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THE IMPACT OF NITROGEN–PHOSPHORUS–POTASSIUM RATIOS ON POTATO (*Solanum tuberosum L.*) YIELD AND VARIETY: A CASE STUDY IN LIANGSHAN YI AUTONOMOUS PREFECTURE IN SICHUAN PROVINCE

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Abstract

Reasonable fertilization is important for promoting potato growth and increasing potato yield and quality. Rational fertilization is crucial for promoting potato growth and enhancing both yield and quality. As a major potato-producing region in China, Liangshan Yi Autonomous Prefecture still commonly faces excessive and improper fertilizer application. This study focuses on the locally predominant cultivar "Chuanliangshu 10" and adopts a fully implemented "3414" fertilizer experimental design, with nitrogen (N), phosphorus (P), and potassium (K) as the main factors, each at four levels. By analyzing the variations in potato agronomic traits, yield, and quality under different NPK ratios, this research aims to explore the optimal fertilization ratio suitable for potato cultivation in the region. The results revealed that the potato yield was greatest in the T3 treatment ($N_1P_2K_2$, N 56.25 kg ha^{-1}, P_2O_5 112.50 kg ha^{-1}, and K_2O 112.50 kg ha^{-1}). By fitting the yield data to a ternary quadratic regression model, the theoretically optimal fertilization treatment was calculated as T13 ($N_1P_2K_1$, N 56.25 kg ha^{-1}, P_2O_5 112.50 kg ha^{-1}, and K_2O 56.25 kg ha^{-1}). In the T5 treatment ($N_2P_1K_2$, N 112.50 kg ha^{-1}, P_2O_5 56.25 kg ha^{-1}, and K_2O 112.50 kg ha^{-1}), the potato plant height, emergence rate, marketable tuber ratio, dry matter content, and amino acid content were relatively balanced. Considering all the factors, the T5 treatment is recommended as the optimal fertilization ratio for potato cultivation in this region.

Keywords: Chemical fertilizer. Chuanliangshu 10. Emergence rate. Plant growth. Tuber traits.

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1. Introduction

Potato plants (Solanum tuberosum L.) are annual herbaceous plants belonging to the nightshade family, Solanaceae (Zhou et al. 2019). Their tubers are edible, and they are the fourth most important staple crop worldwide, following wheat, rice, and maize (Muleta et al. 2021). More than 150 countries worldwide cultivate potatoes, with China, India, Ukraine, and Russia being notable producers. China, in particular, is the largest producer and consumer of potatoes. Potato plants have a relatively short growth cycle, strong adaptability, high yield per unit area, and high nutritional value, with extensive potential for technological applications, making them suitable for large-scale cultivation (Silva et al. 2022). They play a crucial role in helping farmers escape poverty, adjusting planting structures, and ensuring food security.

The yield and quality of potatoes are influenced primarily by genetic factors and environmental conditions. Climatic conditions, cultivation practices, and fertilizers all have varying degrees of impact on potato yield and quality (Van der Bom et al. 2017). Fertilizers play a vital role in the growth and development of potatoes, as they are nutrient-demanding crops (Torabian et al. 2021). Nitrogen (N), phosphorus (P), and potassium (K) are essential nutrients for potato plants throughout their growth process, with K being the nutrient element that is absorbed and transported the most, directly affecting yield and tuber quality (Oliveira et al. 2019). Gelaye et al. (2021) reported that the highest potato tuber yield was achieved under treatments with 34.5 kg P2O5 ha-1 and 200 kg K2O ha-1. Similarly, using higher levels of fertilizer (150–150–90 kg N–P–K per hectare) can significantly increase the growth and yield of potato plants (Sai and Paswan 2024). However, excessive use of NPK fertilizers can lead to imbalances in soil nutrient levels. This excessive application may cause the plant to absorb unnecessary nutrients, resulting in reduced yield. Gondwe et al. (2020) reported that excessive application of NPK fertilizers may adversely affect tuber formation, commercial rates, and yield and could also pose environmental risks such as water eutrophication. Additionally, while increasing the amount of N and P can increase tuber yield, excessive P levels can reduce the starch content (Ciecko et al. 2004). Therefore, proper fertilization practices are crucial for improving crop yield, quality, and soil health.

