agronomy

Article

Optimizing Irrigation and Fertilization to Simultaneously Improve Potato Tuber Yield, Water and Fertilizer Use Efficiency and Net Income in Northwest China

Fan Zhang, **Mengru Chen**, **Yu Zheng**, **Yunxia Xie** and **Yingying Xing** *

College of Life Sciences, Yan'an University, Yan'an 716000, China; zhangfan9264@163.com (F.Z.); zggmcmr123@163.com (M.C.); zhengyuedq@163.com (Y.Z.); x021708@163.com (Y.X.)
* Correspondence: xingyingying@yau.edu.cn

Abstract: Irrigation, fertilization, and variety are important factors affecting potato production in northwest China. Field experiments (2021 and 2022) were performed to investigate the effects of irrigation and fertilization on the plant growth and soil microbial population of different potato varieties. Three irrigation levels were used, i.e., 100% ETc (W1), 80% ETc (W2), and 60% ETc (W3), with ETc standing for crop evapotranspiration. Three fertilization levels were used (N-P-K), i.e., 240-120-300 kg ha^{-1} (F1), 180-90-225 kg ha^{-1} (F2), and 120-60-150 kg ha^{-1} (F3). Three variety types were used, i.e., Feiurita (V1), Longshu 7 (V2), and Qingshu 9 (V3). These factors significantly influenced tuber yield (TY), net income (NI), and water productivity (WP). TY, NI, WP, total nitrogen accumulation (TNA), and nitrogen use efficiency (NUE) peaked at F2. Fertilization significantly impacted soil bacteria quantity (SBQ), fungi quantity (SFQ), and actinomycetes quantity (SAQ). TY, NI, SBQ, SFQ, and SAQ were highest at W2. Soil microbial population was strongly correlated with TY, NI, WP, TNA, and NUE. Comprehensively, this study suggests that irrigation that is varied from 248 to 266 mm, and fertilization (N-P-K) that is varied from 149.09-74.55-186.36 to 212.73-106.36-265.91 kg ha^{-1} can promote the potato industry's sustainable development and provide important references for the optimal field management of potato cultivation in northwest China.

Keywords: crop growth; variety; water productivity; soil microbial population; multiple regression analysis

Citation: Zhang, F.; Chen, M.; Zheng, Y.; Xie, Y.; Xing, Y. Optimizing Irrigation and Fertilization to Simultaneously Improve Potato Tuber Yield, Water and Fertilizer Use Efficiency and Net Income in Northwest China. *Agronomy* **2024**, *14*, 1124. https://doi.org/10.3390/agronomy14061124

Academic Editor: Jiafa Luo

Received: 1 May 2024
Revised: 16 May 2024
Accepted: 23 May 2024
Published: 24 May 2024

1. Introduction

Potato, because of its ease of cultivation, nutritional richness, and economic efficiency, plays a crucial role in maintaining global food security [1,2]. China is the world's largest potato grower and producer (the planted area exceeds 5.78 million hectares and the yield exceeds 94.4 million tons), and the northwest region is the main area for potato cultivation in China [3]. Although loose soil, abundant light and heat resources, suitable climate type, and good drainage and ventilation have created good basic conditions for potato cultivation in the dry zone of northwest China, irrational field management measures (excessive irrigation, excessive fertilizer application, and planting variety selection) are essential factors restricting high potato yield in the region [4]. Thus, exploring efficient agricultural management practices to create a sustainable potato cultivation regime is urgent in the northwest China.

Drip fertigation has been proven to improve yield by optimizing NUE by the crop, as well as prolonging photosynthesis time and rate, and it has been extensively adopted in agricultural production practice [5]. In the context of climate warming, the effects of water deficit on crops have been observed, which could damage leaf stomata, reduce crop physiological metabolic rate, and even lead to crop death [6]. Reasonable water management practice during potato fertility is favorable to the formation of tuber yield and quality [7]. However, excessive water deficit during the seedling and fruiting stages severely damaged the rate of photosynthetic metabolism of the crop, reduced water and fertilizer use efficiency, and ultimately resulted in yield reduction [8]. The response to an optimal irrigation pattern was mainly manifested in improving plant height and resource use efficiency, and increasing irrigation during the growing period slowed down crop senescence [9]. Reasonable increase irrigation has been proven to improve plant growth, accelerate photosynthesis and growth metabolism activities, and eventually achieve higher crop yield and quality [10]. Fertilization is another vital approach to stabilize and increase crop yield. Although soil testing and formulated fertilization methods have been continuously promoted in recent years, fertilizer utilization efficiency remains below 40% [11]. The traditional method of basal application of chemical fertilizer not only causes severe economic losses but also raises numerous environmental pollution problems (soil acidification, water eutrophication, and water resource pollution) [12]. Drip fertigation effectively increased yield and improved the soil microbiological system, which in turn realized sustainable agricultural development. Specifically, optimizing fertilization significantly increased potato yield, tuber nitrogen accumulation, vitamin C content, and nitrate content [13,14]. Under drip fertigation conditions, WP and growth physiological indicators were significantly improved as nitrogen application increased [15]. However, excessive nitrogen application could disrupt the normal sink-source metabolism of potato, thereby affecting yield and quality formation [16]. Consequently, it is imperative to explore effective water and fertilizer management strategies to achieve sustainable agricultural development. The selection of excellent germplasm resources is significant for stabilizing regional economic development and alleviating the food shortage crisis [17]. To avoid the global food scarcity, germplasm with high yield, good quality, high resistance, and high resource efficiency should be selected for cultivation [18]. Tiwari et al. [19] indicated that nitrogen physiological metabolism and dry matter accumulation differed significantly among potato varieties under the same field management practices.

Previous studies primarily concentrated on studying the effects of water–fertilizer coupling on potato growth, yield, economic benefits, and soil nutrients, as well as proposed strategies for efficient field management. Nevertheless, research simultaneously focused on the coupling effects of irrigation, fertilization, and variety on potato growth under drip irrigation conditions is extremely rare. We hypothesized that the response of different potato varieties to water and fertilizer supply would significantly differ. Consequently, the objectives of this study were as follows: (1) to investigate the differences in crop growth, yield, net income, WP, NUE, and soil microbial populations under various combinations of irrigation, fertilization, and variety, and (2) to obtain an optimal water and fertilizer management strategy for potato by quantifying the response of multiple indicators to water and fertilizer supply.

2. Materials and Methods

2.1. Experimental Site Description

Field experiments were performed for two years (2021 and 2022) at the Yan'an City, Shaanxi Province, China (N36°39′, E109°11′). The experimental site is located in the Loess Plateau region, which has a continental monsoon climate. The annual rainfall (mainly concentrated from July to September) and annual evapotranspiration are 473 mm and 1800 mm. The average annual temperature is 8.9 °C. Table 1 displays the basic physicochemical conditions of the soil (0–40 cm soil layer). Three different varieties of potato and an overview of the experiment site are given in Figure 1.

Table 1. The basic physicochemical conditions.

Scheme	Value	Measurement Method
Soil texture	Sandy loam	Laser particle size analyzer (Dandong Haoyu Technology Co., Ltd., Dandong, Liaoning, China) and USDA soil taxonomy system [20]
Soil pH	8.43	Thundermagnetic portable pH meter (1:2.5 soil–water, PHB-4, Shanghai Inesa Scientific Instrument Co., Ltd., Shanghai, China) [21]
Soil bulk density (g cm^{-3})	1.28	Ring knife sampling method
Soil nitrate nitrogen (mg kg^{-1})	13.30	UV spectrophotometer (UV-2600, Shimadzu Corporation, Kyoto, Japan)
Soil available potassium (mg kg^{-1})	98.30	Flame spectrophotometer (FP6410, Shanghai Yidian Analytical Instrument Co., Ltd., Shanghai, China)
Soil available phosphorus (mg kg^{-1})	21.43	UV spectrophotometer (UV-2600, Shimadzu Corporation, Kyoto, Japan)
Soil organic matter (g kg^{-1})	7.66	Concentrated sulfuric acid-potassium dichromate external heating method

