the average maximum and minimum temperatures were 24.4°C and 8.6°C, the average relative humidity was 85%, and the total precipitation and sunshine duration were 1013.5 mm and 918.7 h, respectively. The chemical and physical properties of the soil in the study area were performed through random sampling and testing within the 0 to 30 cm surface layer. The results presented in Table 1 revealed that soil with a loamy texture was designated as high-fertility soil (HFS), whereas soil with a sandy texture was designated as low-fertility soil (LFS) according to relevant classification criterion (Bao, 2018). The potato variety used in these experiments was Favorita, an early-maturing, high-yielding variety introduced from the Netherlands in 1980 by the Chinese Ministry of Agriculture. Its planting area in Guizhou has been expanding, particularly in mid- to low-altitude areas during the autumn season. Favorita has a growing period of around 60 days (d) from germination to maturity. The average yield in Guizhou from 2003-2005 was approximately 18,750 kg/ha.

Experimental Design

Two experiments were conducted in two distinct soil fertility areas (LFS and HFS). Ten treatments of N application rates (N0, control=0 kg/ha, N1=45 kg/ha, N2=90 kg/ha, N3=135 kg/ha, N4=180 kg/ha, N5=225 kg/ha, N6=270 kg/ha, N7=315 kg/ha, N8=360 kg/ha, N9=405 kg/ha) were organized in a randomized complete block design (RCBD), with three replications. Urea (46% N) was used as the N source, K₂SO₄ (50% K₂O) as the K source, and ordinary superphosphate (12% P₂O₅) as the P source. The amount of P₂O₅ applied was 56 kg/ha and K₂O was applied at 158 kg/ha. 40% of

N fertilizer was used as basal fertilizer through row application at seeding time. In comparison, 30% of N was applied as the first top dressing during the budding stage, and the remaining 30% of N was administered as the second top dressing during the flowering stage. Each individual plot was 2 m wide and 6 m length, consisting of four rows and separated from adjacent plots by a 0.5 m wide plant-free border. Seeding was completed at a hill spacing of 0.375 m × 0.5 m with one seed per hill, and each plot contained 64 hills. During the growing period, pesticides were applied twice when insect incidence occurred, and weeding was conducted on two occasions.

Data collection

For plant height measurement, ten plants were randomly selected and marked from each plot or replication. The height of the tallest shoot was measured from the cotyledon node to the base of the last leaf unfolded at 40 d. Additionally, ten plants from each plot or replication were assessed at 40 d, and leaf area was determined using a leaf area meter (LI-3100; LI-COR Inc., Lincoln, NE, USA). Subsequently, the LAI was determined by applying the formula developed by Iwama (Iwama, 2008).

In both experimental fields, the fresh tuber yield at harvest was determined in each plot using a two-center-row section. Tuber yield was counted and weighed to calculate the total tuber yield per hectare. Indexes of quality were assessed in Soil and Fertilizer Research Institute, Guizhou Academy of Agricultural Science, Guiyang, China. Starch content was analyzed for three random samples of plants in each plot, measured only for the fresh part of the tuber. Starch content was examined with a polarimeter (Zeiss, Oberkochen, Germany) at 589 nm, following the procedure described in Koch *et al.* (2019b). Total soluble protein (g/100g) was determined according to the method by Khan *et al.* (2012). Reducing sugars were determined following the procedure described in Koch *et al.* (2019a). The dry matter of the above-ground plant was determined on a fresh weight basis. Three samples of the whole plant from each plot were taken and dried in an oven at 60°C until complete drying to achieve a constant weight. Dry matter was calculated as the ratio between dry and fresh mass and expressed as a percentage.

Table 1. Physical and chemical properties of the soil in the experiment (0–30 cm depth)

Field	Soil Texture	pH	OM (g/kg)	Total N (g/kg)	Available N (mg/kg)	Available P (mg/kg)	Exchangeable K (mg/kg)
HFS	Loamy soil	5.68	28.9	1.624	182.1	42.7	107.4
LFS	Sandy soil	5.42	17.7	0.787	39.4	10.6	27.9

Data on potato price, fertilizer price, and the cost of production were collected. The economic net return was calculated by subtracting the cost of the applied fertilizer from the gross sale value of the crop. The prices of production inputs were determined based on the average market prices in the local area from 2017 to 2023 (Table 2).