Liangshan Yi Autonomous Prefecture is the primary potato-producing region in Sichuan Province, China. It is situated at elevations ranging from 1,800 to 4,000 meters. The region has diverse climatic conditions and abundant light and thermal resources (Sichuan Statistical Yearbook 2023). In recent years, the potato cultivation area in this region has remained consistently above 150,000 hectares, accounting for approximately one-quarter of the total potato planting area in Sichuan Province (Sichuan Statistical Yearbook, 2023). However, practical agricultural practices in the region face challenges such as excessive fertilizer application and imbalanced nitrogen–phosphorus–potassium (NPK) ratios. These issues significantly constrain both the quality and competitiveness of the local potato industry. Therefore, it is highly important to explore the appropriate N–P–K fertilization ratios for potato growth in Liangshan Yi Autonomous Prefecture, where no relevant research has been reported thus far. The “3414” experiment is currently a widely used and efficient field experiment scheme for studying fertilizer effects and consists of three factors (N–P–K), four levels, and 14 treatment groups. (Duan et al. 2023). This scheme offers minimal regression treatments and high efficiency while meeting the necessary conditions for fertilizer trials and fertilization plans (Li et al. 2014; Liu et al. 2014). It provides a comprehensive fertilizer response regression equation, allowing for the determination of optimal fertilizer application rates to achieve maximum yield and economic benefits. Through field experiments, this study aims to explore the effects of combined N, P, and K application on potato agronomic traits, yield, and quality. The goal is to identify suitable N, P, and K ratios for potato production in the experimental area, thereby providing a theoretical basis and technical guidance for improving local potato yield and quality.

2. Material and Methods

Experimental location and materials

The experiment was conducted in 2023 at the potato demonstration base in Xide County, Liangshan Yi Autonomous Prefecture, Sichuan Province, China (latitude 28° 21' N, longitude 102° 18' E, and altitude

2600 m). The soil type in the experimental field was yellow soil. The basic physicochemical properties of the soil were as follows: pH 6.15, organic matter content of 44.1 g kg^{-1}, available N concentration of 182 mg kg^{-1}, available P concentration of 15.8 mg kg^{-1}, and available K concentration of 82 mg kg^{-1}. The area experiences an average annual sunshine duration of 2016 hours, an average annual temperature of 14 ℃, and an average annual rainfall of 1034.2 mm (Sichuan Statistical Yearbook 2023).

The experimental material is the main local cultivar "Chuanliangshu 10" from Liangshan Yi Autonomous Prefecture (Fu et al. 2025). It was jointly bred by Liangshan Yi Autonomous Prefecture Academy of Agricultural Sciences and Yunnan Academy of Agricultural Sciences. This variety is a mid-to-late maturing cultivar with a growth period of 85 days. Its tubers are elliptical in shape and feature yellow skin and white flesh. The average yield is approximately 1,600 kg 667 m^{-2} (Dong, Liu and Xia 2013). The tested fertilizers included urea (N 46%), superphosphate (P_2O_5 16%), and potassium sulfate (K_2O 52%).

Experimental design

The “3414” fertilizer efficiency field experiment was employed (Table 1), with nitrogen, phosphorus, and potassium as the main factors, each having four levels. Level 0 represented no fertilization, Level 2 represented the local recommended fertilizer application amount (N–P_2O_5–K_2O, 15–15–15, and 750 kg ha^{-1}), Level 1 represented Level 2 multiplied by 0.5 (insufficient fertilization), and Level 3 represented Level 2 multiplied by 1.5 (excessive fertilization). In total, there were 14 treatments. The specific experimental design and fertilizer application amounts are provided in Table 1. The experiment commenced on March 2, 2023, when single ridges and double rows were planted. Each treatment was replicated three times. The plot area was 20 m^2 (5×4 m), with a ridge spacing of 80 cm and a plant spacing of 25 cm, resulting in a density of 75,000 plants per hectare. There was a 1.0 m protective row around the plot. All the treatments were arranged randomly, and the fertilizers were applied as base fertilizer in a single application. After seedling emergence, field management was carried out according to traditional local practices, including one intertillage and weeding, one irrigation, and three late blight control treatments. Late blight was controlled using the protective fungicide 75% Mancozeb. The emergence rate during the bud stage, which is the percentage of emerged plants in the planting holes within a plot, was surveyed. The number of main stems during the vegetative stage, which refers to the number of stems growing directly underground, was counted. The plant height during the flowering stage was measured using a ruler. It represents the distance from the base of the stem to the growth point. Ten plants were randomly selected from each plot at each stage for investigation, and the average result was calculated.

Table 1. “3414” design scheme of the experiment.

Treatment	Fertilization level			Amount of fertilizer (kg ha^{-1})		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
T1 ($N_0P_0K_0$)	0	0	0	0	0	0
T2 ($N_0P_2K_2$)	0	2	2	0	112.50	112.50
T3 ($N_1P_2K_2$)	1	2	2	56.25	112.50	112.50
T4 ($N_2P_0K_2$)	2	0	2	112.50	0	112.50
T5 ($N_2P_1K_2$)	2	1	2	112.50	56.25	112.50
T6 ($N_2P_2K_2$)	2	2	2	112.50	112.50	112.50
T7 ($N_2P_3K_2$)	2	3	2	112.50	168.75	112.50
T8 ($N_2P_2K_0$)	2	2	0	112.50	112.50	0
T9 ($N_2P_2K_1$)	2	2	1	112.50	112.50	56.25
T10 ($N_2P_2K_3$)	2	2	3	112.50	112.50	168.75
T11 ($N_3P_2K_3$)	3	2	3	168.75	112.50	168.75
T12 ($N_1P_1K_2$)	1	1	2	56.25	56.25	112.50
T13 ($N_1P_2K_1$)	1	2	1	56.25	112.50	56.25
T14 ($N_2P_1K_1$)	2	1	1	112.50	56.25	56.25

Note: The 0, 1, 2 and 3 of the test factor coding represent the 4 levels of the amount of fertilizer, respectively.