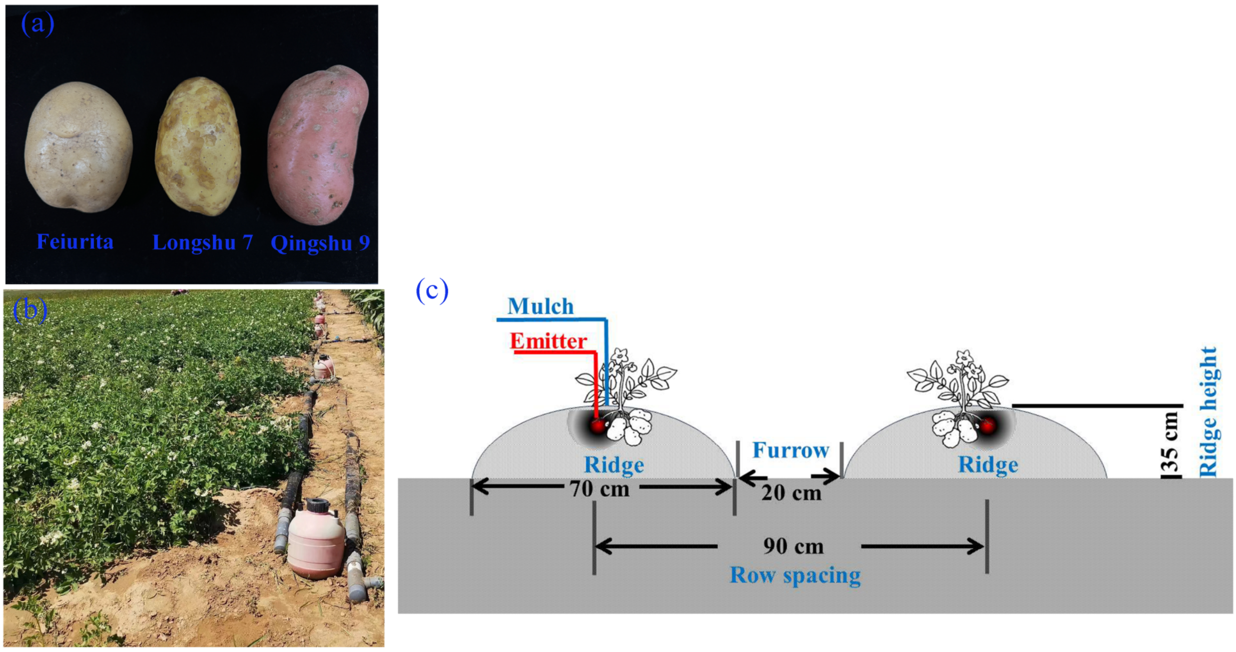

Figure 1. Three different varieties of potato (**a**) and an overview of the experiment site (**b**,**c**).

2.2. Experimental Design

Irrigation and fertilization were set based on previous studies [22,23]. Three irrigation levels were used, i.e., 100% ET_c (W1), 80% ET_c (W2), and 60% ET_c (W3), with ETc standing for crop evapotranspiration. Three fertilization levels were used (N-P-K), i.e., 240-120-300 kg ha^{-1} (F1), 180-90-225 kg ha^{-1} (F2), and 120-60-150 kg ha^{-1} (F3). Three variety types were used, i.e., Feiurita (from Dingxi, China, V1), Longshu 7 (from Dingxi, China, V2), and Qingshu 9 (from Hohhot, China, V3). The experiment consisted of nine treatments using an orthogonal experimental design method (Table 2). In this experiment, each treatment was replicated three times, with a total of 27 plots (area of 11.88 m^2). In both years, potatoes were planted using mechanical ridging and artificial film planting. The planting density was 45,455 plants ha^{-1}, with a spacing of 20 cm. In 2021, the potato planting date was 25 March and the harvest date was 25 July. In 2022, the planting date was 26 March and the harvest date was 27 July. Field weather conditions were recorded using a weather station. Average temperature and ET_0 during the potato growing season in 2021 and 2022 are shown in Figure 2.

Table 2. Experimental treatment combinations.

Treatments	Irrigation (% ET_c)		Fertilization (N-P-K kg ha^{-1})		Variety	
	Code	**Level**	**Code**	**Level**	**Code**	**Type**
T1	W1	100	F1	240-120-300	V1	Feiurita
T2	W1	100	F2	180-90-225	V2	Longshu 7
T3	W1	100	F3	120-60-150	V3	Qingshu 9
T4	W2	80	F1	240-120-300	V2	Longshu 7
T5	W2	80	F2	180-90-225	V3	Qingshu 9
T6	W2	80	F3	120-60-150	V1	Feiurita
T7	W3	60	F1	240-120-300	V3	Qingshu 9
T8	W3	60	F2	180-90-225	V1	Feiurita
T9	W3	60	F3	120-60-150	V2	Longshu 7

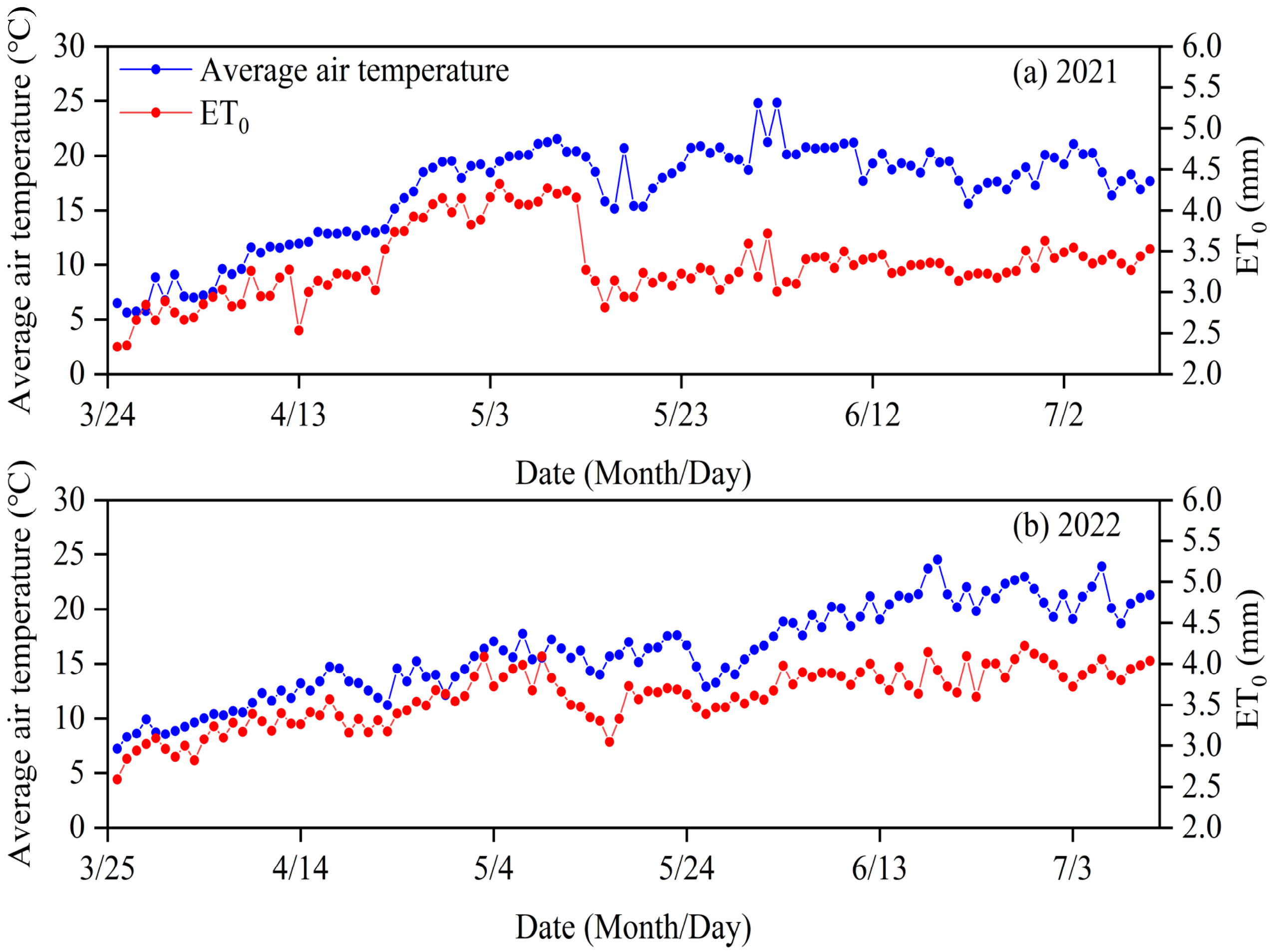

Figure 2. Average temperature and ET_0 during the potato growing season in 2021 (**a**) and 2022 (**b**).

The fertilizers employed in this experiment included urea (N 46%), calcium superphosphate (P_2O_5 12%) and potassium sulfate (K_2O 52%). Before each application, all fertilizers were placed in the fertilizer tank to fully dissolve. Fertilizers were applied five times during the whole growth period. Fertilization of 10%, 20%, 30%, 30%, and 10% was applied at the seedling, tuber formation, tuber enlargement, starch accumulation, and maturity stages, respectively [24]. Irrigation was performed using drip irrigation under the film, and water meters were employed to accurately manage the amount of irrigation for each plot. The amount of irrigation was determined by ET_c, where ET_c was the product of reference evapotranspiration (ET_0) and crop coefficient (K_c). The ET_0 was obtained with the Penman–Monteith formula [25]. The potato K_c was 0.5 (seedling stage), 0.65 (tuber formation stage), 1.15 (tuber enlargement stage), 1.15 (starch accumulation stage), and 0.75 (maturity stage), respectively. Figure 3 exhibits the irrigation plans for 2021 and 2022.