Table 2. Cost components of potato production in Guizhou

Cost components	Unit Price
N	0.65 (\$/kg)
P ₂ O ₅	0.87 (\$/kg)
K ₂ O	1.02 (\$/kg)
Potato seed	0.45 (\$/kg)
Fresh potato	0.36 (\$/kg)
Pesticide	72.75 (\$/ha)
Land rental cost of high fertility soil field	1,575.00 (\$/ha)
Land rental cost of low fertility soil field	900.00 (\$/ha)
Labor cost	1,125.00 (\$/ha)

Statistical analysis and economic evaluation

Analysis of variance (ANOVA) was performed using IBM SPSS Statistics for Windows (v.16.0), with the significance level (α) set at 0.05. Regression analysis was employed to establish the yield response curve to fertilizer rates. The response to N was examined by fitting quadratic response equations for total tuber yield. The quadratic response equation demonstrated the best fit for the relationship between x and Y , as shown below equation (1):

$$Y = a + bx + cx^2 \quad (1)$$

where, Y represented the total tuber yield (kg/ha), x represented the rate of N fertilization (kg/ha), and a , b , and c are constants.

By setting the derivative of the yield equation equal to zero ($y' = 0$) the quantity of N fertilizer required to achieve the maximum yield could be calculated.

The economic response to N was analyzed by fitting quadratic equations for monetary value as shown below equation (2):

$$Y_1 = a_1 + b_1x + c_1x^2 \quad (2)$$

where Y_1 represents the total value (\$/ha), x is the N rate (kg/ha), and a_1 , b_1 and c_1 are constants.

With N fertilizer priced at 0.87 \$/kg, the total costs of N fertilizer per hectare was calculated as follows equation (3):

$$C = 0.65x \quad (3)$$

The quantity of N required to maximize profit from fertilization is estimated by setting the derivative of the crop value equation equal to the derivative of the cost equation ($Y_1' = 0.65$) and solving the resulting equation for the N quantity (optimum N).

From the optimum N rate, the optimum yield price can be calculated. The following economic parameters can be determined as follows:

Maximum net profit from production equation (4):

$$P_p = Y_1 - C_p \quad (4)$$

where P_p represents the maximum net profit from production, Y_1 is the total value (\$/ha), and C_p is the total cost of potato production.

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Results and Discussion

Effects of different N fertilizer rates on potato growth

The analysis of variance revealed significant differences in plant height among N treatments (Table 3). Plant height in the HFS field was considerably taller than that in the LFS field. The maximum plant height was observed at the application N rate of 405 kg/ha in both fields, indicating that increasing N rate led to an increase in plant height. This finding aligns with Hassanpanah *et al.* (2009), who reported a significant increase in plant height with higher levels of N fertilizer. The relationship between N supply and carbohydrate utilization plays a crucial role, as adequate N supply under favorable growth conditions facilitates the formation of proteins from manufactured carbohydrates. This surplus protein contributes to accelerated plant growth, explaining the observed significant increase in plant height with higher levels of N application. These results also find support in the studies conducted by Badr *et al.* (2023), Gupta and Sharma (2010); Sawicka *et al.* (2020). The coefficient of variation (CV) for potato plant height remained steady under both HFS (CV = 11.23%) and LFS (CV = 15.33%) conditions. The results showed that potato plants with increasing N application rates maintain a positive growth response pattern which remains stable throughout. The increasing increment of plant height of potato is most noticeable from N0 to N2, the largest increment reached approximately 4 cm; a similar trend showed in both HFS and LFS field. The increasing increment is relatively little

from N2 to N9, which to a large extent indicates that N2 is the critical point of N application rate in comparison with N0.

LAI exhibited similarly significant differences among N treatments (Table 3). The maximum LAI was observed at the application of 405 kg/ha of N in both soil fertility fields, which aligns with similar results reported in other studies. Li *et al.* (2023) observed an increase in plant height and LAI with higher N levels, highlighting the crucial role of N as the most essential plant macronutrient, required in larger quantities compared to other plant nutrients for most plant species. These results find additional support by Gelaye (2023). N application exerted a significant impact on both aboveground and underground plant weight. High N application during the reproductive stage led to substantial growth of LAI in potato according to Kolodziejczyk (2014). The research of Iwama (2008) supports this observation because he found that higher N levels enable crops to maintain leaf area growth. The present research showed that LAI grew substantially from N0 to N4 as N application rates increased. The additional LAI gains became smaller after N4 (N5–N9 treatments) indicating a saturation point. The study demonstrates that leaf expansion benefits from moderate N application yet additional N inputs above N4 levels produce no significant extra advantages. The observed plateau effect demonstrates that applying N beyond optimal levels results in poor agronomic outcomes while creating economic problems from fertilizer waste and environmental threats from N pollution.