Sample collection and analysis

The tubers were harvested on August 29, 2023. The yield per plot was recorded, and the weight of the marketable tubers (tubers weighing more than 50 g) per plot was recorded. The marketable tuber rate is the percentage of the weight of marketable tubers to the total yield per plot.

After the yield was recorded, 3 kg of tuber sample was collected from each plot for the determination of nutritional indicators. The tubers were washed thoroughly with distilled water and dried in a vertical drying oven (model: WGL-230B) at 68 °C to a constant weight. The dry matter was expressed as a percentage of dry weight to wet weight (Mello et al. 2018). The starch content in the tubers was determined according to the methods of Rickard and Behn (1987). The total potassium content was measured using a flame photometer (model: FP6410) following the procedure described by Rosen et al. (1957). Reducing sugars were determined using the 3,5-dinitrosalicylic acid (DNS) colorimetric method as described by Dubois et al. (1956), and the absorbance of the samples was measured at a wavelength of 540 nm using a UV–visible spectrophotometer (model: L6). The potato samples were ground in a mortar and pestle and then mixed with an appropriate amount of extraction buffer (phosphate buffer). The absorbance of the protein was measured at a wavelength of 595 nm using a UV–visible spectrophotometer (model: L6) with Coomassie Brilliant Blue G-250 dye according to Marion and Bradford (1976). Vitamin C was determined by high-performance liquid chromatography (model: Series 200) following the method of Tumbas et al. (2013). The zinc content in the potato samples was determined using an inductively coupled plasma optical emission spectrometer (model: iCAP PRO) after digestion with a microwave digestion system according to the method described by Gupta and Gupta (2012).

Statistical analysis

Analysis of variance (ANOVA) was performed with a data processing system (DPS) (Tang et al. 2013). The data are presented as the means of three replicates. Means were compared by the least significant difference (LSD) test. $P \leq 0.05$ was considered to indicate a significant difference. Spreadsheet and graphical work were processed in Excel 2016 and Origin 2021, respectively. Statistical analysis was conducted on the potato yields corresponding to different N, P, and K fertilizer treatments. The experimental results were fitted to a ternary quadratic fertilizer response model to calculate the maximum yield and the optimal application rates of associated N, P, and K fertilizers.

3. Results

Potato growth

Nitrogen, phosphorus, and potassium fertilizers play crucial roles in the plant morphology and growth development of potatoes. Different fertilization treatments resulted in varying plant heights for potatoes (Table 2). Compared with the nonfertilized control (T1), none of the treatments reached statistical significance. Compared with those in T2 and T4, the plant height in T6 was significantly greater, reaching 45.41 cm ($p \leq 0.05$). With respect to the number of main stems in the potatoes, the number of main stems in the T8 treatment was significantly greater than that in the T10 treatment (by 0.3 stems) ($p \leq 0.05$); however, no significant differences were observed among the other treatments. With respect to the emergence rate, the emergence rates of potatoes in the different treatments were greater than 80%. The highest emergence rate of potatoes was observed in T12, at 89.04%, which was significantly higher than that in T11 ($p \leq 0.05$) by 7.68%. There were no significant differences among the other treatments. With the exception of T11, the emergence rates of potatoes in all the other fertilization treatments were higher than those in T1 (81.80%), indicating a trend toward an increased emergence rate with increasing fertilization.

Table 2. Effects of different fertilization treatments on potato growth indicators.

Treatment	Plant height (cm)	Main stem number	Emergence rate (%)
T1	40.36±5.67^{abc}	1.2±0.20^{ab}	81.80±5.71^{ab}
T2	39.01±6.07^{bc}	1.3±0.23^{ab}	83.77±3.00^{ab}
T3	43.95±1.20^{ab}	1.3±0.31^{ab}	83.11±2.23^{ab}
T4	38.71±1.45^{c}	1.2±0.20^{ab}	86.84±5.47^{ab}
T5	43.03±2.43^{abc}	1.3±0.12^{ab}	87.72±4.71^{ab}
T6	45.41±2.52^{a}	1.2±0.20^{ab}	82.02±11.87^{ab}
T7	43.78±2.03^{abc}	1.2±0.20^{ab}	82.89±0.62^{ab}
T8	42.71±2.27^{abc}	1.4±0.20^{a}	85.96±0.76^{ab}
T9	41.61±6.17^{abc}	1.2±0.08^{ab}	87.94±3.87^{ab}
T10	41.58±2.86^{abc}	1.1±0.12^{b}	85.31±0.83^{ab}
T11	42.3±2.34^{abc}	1.2±0.20^{ab}	81.36±1.26^{b}
T12	41.91±2.66^{abc}	1.2±0.20^{ab}	89.04±4.17^{a}
T13	41.96±0.90^{abc}	1.1±0.12^{ab}	86.84±2.05^{ab}
T14	41.31±3.32^{abc}	1.3±0.12^{ab}	84.87±1.72^{ab}