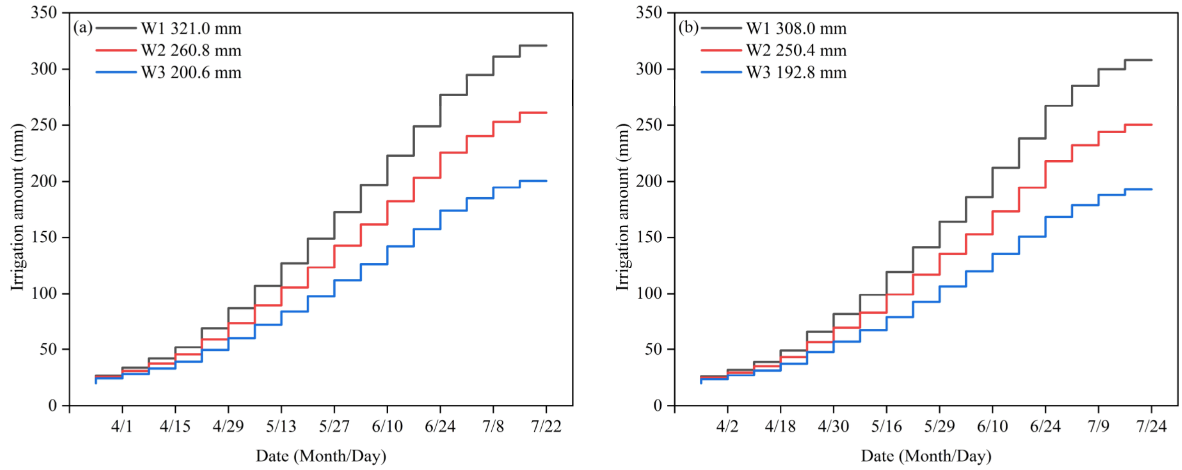

Figure 3. The 2021 (**a**) and 2022 (**b**) irrigation plans.

2.3. Measurements and Calculations

2.3.1. Potato Plant Height

The plant height at various growing stages was measured (2021 (2022): 24 (24) days after sowing (DAS), 48 (47) DAS, 80 (81) DAS, 96 (96) DAS, and 112 (109) DAS).

2.3.2. Potato Tuber Yield and Net Income

Ten representative plants were randomly collected from every plot at the harvest stage. Tuber yield (TY, kg ha^{-1}) was dependent on the product of tuber yield per plant and plant density.

In this experiment, the water input, urea input, superphosphate input, potassium sulfate input, other inputs, and potato price were 4 CNY mm^{-1}, 5.5 CNY kg^{-1}, 3.4 CNY kg^{-1}, 8.3 CNY kg^{-1}, 10,000 CNY ha^{-1}, and 1.2 kg ha^{-1}, respectively. Net income (NI, CNY ha^{-1}) was the difference between total income and total input.

2.3.3. Crop Evapotranspiration and Water Productivity

Crop evapotranspiration (*ET*, mm) was computed using the water balance equation as follows [26]:

$$ET = P + U + I - D - R - \Delta W \quad (1)$$

where *P* denotes effective precipitation (mm), *U* denotes underground water replenishment (mm), *I* denotes irrigation amount (mm), *D* denotes deep water seepage (mm), *R* denotes ground surface runoff (mm), and ΔW denotes the variation in soil water storage in the 0–60 cm soil layer from pre-planting to harvest (mm). In this experiment, *D*, *R*, and *U* were negligible.

Water productivity (*WP*, kg m^{-3}) was obtained as follows:

$$WP = \frac{TY}{ET} \quad (2)$$

where *TY* stands for tuber yield (kg ha^{-1}) and *ET* stands for crop evapotranspiration (mm).

2.3.4. Total Nitrogen Accumulation and Nitrogen Use Efficiency

Plant samples were digested by utilizing H_2SO_4-H_2O_2 solution, while the nitrogen uptake (%) was detected using a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany). Total nitrogen accumulation (*TNA*, kg ha^{-1}) was equal to the multiplication of nitrogen uptake and dry matter accumulation.

Nitrogen use efficiency (NUE, kg kg^{-1}) was obtained as follows [27]:

$$NUE = \frac{TY}{TNA} \quad (3)$$

where TY stands for tuber yield (kg ha^{-1}) and TNA stands for total nitrogen accumulation (kg ha^{-1}).

2.3.5. Soil Microbial Population

Root zone soil (0–40 cm layer) was collected using a soil auger at the potato harvest stage, and fresh soil was immediately sieved through a 1 mm sieve and stored at 4 °C until analysis. Soil microbial population was determined by the smear plate counting method. First, 10 g of soil sample was weighed, placed in a triangle bottle containing sterile water, and diluted in the ratio of 1:10 (soil: water). Second, the diluted solution was placed on a shaker at 25 °C for 20 min. Third, 1 mL of soil suspension was pipetted into 9 mL of sterile water to make a 10^{-2} concentration of soil suspension. The above operation was repeated to make soil suspensions of different concentrations of 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7}. Fourth, soil suspensions of different concentrations were inoculated on three Petri dishes. The bacterial quantity (SBQ, cfu g^{-1}), fungal quantity (SFQ, cfu g^{-1}), and actinomycete quantity (SAQ, cfu g^{-1}) were measured by peptone broth medium, Martin-Bengal medium, and starch ammonium salt medium, respectively [28].

2.4. Data Analysis

We used Origin 8.0 and R 4.1.0 software to create figures. Correlation analysis figure was plotted using the psych package in R 4.1.0 software. Analysis of variance (ANOVA) was employed with SPSS Statistics 23.0 software. Tukey's honest significant difference (HSD) test was utilized to examine for difference across all treatments at the significance level ($p < 0.05$).

3. Results

3.1. Plant Height

Except for the seedling stage, W, F, and V significantly influenced plant height across the growth stage ($p < 0.01$) (Table 3). The dynamics of plant height over the entire fertility period was well described using Logistic function, with $R^2 \geq 0.994$ (Table 4). Potato plant height exhibited an "S" trend in the whole fertility period (Figure 4). t_1 occurred 38.42–39.12 DAS in 2021 and 34.04–36.02 DAS in 2022. t_2 occurred 66.33–71.57 DAS in 2021 and 59.03–65.81 DAS in 2022. The average t_2 of W1 was 4.65 d and 4.17 d ahead of that of W3 in 2021 and 2022, respectively. In 2022, the average t_2 in V3 was 1.50 d and 1.97 d later than that in V1 and V2, respectively. In 2021 (2022), t_m, V_M, and G_T occurred 52.55–55.08 d (47.06–50.70 d), 1.39–2.16 cm d^{-1} (1.29–2.15 cm d^{-1}), and 1.21–1.89 cm d^{-1} (1.23–1.89 cm d^{-1}), respectively. V_M rose with increasing irrigation. Across irrigation and variety, the average V_M for F3 was 7.52% and 6.69% less than that for F1 and F2 in 2021, as well as 11.85% and 7.77% in 2022, respectively. In 2021 (2022), the average V_M in V2 was 3.44% (1.90%) and 4.07% (3.61%) greater than that in V1 and V3, respectively. The maximum G_T occurred in treatment T2 (1.89 cm d^{-1}) and treatment T1 (1.89 cm d^{-1}) in 2021 and 2022, respectively.

Table 3. The significance test of plant height in 2021 and 2022.

Year	Growth Period				
	Seedling Stage	Tuber Formation Stage	Tuber Expansion Stage	Starch Accumulation Stage	Tuber Maturity Stage
2021	ns	**	**	**	**
2022	ns	**	**	**	**

Note: **, and ns indicate significance of effect at 0.01 level, and no significant effect, respectively.

Table 4. The Logistic function fitting for plant height and growth time in 2021 and 2022.