Effects of different N fertilizer rates on potato yield

The results indicated significant differences in tuber yields among N rates (Table 4). Fresh tuber yields in the HFS were considerably higher than

those in the LFS. Among fertilizer levels, the application of 180 kg/ha of fertilizer in the HFS produced the highest yield (32,583 kg/ha), while in the LFS, the highest yield (9,167 kg/ha) was obtained at the N rate of 315 kg/ha. The research indicates that potato yield increases when N fertilizer application reaches a specific threshold, but excessive application leads to decreased yields, especially when soil fertility is low. N plays a crucial role in plant growth, but excessive N content is not conducive to achieving optimal fresh tuber yield in potato. Although fresh tuber yields of potato showed a rising trend from N0 to N5, no significant difference was observed from N2 to N5 along with the addition of N application rate in the HFS. Similar results appeared from N5 to N7 in the LFS.

The experimental results showed that N application requirements depended on the soil fertility levels. The highest potato yields under HFS conditions were obtained at N application rates of 135–225 kg/ha, while LFS conditions needed 270–315 kg/ha to achieve equivalent yields. The results match Kolodziejczyk (2014), who found the highest marketable tuber yields at 120–180 kg/ha on silty loam soils. The differences in optimal N application rates between studies probably result from variations in soil fertility. The results support Li *et al.* (2010), who found that excessive N application above 210 kg/ha resulted in yield decreases. Farmers need to use fertilization methods that match their specific soil conditions. The research confirms the need for N recommendations that are specific to each site, following experimental assessments of soil fertility.

Table 3. Effects of N application on plant height and leaf area index

TRT	Plant height (cm)		LAI	
	HFS	LFS	HFS	LFS
N0	40.4i	22.7 i	2.07 g	1.13 e
N1	44.9h	26.7 h	2.31 f	1.37 d
N2	48.7g	29.2 g	2.57 e	1.45 cd
N3	49.3fg	30.3 f	2.74 de	1.48 cd
N4	50.4ef	31.1 e	3.01 c	1.54 c
N5	51.0de	32.8 de	3.09 bc	1.60 bc
N6	51.8 cd	33.6 cd	3.21 b	1.68 bc
N7	52.4 c	34.4 bc	3.22 b	1.70 b
N8	53.3 b	35.1 b	3.34 ab	1.75 ab
N9	54.9 a	37.1 a	3.46 a	1.88 a
CV (%)	11.23	15.33	12.46	11.54

Note : The mean in a column followed by the same letters is not a significant difference at $p < 0.05$ by DMRT.

Effects of different N fertilizer rates on potato quality

The quality of potatoes depends on soluble protein, starch, reducing sugars, and dry matter content because these factors determine processing capabilities, nutritional value, and sensory characteristics. The product quality will suffer substantially when any of these indicators are outside their optimal ranges. The combination of excessive soluble protein with reducing sugars during frying produces undesirable browning in potato chips through Maillard reactions (Wang *et al.*, 2023). The starch content exceeds 22% which causes French fries to become hard in their core. The presence of more than 0.5% reducing sugars in the product leads to darkening and the development of a bitter taste. The dry matter exceeding 26% results in a coarse texture and poor mouthfeel (Wang *et al.*, 2023).

Table 4 revealed significant differences in starch content among N rates. Starch content in the treatment with 0 kg/ha of N ranked in the superior group, displaying the highest starch content. The observed decrease in starch content with increasing N fertilizer suggests that an excess of N fertilizer promotes the growth of excessive aboveground vegetative organs, thereby limiting the amount of photosynthate translocated to produce starch for underground tubers (Kwambai *et al.*, 2022). However, contrasting findings exist, as demonstrated by Khan *et al.* (2012), who reported a significant difference in starch contents among different cultivars and N levels, emphasizing that excessively high or low N levels could reduce tuber starch content (Khan *et al.*, 2012; Zaman *et al.*, 2019). Although the whole trend of starch content is declining along with the addition of N application rate, no significant difference was shown from N0 to N2 in the HFS field and N0 to N1 in the LFS field, which indicates that a critical point of N application rate exists.