Note: According to the ANOVA and LSD multiple range tests, different lowercase letters following the mean ± standard deviation indicate a significant difference (P ≤ 0.05) between treatments. T1, $N_0P_0K_0$ (N 0 kg ha^{-1}, P 0 kg ha^{-1}, and K 0 kg ha^{-1}); T2, $N_0P_2K_2$ (N 0 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T3, $N_1P_2K_2$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T4, $N_2P_0K_2$ (N 112.50 kg ha^{-1}, P 0 kg ha^{-1}, and K 112.50 kg ha^{-1}); T5, $N_2P_1K_2$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T6, $N_2P_2K_2$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T7, $N_2P_3K_2$ (N 112.50 kg ha^{-1}, P 168.75 kg ha^{-1}, and K 112.50 kg ha^{-1}); T8, $N_2P_2K_0$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 0 kg ha^{-1}); T9, $N_2P_2K_1$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); T10, $N_2P_2K_3$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T11, $N_3P_2K_3$ (N 168.75 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T12, $N_1P_1K_2$ (N 56.25 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T13, $N_1P_2K_1$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); and T14, $N_2P_1K_1$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 56.25 kg ha^{-1}).

Potato yield and commercial potato rate

Fertilization had a significant effect on potato yield. With the exception of the T2, T4, and T8 treatments, the potato yields of all the other fertilization treatments were significantly greater than that of the nonfertilized control (T1) ($p \le 0.05$), with increases ranging from 24.53% to 48.60% (Figure 1). Among them, the T3 treatment resulted in the highest potato yield, reaching 39,635.33 kg ha^{-1}, which was significantly greater than the yields of the T2, T4, T6, and T8 treatments ($p \le 0.05$).

The commercial potato rate is among the important indicators for determining profitability. No significant differences were detected between any of the treatments and the nonfertilized control (T1) (Figure 2). With the exception of T6, the marketable tuber rates of all the other treatments remained above 90%. Specifically, the marketable tuber rates of treatments T7, T11, and T13 were significantly higher than that of T6 ($p \le 0.05$), with T7 performing the best, reaching 95.73%. No significant differences were detected among the remaining fertilization treatments.

Potato quality

Different fertilization treatments had different effects on potato quality indicators (Figure 3[A]-A). The dry matter content of potatoes varied among the different treatments. In treatment T5, the dry matter content was the highest, reaching 27.01%. With the exception of treatments T3, T10, T13, and T14, the dry matter content of the remaining treatments was significantly greater than that of T1 ($p \le 0.05$).

Fertilization significantly affected the starch content of potatoes. The starch content among the different treatments ranged from 8.88 to 15.71 g 100 g^{-1} (Figure 3[A]-B). Compared with those in the other treatments, the starch content in the T6 and T10 treatments was significantly greater ($p \le 0.05$), at 15.68 g 100 g^{-1} and 15.71 g 100 g^{-1}, respectively.

Compared with that in the nonfertilized treatment (T1), the reducing-sugar content in treatments T3, T5, T7, T9, and T10 significantly increased ($p \le 0.05$), whereas no significant differences were observed in the remaining treatments (Figure 3[A]-C). Among the fertilization treatments, the reducing-sugar content of T9 was significantly greater than that of treatments T2, T4, T6, T11, T12, T13, and T14, reaching 0.36%.

Among all the treatments, the vitamin C content of the nonfertilized control (T1) was significantly greater than that of all the other treatments ($p \le 0.05$), reaching 10.61 mg 100 g^{-1} (Figure 3[A]-D). Among the fertilization treatments, the vitamin C content of T13 was significantly greater ($p \leq 0.05$), at 9.52 mg 100 g^{-1}. In contrast, treatments T7, T8, and T10 resulted in lower vitamin C contents.