Year	Treatments	Value					Regression Equation	R^2
		t_1 (d)	t_2 (d)	t_m (d)	V_M (cm d^{-1})	G_T (cm d^{-1})		
2021	T1	38.78	66.83	52.80	2.11	1.85	$y = 89.68/(1 + 142.34e^{-0.0939t})$	0.996
	T2	38.78	66.33	52.55	2.16	1.89	$y = 90.28/(1 + 152.04e^{-0.0956t})$	0.999
	T3	38.42	67.11	52.77	1.92	1.68	$y = 83.70/(1 + 127.00e^{-0.0918t})$	0.998
	T4	38.82	67.05	52.93	2.06	1.81	$y = 88.32/(1 + 139.55e^{-0.0933t})$	0.994
	T5	38.89	67.15	53.02	2.00	1.76	$y = 85.96/(1 + 139.96e^{-0.0932t})$	0.998
	T6	39.12	68.64	53.88	1.90	1.66	$y = 85.05/(1 + 122.25e^{-0.0892t})$	0.998
	T7	38.71	71.22	54.97	1.46	1.28	$y = 72.11/(1 + 85.82e^{-0.0810t})$	0.997
	T8	38.67	71.43	55.05	1.42	1.24	$y = 70.40/(1 + 83.61e^{-0.0804t})$	0.998
	T9	38.60	71.57	55.08	1.39	1.21	$y = 69.35/(1 + 81.54e^{-0.0799t})$	0.998
2022	T1	35.21	59.51	47.36	2.15	1.89	$y = 79.46/(1 + 169.64e^{-0.1084t})$	0.997
	T2	35.10	59.03	47.06	2.11	1.85	$y = 76.55/(1 + 177.99e^{-0.1101t})$	0.997
	T3	34.55	60.99	47.77	1.82	1.60	$y = 73.25/(1 + 116.51e^{-0.0996t})$	0.997
	T4	35.45	62.16	48.80	1.82	1.60	$y = 74.03/(1 + 122.99e^{-0.0986t})$	0.999
	T5	35.84	62.91	49.37	1.77	1.55	$y = 72.80/(1 + 121.97e^{-0.0973t})$	0.997
	T6	34.04	60.81	47.42	1.67	1.46	$y = 67.73/(1 + 106.32e^{-0.0984t})$	0.998
	T7	36.02	65.38	50.70	1.45	1.27	$y = 64.63/(1 + 94.41e^{-0.0897t})$	0.999
	T8	34.75	64.48	49.61	1.31	1.15	$y = 59.11/(1 + 81.09e^{-0.0886t})$	0.999
	T9	35.09	62.19	48.64	1.29	1.13	$y = 53.26/(1 + 113.06e^{-0.0972t})$	0.996

Note: t_1 and t_2 indicate the start time and end time of the rapid plant height growth period, respectively. t_m indicates the time when the daily maximum growth appeared, V_M indicates the daily maximum growth, and G_T indicates the average growth rate of plant height from t_1 to t_2.

Figure 5 displays the growth rate of plant height at various periods. Maximum plant height growth rate was found at 50 DAS. At W1 level, the mean plant height achieved the maximum value. In 2021, the average plant height at the F1 level was 6.94% and 2.68% greater than at the F2 and F3 level, respectively. A similar trend also occurred in 2022.

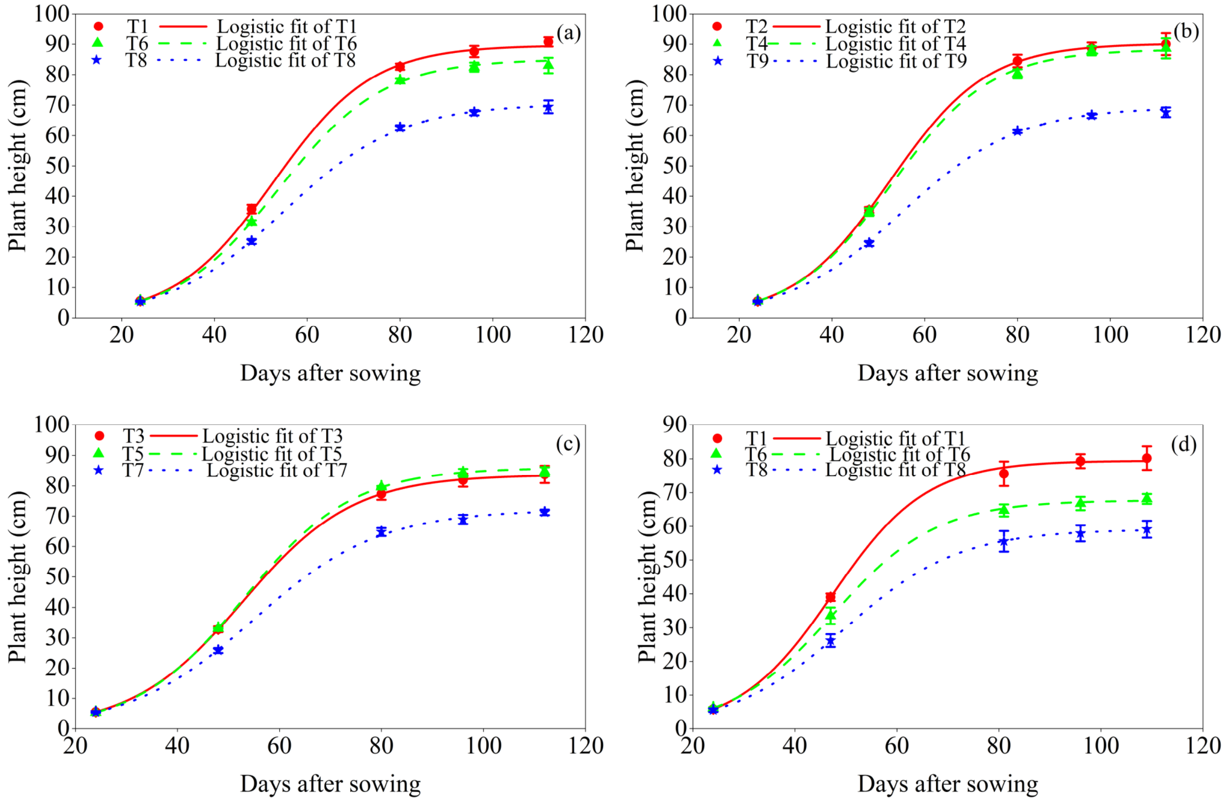

Figure 4. *Cont.*

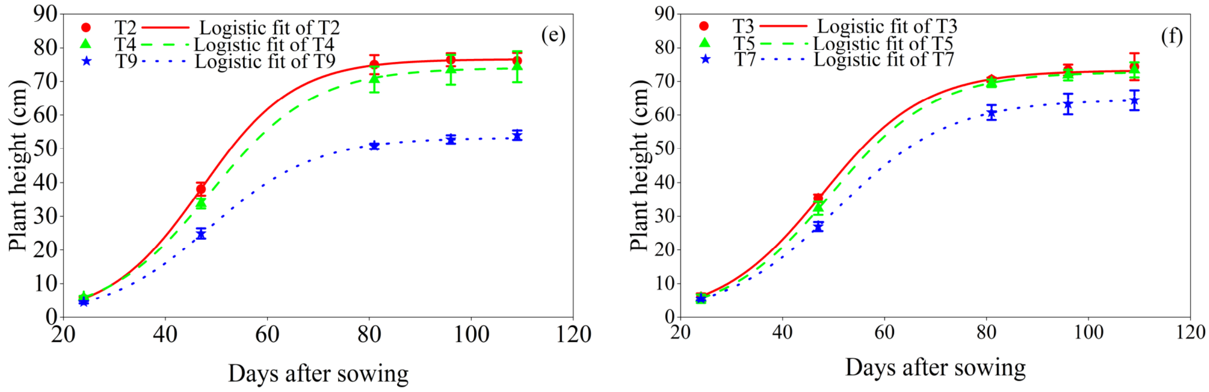

Figure 4. Effects of different combinations on plant height in 2021 (**a**–**c**) and 2022 (**d**–**f**).