Soluble protein content in this experiment exhibited significant differences among N rates (Table 4). The soluble protein content in the tubers of both fields increased significantly under the influence of N fertilization. Specifically, the increase in soluble protein content after the application of N fertilizer (405 kg N/ha) was 1.624 g/100 g for HFS field and 1.599 g/100 g for LFS field. These findings are consistent with Kolodziejczyk (2014) who concluded that an increase in N doses regularly increases the soluble protein content in potatoes (Khan *et al.*, 2012; Kolodziejczyk, 2014). On the whole, soluble protein content increases with the addition of N application rate, with similar results exhibited in

both fields. The growth point ended in N9 in the HFS field, because no significant difference was shown between N8 and N9, while the growth point did not end in the LFS field.

Reducing sugar content showed significant differences among N rates (Table 4). The means comparison revealed that, among fertilizer levels, the N rate of 405 kg/ha produced the highest reducing sugar content in both fields. N fertilizer application was found to increase the reducing sugar content in potato tubers. The trend of reducing sugar content is similar in both fields, namely, along with the increase of N application rate, reducing sugar content is increasing. This result is consistent with Lv *et al.* (2018) who reported an increase in reducing sugar content with higher N application rates (Lv *et al.*, 2018). However, the growth point ended in N7 treatment, because from N7 to N9 there is no significant difference in the HFS field, while that did not end in the LFS field. The variation trend of reducing sugar content is the same as that of soluble protein content, namely in accompanying with the increasing of N application rate, both content increases gradually.

Dry matter percentage in the HFS field was considerably higher than that in the LFS field (Table 4). Among N fertilizer levels, the application of 180 kg/ha in the HFS field produced the highest dry matter percentage (19%). In the LFS field, the highest dry matter percentage (17.4%) was obtained at the N rate of 315 kg/ha. The results aligns with the findings of Wang *et al.*, 2023 where dry matter accumulation of fleshy roots increased initially and then decreased with the increase of N application rates (Akkamis and Caliskan, 2024). However, the results diverge from those of Koch *et al.* (2020), who reported a positive effect of N fertilizer on dry matter content (Koch *et al.*, 2019a). Kolodziejczyk (2014) also suggested that excessive levels of available N fertilizer stimulate tuber reformation, potentially lengthening the tuber formation period and resulting in differences in tuber maturity, thereby impacting tuber dry matter content. The variation trend of dry matter percentage exhibited the same result as that of fresh tuber yield, namely, a suitable N application rate contributes to the accumulation of dry matter percentage, but beyond that, it could lead to a decrease. Dry matter percentage of potato in both fields was generally up to the maximum in the N5 treatment, although the first maximum was at the N4 treatment in the HFS field, and there was no significant difference between N4 and N5. Similarly, no significant difference was exhibited between N5 and N7 in the LFS field.

Table 4. Effects of N application on potato tuber yield and quality

TRT	Yield (kg/ha)		Starch (%)		Soluble protein (g/100g)		Reducing sugar (%)		Dry matter (%)	
	HFS	LFS	HFS	LFS	HFS	LFS	HFS	LFS	HFS	LFS
N0	20,417 f	3,417 f	69.2 a	65.9 a	0.966 f	0.806 f	0.314 f	0.558 g	14.2 e	11.2 f
N1	27,917 c	5,000 de	67.4 ab	65.3 ab	0.979 f	0.826 f	0.346 ef	0.590 fg	15.3 de	12.4 e
N2	30,667 ab	6,000 cd	65.4 abc	60.7 bc	1.008 ef	0.926 ef	0.385 de	0.646 e	16.7 bc	13.3 de
N3	32,333 a	7,333 bc	56.4 cd	54.7 cd	1.173 de	0.994 de	0.419 d	0.658 def	17.3 bc	15.7 bc
N4	32,583 a	8,167 b	47.5 de	49.5 de	1.203 de	1.017 de	0.441 cd	0.668 de	19.0 a	16.8 ab
N5	32,250 a	8,500 ab	47.3 de	39.4 fg	1.227 d	1.029 de	0.478 bc	0.691 d	18.9 ab	16.9 ab
N6	31,667 ab	9,000 a	41.4 f	35.0 gh	1.260 cd	1.053 de	0.484 bc	0.729 bcd	17.7 abc	17.1 a
N7	27,667 cd	9,167 a	40.6 fg	34.4 gh	1.334 cd	1.185 cd	0.496 abc	0.737 bc	17.5 bc	17.4 a
N8	23,417 de	8,917 ab	37.5 fg	34.2 gh	1.547 ab	1.444 b	0.522 ab	0.757 bc	17.2 bcd	16.7 ab
N9	23,083 de	8,750 ab	35.8 g	32.2 h	1.624 a	1.599 a	0.559 a	0.824 a	16.1 cd	15.8 bc
CV (%)	20.76	23.84	14.42	13.78	10.75	16.93	12.32	16.62	25.15	24.49

Note: The mean in a column followed by the same letters is not a significant difference at the 5% level by DMRT.