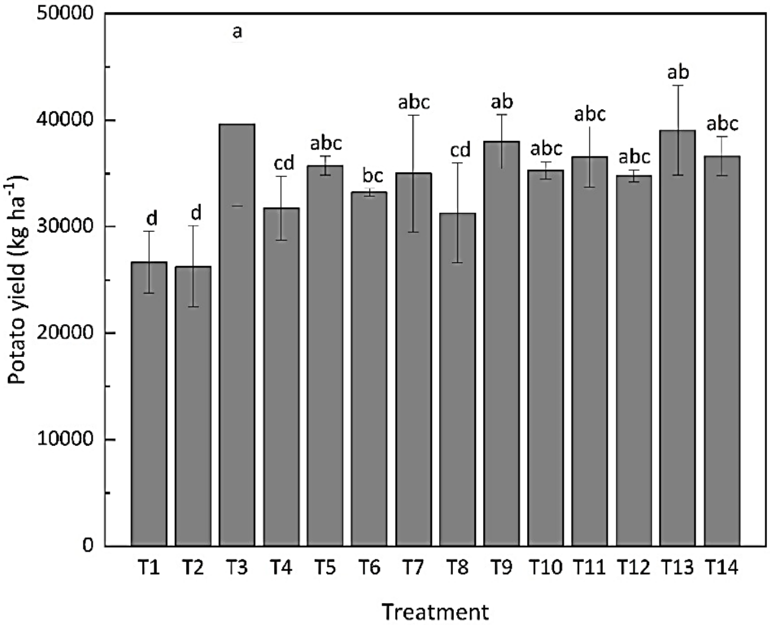


Figure 1. Effects of different fertilizer treatments on potato yield. The different lowercase letters in the data in the figure represent significant differences ($P \leq 0.05$). The error bars represent the standard deviation.
T1, $N_0P_0K_0$ (N 0 kg ha^{-1}, P 0 kg ha^{-1}, and K 0 kg ha^{-1}); T2, $N_0P_2K_2$ (N 0 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T3, $N_1P_2K_2$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T4, $N_2P_0K_2$ (N 112.50 kg ha^{-1}, P 0 kg ha^{-1}, and K 112.50 kg ha^{-1}); T5, $N_2P_1K_2$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T6, $N_2P_2K_2$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T7, $N_2P_3K_2$ (N 112.50 kg ha^{-1}, P 168.75 kg ha^{-1}, and K 112.50 kg ha^{-1}); T8, $N_2P_2K_0$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 0 kg ha^{-1}); T9, $N_2P_2K_1$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); T10, $N_2P_2K_3$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T11, $N_3P_2K_3$ (N 168.75 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T12, $N_1P_1K_2$ (N 56.25 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T13, $N_1P_2K_1$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); and T14, $N_2P_1K_1$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 56.25 kg ha^{-1}).

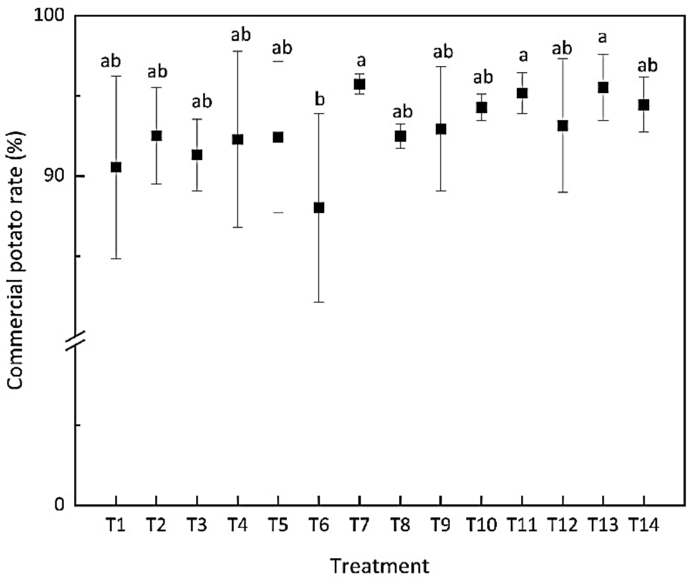


Figure 2. Effects of different fertilization treatments on the commercial rate of potatoes. The different lowercase letters in the data in the figure represent significant differences ($P \leq 0.05$). The error bars represent the standard deviation.
T1, $N_0P_0K_0$ (N 0 kg ha^{-1}, P 0 kg ha^{-1}, and K 0 kg ha^{-1}); T2, $N_0P_2K_2$ (N 0 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T3, $N_1P_2K_2$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T4, $N_2P_0K_2$ (N 112.50 kg ha^{-1}, P 0 kg ha^{-1}, and K 112.50 kg ha^{-1}); T5, $N_2P_1K_2$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T6, $N_2P_2K_2$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T7, $N_2P_3K_2$ (N 112.50 kg ha^{-1}, P 168.75 kg ha^{-1}, and K 112.50 kg ha^{-1}); T8, $N_2P_2K_0$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 0 kg ha^{-1}); T9, $N_2P_2K_1$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); T10, $N_2P_2K_3$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T11, $N_3P_2K_3$ (N 168.75 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T12, $N_1P_1K_2$ (N 56.25 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T13, $N_1P_2K_1$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); and T14, $N_2P_1K_1$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 56.25 kg ha^{-1}).

With the exception of treatments T2 (Figure 3[B]-E), T4, T6, T7, and T12, whose protein content did not significantly differ from that of the nonfertilized control (T1), the protein content of all the other treatments was significantly lower than that of T1 ($p \leq 0.05$). The protein content of T1 was 3.04 g 100 g^{-1}. Treatments T3, T5, T10, and T13 resulted in relatively low protein contents.