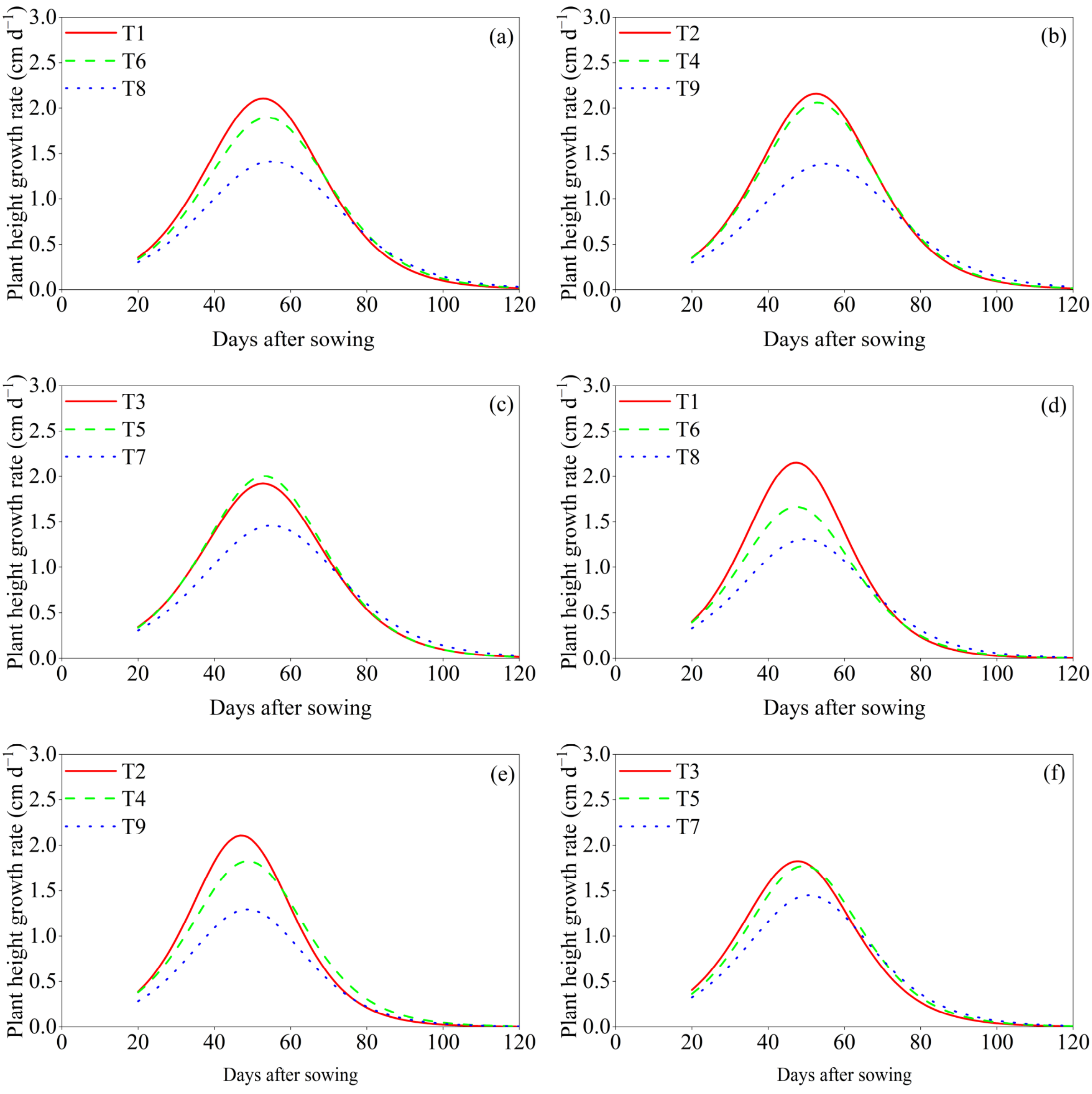

Figure 5. Effects of different combinations on plant height growth rate in 2021 (**a**–**c**) and 2022 (**d**–**f**).

3.2. TY and NI

W, F, and V greatly influenced TY and NI in both years ($p < 0.01$) (Figure 6). F had the most impact on TY in 2021. However, in 2022, W had the most impact on TY, followed by F and V (Table 5). T5 treatment exhibited the highest TY (49,222.33 kg ha^{-1} in 2021 and 40,939.80 kg ha^{-1} in 2022). Overall, TY in 2021 was higher than in 2022. In 2021, the average TY at F2 level was 19.28% and 21.48% greater than that at F1 and F3 level, respectively, and showed the same trend in 2022. Compared with W2 level, average TY for W1 and W3 level was reduced by 2.74% and 18.16% in 2021, with the same trend occurring in 2022. Averaging all W and F, TY of V2 was remarkably less than that of V1 and V3.

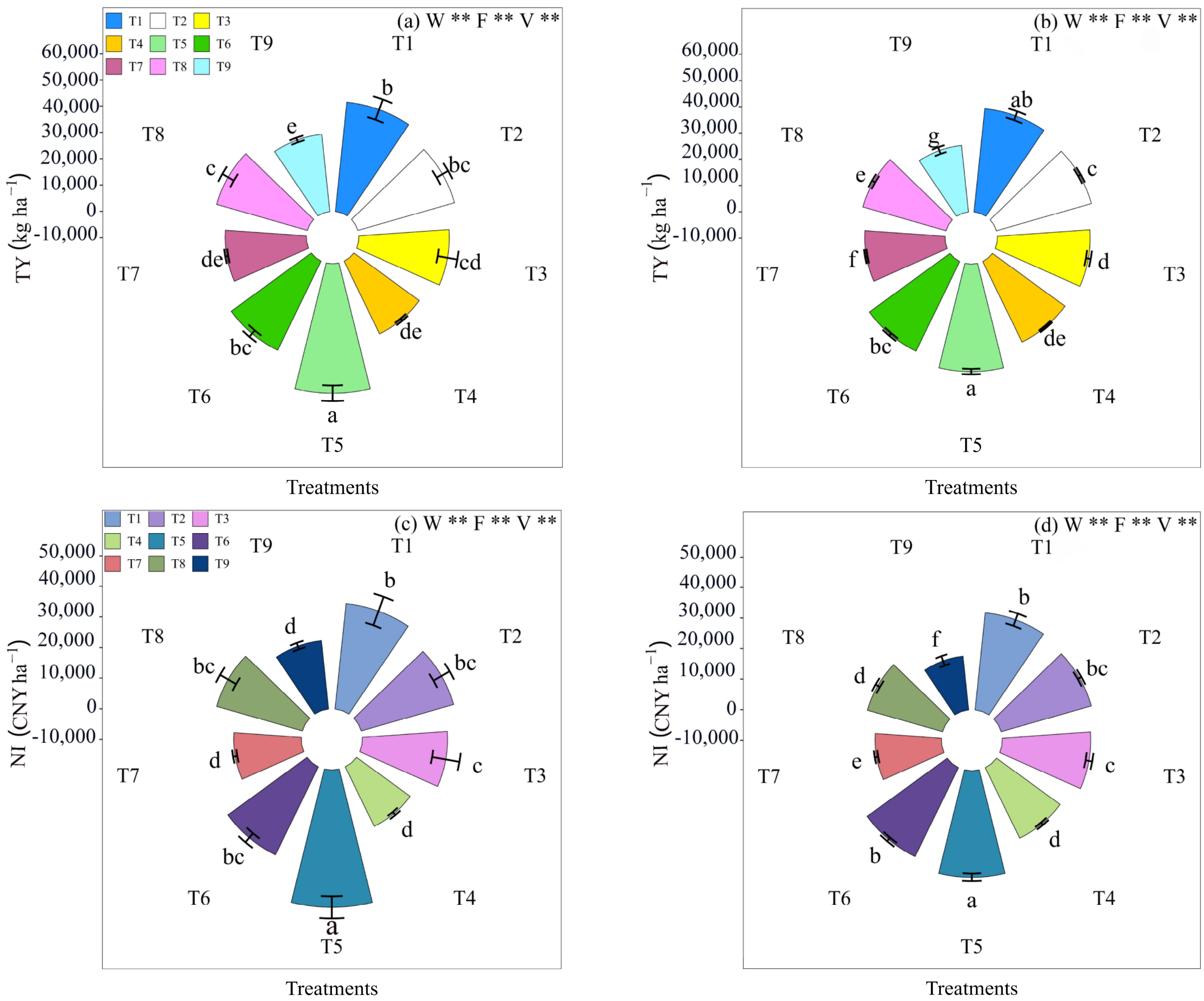

Figure 6. Effects of different combinations on TY and NI in 2021 (**a**,**c**) and 2022 (**b**,**d**). Note: Bars are mean ± standard deviation ($n = 3$). W, F, and V indicate irrigation, fertilization, and variety, respectively. ** indicates significance of effect at 0.01 level. Different lowercase letters indicate significant differences among treatments ($p < 0.05$). TY and NI represent tuber yield and net income, respectively.

In 2021, the NI was most influenced by F, followed by W and V. However, in 2022, the NI was most influenced by W, followed by F and V (Table 5). Overall, NI in 2021 was higher than in 2022. NI ranged across 21,621.22–44,844.10 CNY ha^{-1} in 2021 and 17,668.42–34,946.66 CNY ha^{-1} in 2022. T5 treatment had the greatest NI in both years. The change in NI was closely related to TY, and showed the same trend. The average NI of variety V2 was 21.19% and 20.35% lower than that of variety V1 and V3 in 2021, and 17.64% and 13.40% in 2022, respectively.

Table 5. Sensitivity test for TY and NI in 2021 and 2022.

Year	Items	TY			NI		
		W	F	V	W	F	V
2021	k1	38,139.00	34,474.22	38,452.89	31,265.47	26,091.87	31,906.93
	k2	39,212.44	41,119.44	32,817.56	32,818.40	35,120.63	25,144.53
	k3	32,089.89	33,847.67	38,170.89	24,536.13	27,407.50	31,568.53
	R	7122.56	7271.78	5635.33	8282.27	9028.77	6762.40
2022	k1	37,505.43	34,773.08	36,848.85	30,557.18	26,492.09	30,023.69
	k2	37,712.50	37,187.24	32,434.67	31,060.06	30,443.59	24,726.67
	k3	29,687.17	32,944.77	35,621.57	21,684.07	26,365.63	28,550.95
	R	8025.33	4242.47	4414.19	9376.00	4077.96	5297.02

Note: W, F, and V indicate irrigation, fertilization, and variety, respectively. k1, k2, k3, and R represent different constants for the sensitivity test. TY and NI represent tuber yield and net income, respectively.