Economic evaluation of N application

In this experiment, where fixed P and K applications were employed, we observed a response in potato yield to varying N rates. The relationship between potato yield and N application was well-described by a quadratic equation (Figure 1).

The response functions applied in the HFS field were as follows:

$$(a) Y = 22,241 + 107.3x - 0.273x^2, R^2 = 0.904$$

In the LFS field, the response function was:

$$(b) Y = 3,427 + 35.7x - 0.056x^2, R^2 = 0.997$$

Where Y represents potato yield (kg/ha), and x denotes the application of N fertilizer (kg/ha). The results depicted in Figure 1 indicated that at low N levels in both soil fields, potato yield exhibited a positive response to N rate, reaching a maximum at specific N levels. Subsequently, beyond this optimum point, the yield gradually decreased with the increased N application.

From the regression analysis of the quadratic model, the results indicated that in the HFS field, the maximum potato yield (32,784 kg/ha) was obtained at an N rate of 197 kg/ha. In the LFS field, the maximum yield (9,117 kg/ha) was obtained at an N rate of 319 kg/ha. These findings suggest limitations in available N in both fields, with a greater limitation observed in the LFS field. This implies that the proportion of N fertilizer in the high soil fertility field was relatively high. The application of N fertilizer led to an excessive N presence in both fields, causing the potato plants to grow excessively tall, consuming an excessive amount of photosynthetic products and reducing the yield of potato tubers. This result is supported by Dou *et al.* (2017) who also demonstrated that in low

soil fertility fields, gradual increases in N application levels corresponded to increased production until reaching a certain threshold. Beyond this threshold, further increases in N resulted in decreased production. This phenomenon may be attributed to the fact that in low soil fertility fields, appropriate application of N fertilizer can increase both the number and weight of potatoes, while excessive application of N fertilizer may lead to delayed tuber formation, decreased individual potato weight, and an overall decrease in potato yield.

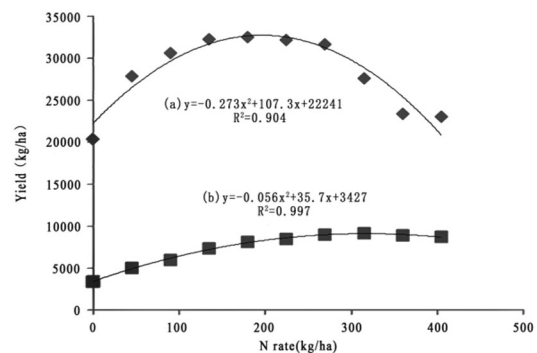


Figure 1. Relationships between potato yield and nitrogen fertilizer application under HFS (a) and LFS (b) conditions

Optimum N fertilizer application and optimum yield price

The application of economic principles to fertilizer use is typically illustrated in situations where the supply of capital is abundant, and no other investment opportunities would yield a more profitable return. In such cases, the optimum application of fertilizer is the quantity that results in the maximum net profit. The optimum yield price

from fertilization is determined by the fertilizer application rate at which the monetary value of the optimum N fertilizer rate is maximized. When the response curve is represented by a mathematical function, the quantity of fertilizer that yields the optimum yield price is estimated mathematically. This process can be better understood by first multiplying the yield response function by the price per unit of the crop to convert the function into monetary units. The procedure can then be visualized as depicted in Figure 2.

In these two experiments, N fertilizer was side dressed in varying quantities, and the employed response function used for both experiments followed a quadratic model:

$$Y = a + bx + cx^2$$

Where Y represents the monetary value of potato per hectare and x denotes the application of N fertilizer in kilograms per hectare.