The amino acid content varied among the different treatments. Compared with those in the nonfertilized treatment (T1) (Figure 3[B]-F), the amino acid contents in treatments T2, T4, T5, T7, and T11 were significantly greater ($p \leq 0.05$). Among the fertilization treatments, except for T2 and T7, the amino acid contents of treatments T4 and T5 were significantly greater than those of the other fertilization treatments.

With respect to the total potassium content (Figure 3[B]-G), except for that in treatment T3, the total potassium content in treatment T6 was significantly greater than that in the other treatments ($p \leq 0.05$), reaching 5.53 g kg^{-1}. In contrast, treatments T4, T7, and T14 resulted in relatively low total potassium contents.

The zinc content varied among the different treatments. The zinc contents of treatments T1 and T6 were relatively high (Figure 3[B]-H), at 2.61 mg kg^{-1} and 2.53 mg kg^{-1}, respectively. Compared with those in the T3 and T8 treatments, the zinc contents in the T3 and T8 treatments were not significantly greater ($p \leq 0.05$). In contrast, treatment T11 resulted in a lower zinc content.

N, P and K fertilizer model

In accordance with the polynomial regression equation, $Y = b_0 + b_i X_i + \sum b_{ij} X_i X_j + \sum Xii^2$, the coefficients of the three-dimensional quadratic regression equation were calculated on the basis of the experimental results. The regression mathematical model for yield (Y) with N, P, and K is obtained as $Y = 26853.53 + 84.72 X_1 + 156.56 X_2 + 12.38 X_3 - 0.91 X_1^2 - 0.69 X_2^2 - 0.72 X_3^2 - 0.15 X_1 X_2 + 1.14 X_1 X_3 - 0.01 X_2 X_3$ (where X_1 = N, X_2 = P, and X_3 = K). Regression analysis was performed on the yield of each treatment, and the goodness of fit R square was 0.7786, indicating a good fit of the regression model (Table 3). Further analysis of variance was conducted on the regression relationship, with $F > F_{0.05}$, indicating that the regression equation reflected the relationships between yield and N, P, and K. According to the N–P–K response model, the optimal fertilization amounts were calculated as follows: N concentration of 56.25 kg ha^{-1}, P_2O_5 concentration of 112.5 kg ha^{-1}, and K_2O concentration of 56.25 kg ha^{-1}. With these fertilizer amounts, the potato yield could reach a maximum value of 38632.7 kg ha^{-1}.

Table 3. Regression and analysis of variance (ANOVA).

Multiple R	R Square	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{0.05}$
0.8824	0.7786	9	1.71E+08	18966809	1.5625	0.3528

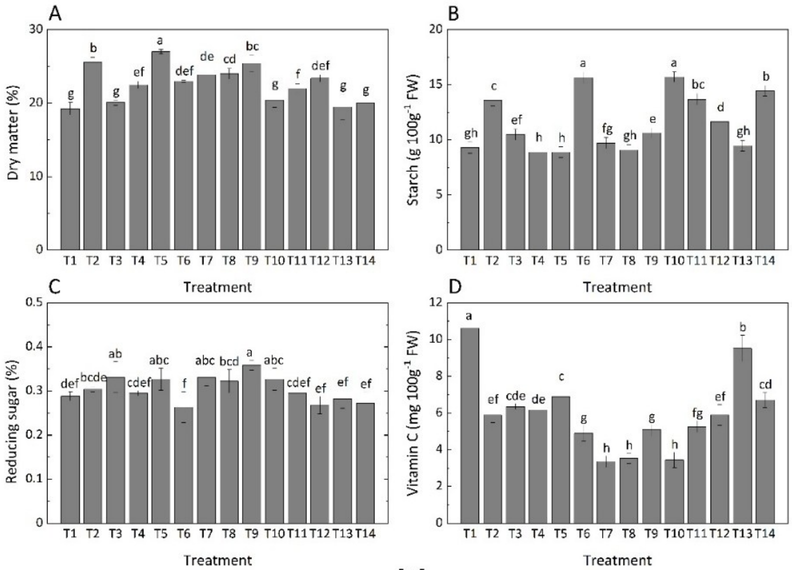
4. Discussion

N, P, and K are essential for the physiological activities of potatoes and play a vital role in their nutritional growth. The growth and development of potato plants are influenced not only by genetic background but also by planting conditions (Zörb, Senbayram and Peiter 2014). Fertilizers, in particular, have a significant effect on potato growth.