3.3. ET and WP

W exhibited a very remarkable effect on ET in both years ($p < 0.01$). F did not significantly influence ET in 2021 ($p > 0.05$) and greatly influenced ET in 2022 ($p < 0.05$). V significantly influenced ET in 2021 ($p < 0.05$) (Figure 7). In both years, ET was most affected by W (Table 6). The highest ET was obtained at the tuber enlargement stage, while the lowest ET was obtained at the tuber maturity stage. Treatment T2 had the highest ET (305.94 mm in 2021 and 307.19 mm in 2022), which ranged from 1.16 to 60.73% and 0.93 to 65.50% greater than other treatments, respectively. W was positively correlated with ET. Compared with W2 and W3, the average ET for W1 was increased by 20.85% and 52.05% in 2021, respectively, and displayed a similar trend in 2022. ET displayed a tendency of rising and then dropping as the increase in fertilizer application. In 2021, V1's average ET was 2.22% and 6.10% greater than V2's and V3's, respectively. However, there were no significance differences in ET among the three varieties in 2022.

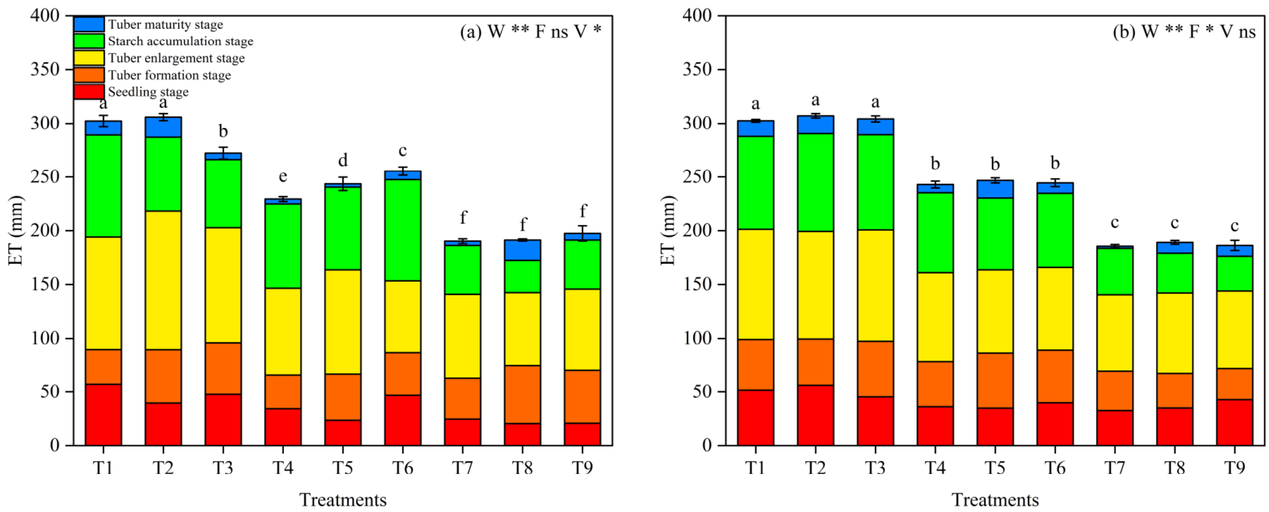

Figure 7. Effects of different combinations on ET in 2021 (**a**) and 2022 (**b**). Note: Bars are mean ± standard deviation (n = 3). W, F, and V indicate irrigation, fertilization, and variety, respectively. *, **, and ns indicate significance of effect at 0.05 level, 0.01 level, and no significant effect, respectively. Different lowercase letters indicate significant differences among treatments ($p < 0.05$). ET stands for crop evapotranspiration.

Table 6. Sensitivity test for ET, WP, TNA, and NUE in 2021 and 2022.

Year	Items	ET			WP			TNA			NUE		
		W	F	V	W	F	V	W	F	V	W	F	V
2021	k1	293.55	240.80	249.77	12.98	14.48	15.77	116.68	118.91	119.05	326.64	290.29	322.81
	k2	242.90	246.98	244.34	16.12	17.16	13.60	121.50	120.43	119.38	324.19	341.64	275.24
	k3	193.06	241.74	235.40	16.64	14.11	16.37	112.27	111.11	112.02	285.63	304.53	338.41
	R	100.48	6.18	14.37	3.66	3.05	2.76	9.23	9.32	7.36	41.01	51.36	63.18
2022	k1	304.70	243.70	245.43	12.31	14.54	15.35	95.62	94.67	96.28	393.43	368.30	385.51
	k2	244.75	247.74	245.50	15.40	15.42	13.33	105.27	98.54	89.47	361.41	382.55	361.26
	k3	187.07	245.08	245.58	15.86	13.61	14.89	84.23	91.92	99.37	353.98	357.97	362.05
	R	117.62	4.03	0.16	3.55	1.81	2.02	21.04	6.62	9.90	39.45	24.59	24.25

Note: W, F, and V indicate irrigation, fertilization, and variety, respectively. k1, k2, k3, and R represent different constants for the sensitivity test. ET, WP, TNA, and NUE represent crop evapotranspiration, water productivity, total nitrogen accumulation, and nitrogen use efficiency, respectively.

In both years, W, F, and V exhibited an obviously significant impact on WP ($p < 0.01$) (Figure 8). WP was most sensitive to W (Table 6). Overall, WP in 2021 was greater than in 2022. WP varied from 12.49 to 20.22 kg m^{-3} in 2021, with maximum value acquired at treatment T5. In 2022, treatment T8 had the highest WP (17.42 kg m^{-3}), which was obviously greater than other treatments. W was negatively correlated with WP. In 2021, F2's mean WP was 18.54% and 21.63% greater than that of F1 and F3, respectively, and 6.05% and 13.31% in 2022, respectively, and displayed a similar tendency in 2022. The average WP for V1, V2, and V3 was 15.77, 13.60, and 16.37 kg m^{-3} in 2021 and 15.35, 13.33, and 14.89 kg m^{-3} in 2022, respectively.

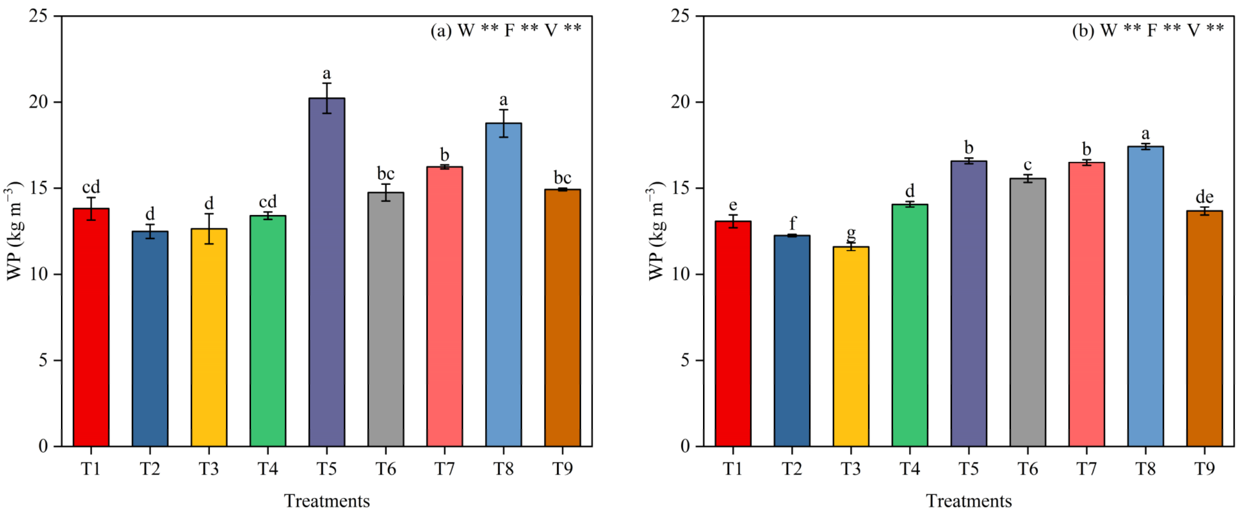

Figure 8. Effects of different combinations on WP in 2021 (**a**) and 2022 (**b**). Note: Bars are mean ± standard deviation (n = 3). W, F, and V indicate irrigation, fertilization, and variety, respectively. ** indicates significance of effect at 0.01 level. Different lowercase letters indicate significant differences among treatments ($p < 0.05$). WP stands for water productivity.