The specific response functions for the HFS field was:

$$Y = 53,446.199 + 261.551x - 0.655x^2$$

For the LFS field, the response function was:

$$Y = 9,012.555 + 86.325x - 0.135x^2$$

Considering the cost of fertilizer at 0.65 \$/kg, the total costs of N fertilizer in \$/ha were calculated using the equation:

$$Y = 0.65x$$

Where Y represents the cost of N fertilizer, and x is N rate.

In terms of economic benefits, primarily driven by economic output and overall performance, value, and cost considerations, an increase in N fertilizer can lead to higher yields and production value. However, it also results in increased corresponding costs. Therefore, the maximum yield does not necessarily translate to the highest economic benefits. The optimum benefits

are achieved when marginal costs equal marginal output, and the profit margin is zero. Through the calculation of these two equations, the optimum N fertilizer application in high fertility soil was determined to be 193 kg/ha, with an optimum yield price of 11,799 \$/ha. In low fertility soil, the optimum N fertilizer application was 302 kg/ha, with an optimum yield price of 3,274 \$/ha.

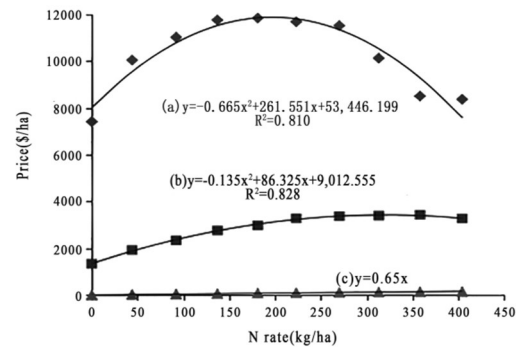


Figure 2. Relationships between N fertilizer application and monetary value in HFS (a), LFS (b), and the effect of fertilizer price on economic returns (c)

Maximum net profit and benefit cost ratio in potato production

The maximum net profit was 8,152 \$/ha in the HFS field and 232 \$ in the LFS field (Table 5). The results indicate that the total cost is higher in the HFS field, but the yield in the HFS field is 3.6 times higher than that in the LFS field, resulting in a higher maximum net profit. This result is supported by Qin *et al.*, (2022) who also demonstrated that high productivity could compensate for higher input costs and thereby increase the maximum net profit for oilseed rape (Naeem *et al.*, 2015; Qin *et al.*, 2022). The benefit-cost ratio is directly proportional to the net return; a higher benefit-cost ratio results in a higher net return.

Table 5. The maximum net profit and benefit-cost ratio in potato production

Economic valuation	HFS	LFS
Cost of N fertilizer (\$/ha)	125	195
Field cost (\$/ha)	3,522	2,847
Total cost (\$/ha)	3,647	3,042
Optimum yield price (\$/ha)	11,799	3,274
Maximum net profit (\$/ha)	8,152	232
Benefit cost ratio(Maximum net profit/Total cost)	2.235	0.076

The total costs of production, including the cost of all fertilizers, seeds, pesticides, labor, and land rent, were estimated at 3,647 \$/ha in the HFS field and 3,042 \$/ha in the LFS field. In the HFS field, the benefit-cost ratio in crop production was 2.235, while in the LFS field, the benefit-cost ratio in crop production was 0.076. These results indicate that it is more economically viable to invest in the HFS field than in the LFS field.

Conclusions

Appropriate N fertilizer management is the key to ensure high yield of high-quality potatoes. Excessive N fertilizer application increases planting costs, thereby reducing the income of growers, and can also cause certain pollution to the environment. Elevated N levels were positively correlated with increased plant height, LAI, soluble protein content, and reducing sugar content in potato tubers, but negatively correlated with starch content. In HFS, the maximum yield of 32,784 kg/ha was achieved at an N application rate of 197 kg/ha, whereas in LFS, a yield of 9,117 kg/ha was obtained at 319 kg/ha N application. However, the N rate that maximized yield did not necessarily correspond to the highest net profit. The economically optimal N rates were determined to be 193 kg/ha for HFS, yielding a net profit of \$11,799/ha, and 302 kg/ha for LFS, resulting in \$3,274/ha. The maximum net profits reached \$8,152/ha in HFS and \$232/ha in LFS with benefit-cost ratios of 2.235 and 0.076, respectively.

In Guizhou Province, China, limited research has been conducted on optimal N application rates for potato cultivation. These findings underscore the importance of rational N fertilization in enhancing yield while minimizing waste and environmental impact. This study provides valuable insights into N management strategies tailored to different soil fertility conditions, offering practical recommendations for improving potato production efficiency.

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