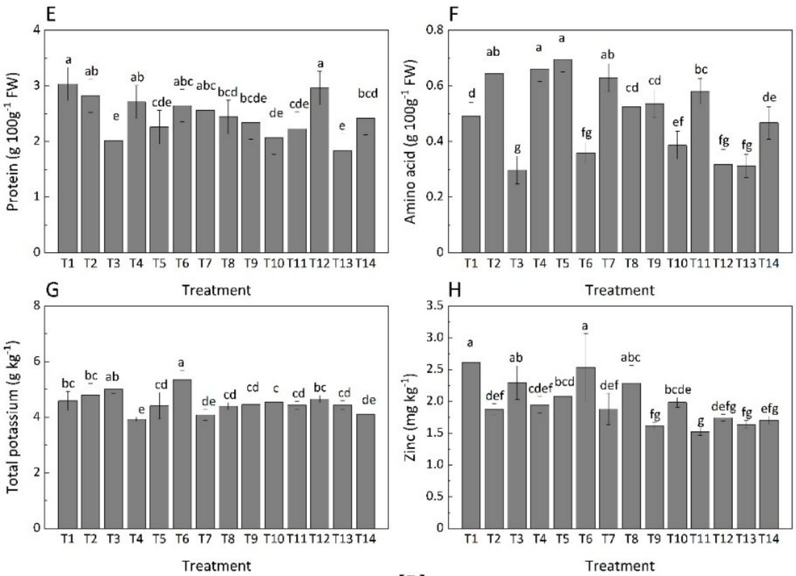
Effects of Combined N–P–K Fertilizers on the Agronomic Traits of Potato Plants

In this experiment, the combined application of N–P–K fertilizers increased the plant height of the potatoes to varying degrees (Table 2). This finding is similar to the findings of Zelelew et al. (2016), who reported that fertilizer application significantly increased plant height. When K_2O application was within the range of 100–150 kg ha^{-1}, it increased the absorption of N by plants, resulting in maximum plant height (Pervez et al. 2013). The number of main stems in a plant plays an important role in photosynthesis and the growth and development of potatoes. In some studies, the number of main stems in potato plants significantly increased with increasing fertilizer application (Ayalew and Beyene 2011; Zelelew et al. 2016).

In this experiment (Table 2), no significant differences were observed in the number of main stems between any fertilization treatment and the nonfertilized control (T1). These findings also indicate that different ratios of nitrogen, phosphorus, and potassium fertilizers were not the main factors affecting the number of main stems in the potato plants. However, within the comparisons among the fertilization treatments, the number of main stems in treatment T8 was significantly greater than that in treatment T10. It is possible that an increase in potassium enhances leaf photosynthetic efficiency, promotes the allocation of assimilates to the apical meristem, provides energy for axillary bud sprouting, and thereby stimulates the emergence and growth of more main stems (Ali et al. 2021).



[A]



[B]

Figure 3. Effects of different fertilization treatments on potato tuber quality. [A] and [B] indicate the two parallel panels in Figure 3. A - Dry matter; B - starch content; C – reducing-sugar content; D - vitamin C content; E - protein content; F - amino acids; G – total potassium content; and H - zinc content. The different lowercase letters in the data in the figure represent significant differences ($P \leq 0.05$).

T1, $N_0P_0K_0$ (N 0 kg ha^{-1}, P 0 kg ha^{-1}, and K 0 kg ha^{-1}); T2, $N_0P_2K_2$ (N 0 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T3, $N_1P_2K_2$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T4, $N_2P_0K_2$ (N 112.50 kg ha^{-1}, P 0 kg ha^{-1}, and K 112.50 kg ha^{-1}); T5, $N_2P_1K_2$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T6, $N_2P_2K_2$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 112.50 kg ha^{-1}); T7, $N_2P_3K_2$ (N 112.50 kg ha^{-1}, P 168.75 kg ha^{-1}, and K 112.50 kg ha^{-1}); T8, $N_2P_2K_0$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 0 kg ha^{-1}); T9, $N_2P_2K_1$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); T10, $N_2P_2K_3$ (N 112.50 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T11, $N_3P_2K_3$ (N 168.75 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 168.75 kg ha^{-1}); T12, $N_1P_1K_2$ (N 56.25 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 112.50 kg ha^{-1}); T13, $N_1P_2K_1$ (N 56.25 kg ha^{-1}, P 112.50 kg ha^{-1}, and K 56.25 kg ha^{-1}); and T14, $N_2P_1K_1$ (N 112.50 kg ha^{-1}, P 56.25 kg ha^{-1}, and K 56.25 kg ha^{-1}).

In this study, compared with those in the nonfertilized control (T1), the emergence rates of potato plants in the fertilization treatments (T2–T14) generally tended to increase, but the differences did not reach statistical significance (Table 2). However, within the fertilization treatments, the emergence rate of T12 was significantly greater than that of T11. This difference may be related to the nitrogen-to-phosphorus ratio (N:P) of the two treatments: T12 adopted a more balanced N:P ratio, which is conducive to coordinating early root development and aboveground growth, whereas the higher nitrogen level in T11 may lead to excessive shoot elongation or an increased risk of salt stress, thereby affecting emergence performance. These results are consistent with the findings of Mokrani, Hamdi and Tarchoun (2018), who reported that rational regulation of the nitrogen-to-phosphorus ratio helps optimize the potato emergence rate and early growth.