3.4. TNA and NUE

W, F, and V demonstrated a very notable impact on TNA in 2021 ($p < 0.01$). However, in 2022, W had the most remarkable impact on TNA ($p < 0.01$) (Figure 9a,b). F had the greatest impact on TNA in 2021. However, W had the greatest impact on TNA in 2022 (Table 6). Significant differences in TNA were observed among W1, W2, and W3 levels. The average TNA in W1, W2, and W3 was 116.68, 121.50, and 112.27 kg ha^{-1} in 2021 and 95.62, 105.27, and 84.23 kg ha^{-1} in 2022, respectively. Compared with F3, the mean TNA in F1 and F2 was increased by 7.02% and 8.39% in 2021, respectively, and the same trend was observed in 2022. In 2021, there were significant differences in TNA among the varieties; the average TNA in V1, V2, and V3 was 119.05, 119.38, and 112.02 kg ha^{-1}. However, there was no significant difference in TNA among the three varieties in 2022.

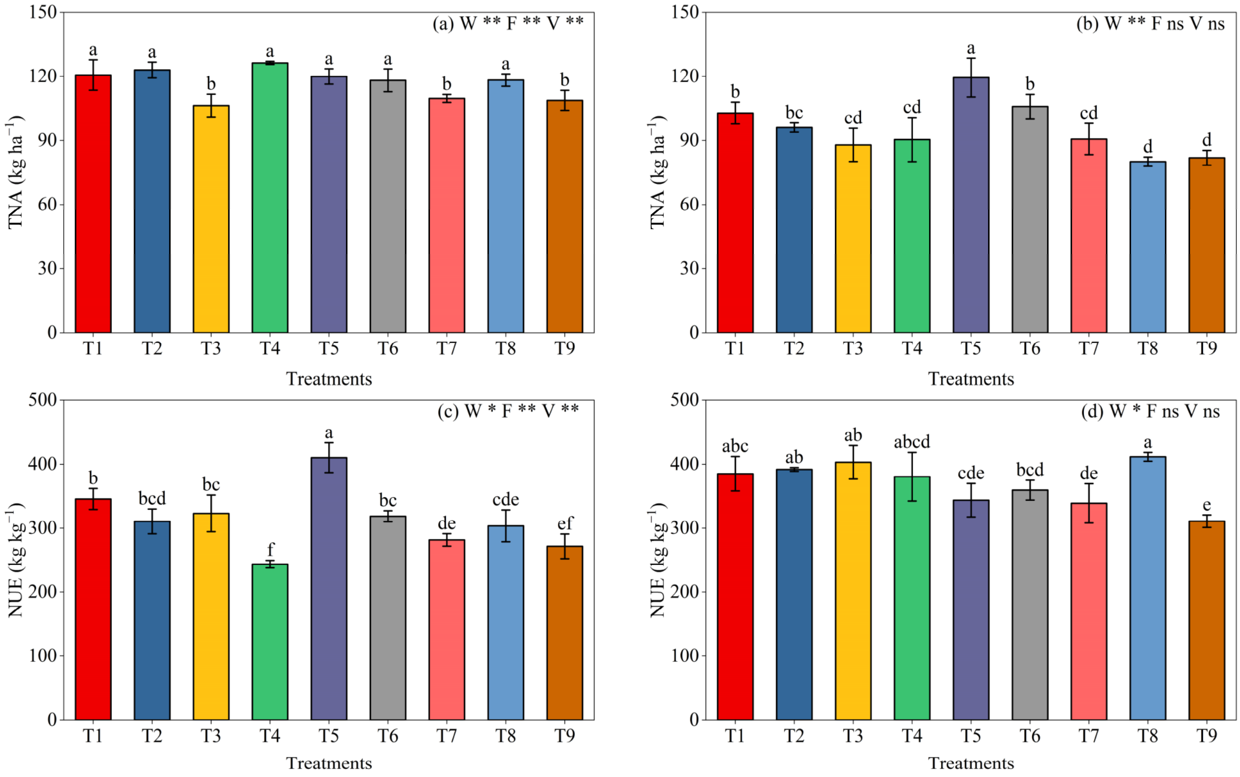

Figure 9. Effects of different combinations on TNA and NUE in 2021 (**a**,**c**) and 2022 (**b**,**d**). Note: Bars are mean ± standard deviation (*n* = 3). W, F, and V indicate irrigation, fertilization, and variety, respectively. *, **, and ns indicate significance of effect at 0.05 level, 0.01 level, and no significant effect, respectively. Different lowercase letters indicate significant differences among treatments ($p < 0.05$). TNA and NUE represent total nitrogen accumulation and nitrogen use efficiency, respectively.

In both years, W significantly influenced NUE ($p < 0.05$). F and V had strongly significant influences on NUE in 2021 ($p < 0.01$) (Figure 9c,d). In 2021, NUE was most affected by V. However, NUE was most affected by W in 2022 (Table 6). NUE varied from 243.40 to 410.33 kg kg^{-1} in 2021 with the highest NUE acquired at treatment T5. In 2022, NUE varied from 311.15 to 411.70 kg kg^{-1} and reached a maximum in treatment T8. The average NUE for W1, W2, and W3 was 326.64, 324.19, and 285.63 kg kg^{-1} in 2021 and 393.43, 361.41, and 353.98 kg kg^{-1} in 2022, respectively. NUE rose and then dropped as fertilizer application increased, obtaining the maximum at the F2 level. In 2021, mean NUE for V2 was 14.74% and 18.67% less than that for V1 and V3, respectively.

3.5. Soil Microbial Population

In both years, SBQ and SFQ were most affected by F. SAQ was most affected by F in 2021 and by W in 2022 (Table 7). F exhibited remarkable influence on SBQ, SFQ, and SAQ in 2021 ($p < 0.05$). W and F significantly impacted SBQ and SAQ in 2022 ($p < 0.01$) (Table 8). In 2021 (2022), the SBQ, SFQ, and SAQ were 29.71–42.16 × 10^{4} cfu g^{-1} (24.52–39.77 × 10^{4} cfu g^{-1}), 2.37–3.74 × 10^{2} cfu g^{-1} (2.10–3.98 × 10^{2} cfu g^{-1}), and 46.46–68.59 × 10^{4} cfu g^{-1} (46.58–74.41 × 10^{4} cfu g^{-1}), respectively. In 2021 (2022), the average SBQ, SFQ, and SAQ in W2 were 14.93% (15.09%), 7.41% (8.29%), and 6.27% (31.76%) higher than those in W1, respectively. Similarly, they were 4.34% (16.71%), 8.62% (34.88%), and 6.70% (26.94%) higher than those in W3. SAQ, SFQ, and SBQ dropped as fertilizer application increased. In 2021 (2022), the average SBQ, SFQ, and SAQ of F1 were 20.34% (26.34%), 16.71% (30.05%), and 17.29% (14.21%) lower than those of F3, respectively.

Table 7. Sensitivity test for SBQ, SFQ, and SAQ in 2021 and 2022.

Year	Items	SBQ			SFQ			SAQ		
		W	F	V	W	F	V	W	F	V
2021	k1	32.36	30.63	35.05	2.90	2.66	2.81	58.23	51.90	58.97
	k2	37.19	36.12	35.17	3.11	3.03	3.01	61.88	63.44	59.54
	k3	35.65	38.45	34.98	2.87	3.19	3.06	57.99	62.76	59.59
	R	4.83	7.82	0.19	0.25	0.53	0.25	3.89	11.53	0.62
2022	k1	31.87	27.75	33.30	3.23	2.48	3.06	53.25	54.79	59.34
	k2	36.68	34.58	33.47	3.50	3.30	3.10	70.16	60.48	59.81
	k3	31.43	37.67	33.22	2.59	3.54	3.16	55.71	63.86	59.97
	R	5.25	9.92	0.24	0.90	1.06	0.09	16.91	9.07	0.64

Note: W, F, and V indicate irrigation, fertilization, and variety, respectively. k1, k2, k3, and R represent different constants for the sensitivity test. SBQ, SFQ, and SAQ stand for soil bacterial quantity, fungal quantity, and actinomycete quantity, respectively.

Table 8. Effects of different combinations on SBQ, SFQ, and SAQ in 2021 and 2022.