Effects of the Combined Application of N–P–K Fertilizers on the Yield-Related Traits of Potato Plants

The formation of potato yield is achieved through a series of physiological and biochemical processes involving the absorption of mineral elements and water and the assimilation of CO_2 (Maltas et al. 2018). Therefore, factors that affect these processes play a decisive role in potato yield formation. The potato yield is determined by factors such as the tuber number and marketable tuber rate. Formulated fertilization and balanced fertilization are important cultivation methods for ensuring the growth and development of potatoes, increasing potato yield, and increasing economic benefits.

In this experiment, with the exception of T2, T4, and T8, the application of different N–P–K ratios significantly increased potato yield compared with that of the control (T1). This finding is consistent with the results reported in some related studies (Mokrani et al. 2019). Eleiwa et al. (2012) reported that increasing N–P–K application significantly increased potato yield, with the N–P–K (120–80–100) treatment resulting in higher yields than the other two N–P–K (102–68–85; 90–60–75) treatments did. The potato yield did not significantly increase in T2, T4, or T8, which may be attributed to insufficient nutrient supply, as T2 had 0 kg ha^{-1} N application, T4 had 0 kg ha^{-1} P application, and T8 had 0 kg ha^{-1} K application, which could have affected tuber growth. In contrast, Gondwe et al. (2020) reported that increasing N–P–K fertilizer application did not result in significant changes in potato yield under high-soil-nutrient conditions. These findings suggest that a proper fertilizer formula plays a crucial role in the growth and development of potatoes. In this study, the application of N–P–K fertilizer at different levels increased the proportion of marketable potatoes, but the differences between treatments were not statistically significant.

However, in a study conducted by Khan et al. (2012), the application of N 250 kg ha^{-1}, P_2O_5 150 kg ha^{-1}, and K_2O 225 kg ha^{-1} significantly increased the proportion of marketable potatoes. This discrepancy may be attributed to the relatively high proportion of marketable potatoes observed in all the treatments in our study.

Effects of the Combined Application of N–P–K Fertilizers on Potato Quality

The quality of potatoes is influenced by various factors, including not only their genetic characteristics but also the local climate, soil, and cultivation practices, with the fertilizer ratio playing a significant role. Important indicators for assessing potato quality include dry matter, starch, protein, reducing sugars, and amino acids. Excessive K application can increase the water content of potato tubers, resulting in a decrease in dry matter content (Westermann et al. 2000). The effective and appropriate application of N–P–K fertilizer can contribute to the improvement of potato tuber quality. Research has shown that applying N–P–K fertilizer at 125% of the recommended local rate significantly increases dry matter, starch, and reducing-sugar contents in tubers (Devi et al. 2023). Similar results were also observed in a study by Assuncao et al. (2021).

In this experiment, the application of different ratios of N–P–K fertilizer tended to increase the dry matter, starch, and reducing-sugar contents in potatoes. Ko1be et al. (1995) suggested that applying a certain amount of N fertilizer can increase total potato yield but has a negative effect on vitamin C content in tubers. This finding is consistent with the results of this study, as the vitamin C content in all the N–P–K ratio treatments was significantly lower than that in the no-fertilizer treatment (T1). This may be due to the impact of N fertilizer on photosynthesis and sugar metabolism, which subsequently affects the synthesis and accumulation of vitamin C (Gao et al. 2015). Studies have shown that the application of N–P–K fertilizer can significantly increase the protein content in tubers (Yusuf et al. 2017; Abdeldaym et al. 2019). However, this study yielded opposite results, as the protein content was significantly lower than that in T1 in all treatments except T2, T4, T6, T7, and T12. Further investigations are needed to explore the specific reasons. This could be due to the competition for Zn absorption and utilization by the application of N–P–K fertilizers, which in turn affects the absorption of Zn by the plants.

5. Conclusions

Different N–P–K fertilization treatments variably influence potato agronomic traits, yield, and quality. In this study, the fertilization treatments did not significantly affect plant height, main stem number, or emergence rate but generally increased potato yield, with the T3 treatment ($N_1P_2K_2$) resulting in the greatest yield. In terms of tuber quality, compared with the other treatments, the T5 treatment ($N_2P_1K_2$) resulted in significantly greater dry matter content and amino acid levels. By fitting the yield data to a ternary quadratic regression equation model, the theoretically optimal fertilization treatment was identified as T13 ($N_1P_2K_1$). Considering both yield and quality traits, T5 ($N_2P_1K_2$) is recommended as the optimal fertilization ratio for potato cultivation in the region, with N at 112.50 kg ha^{-1}, P_2O_5 at 56.25 kg ha^{-1}, and K_2O at 112.50 kg ha^{-1}.

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