Year	Treatments	SBQ (10^4 cfu g^{-1})	SFQ (10^2 cfu g^{-1})	SAQ (10^4 cfu g^{-1})
2021	T1	30.93 d	2.90 cd	52.79 cd
	T2	32.11 d	2.72 cd	58.18 bc
	T3	34.04 cd	3.08 bc	63.71 ab
	T4	31.24 d	2.71 cd	56.46 bc
	T5	41.18 ab	3.74 a	68.59 a
	T6	39.15 abc	2.90 cd	60.58 abc
	T7	29.71 d	2.37 d	46.46 d
	T8	35.07 bcd	2.63 cd	63.54 ab
	T9	42.16 a	3.60 ab	63.98 ab
	W	ns	ns	ns
	F	**	*	**
	V	ns	ns	ns
2022	T1	25.12 d	2.47 bc	46.58 d
	T2	32.03 c	3.50 abc	54.59 cd
	T3	38.47 ab	3.72 ab	58.58 bc
	T4	33.60 bc	2.87 abc	66.26 ab
	T5	36.69 abc	3.64 ab	69.82 a
	T6	39.77 a	3.98 a	74.41 a
	T7	24.52 d	2.10 c	51.52 cd
	T8	35.01 abc	2.75 abc	57.02 bcd
	T9	34.77 abc	2.93 abc	58.60 bc
	W	**	*	**
	F	**	*	**
	V	ns	ns	ns

Note: W, F, and V indicate irrigation, fertilization, and variety, respectively. *, **, and ns indicate significance of effect at 0.05 level, 0.01 level, and no significant effect, respectively. Different lowercase letters indicate significant differences among treatments ($p < 0.05$). SBQ, SFQ, and SAQ stand for soil bacterial quantity, fungal quantity, and actinomycete quantity, respectively.

3.6. Correlation Analysis

PH displayed a positive correlation with TY, NI, ET, and TNA ($p < 0.01$), and the correlation coefficients were 0.55, 0.50, 0.68, and 0.69, respectively. TY showed significantly correlated with NI, ET, WP, TNA, NUE, and SFQ ($p < 0.05$), and correlation coefficients were 0.99, 0.55, 0.33, 0.47, 0.52, and 0.30, respectively. NI displayed a positive correlation with all indicators ($p < 0.05$), and notably, it displayed a significant level of correlation with SBQ, SFQ, and SAQ, with correlation coefficients of 0.27, 0.36, and 0.31, respectively. ET was closely related to WP and NUE. Notably, ET was negatively correlated with WP ($p < 0.01$), with a correlation coefficient of −0.60. WP displayed a positive correlation with SAQ ($p < 0.05$), and the correlation coefficient was 0.28. TNA showed highly negative correlation with NUE ($p < 0.01$), with a correlation coefficient of −0.49. SBQ showed a significant positive correlation with SFQ and SAQ ($p < 0.01$), and the correlation coefficients were all 0.56. SFQ displayed a significant positive correlation with SAQ ($p < 0.01$), with a correlation coefficient of 0.43 (Figure 10).

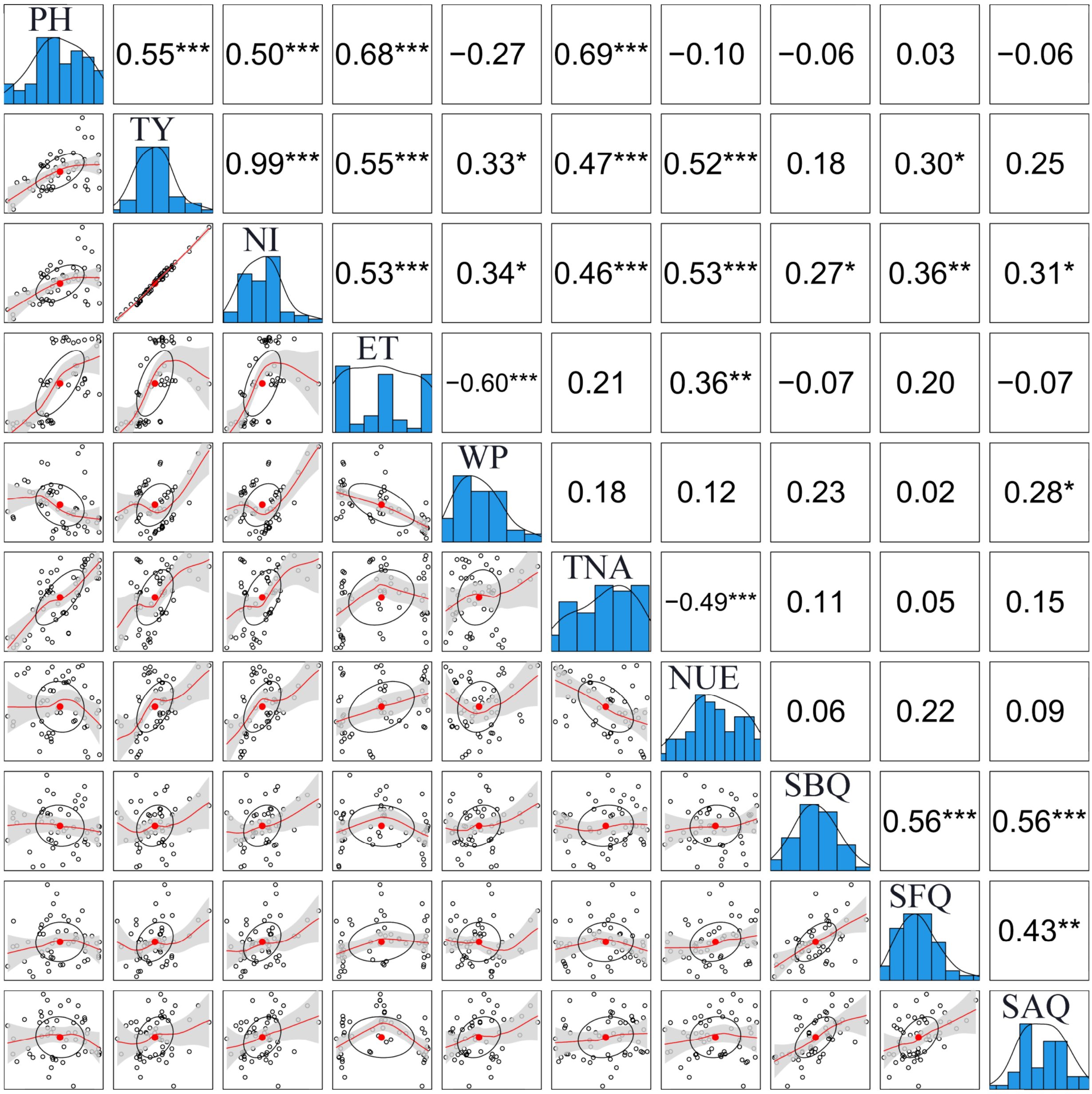

Figure 10. Pearson correlation analysis of plant height at maturity (PH), yield (TY), net income (NI), crop evapotranspiration (ET), water productivity (WP), total nitrogen accumulation (TNA), nitrogen utilization efficiency (NUE), soil organic matter (SOM), soil bacteria quantity (SBQ), soil fungi quantity (SFQ), and soil actinomycetes quantity (SAQ). Note: *, **, and *** indicate correlation at the 0.05, 0.01, and 0.001 level, respectively.

3.7. Multi-Objective Optimization Based on TY, NI, WP, TNA and NUE

In agricultural production practice, increasing fertilizer application can effectively improve potato growth and yield. However, it also increases inputs, reduces benefits, and even reduces resource utilization efficiency. When the fertilizer application was reduced, agricultural input was reduced and resource utilization efficiency was effectively improved. However, potato yield and economic benefits decreased. Consequently, simultaneously optimizing crop TY, NI, WP, TNA, and NUE is critical for potato production. Multiple regression analysis was used, and irrigation (W) and fertilization (F) were used as independent variables and potato TY, NI, WP, TNA, and NUE as dependent variables. The R^2 values of the fitted equations were ≥0.429 (Table 9). The optimal values and their corresponding W and F of each regression equation were obtained using Matlab R2022a software. Table 10 shows the difficulty of simultaneously obtaining the optimum values of TY, NI, WP, TNA, and NUE under the same irrigation amount and fertilizer rate.

Table 9. Regression relationships of the coupled effects of irrigation amount and fertilization rate on potato TY, NI, WP, TNA, and NUE.

Dependent Variable	Regression Equation	R^2
TY (kg ha^{-1})	$-76{,}732.998 + 516.043 \times W - 0.94278 \times W^2 + 175.977 \times F + 0.056915 \times WF - 0.18892 \times F^2$	0.649
NI (CNY ha^{-1})	$-102{,}328.598 + 615.251 \times W - 1.13134 \times W^2 + 205.662 \times F + 0.068298 \times WF - 0.22747 \times F^2$	0.634
WP (kg m^{-3})	$-16.837 + 0.12511 \times W - 2.7464 \times 10^{-4} \times W^2 + 0.083398 \times F - 1.8574 \times 10^{-5} \times WF - 7.7381 \times 10^{-5} \times F^2$	0.652
TNA (kg ha^{-1})	$-87.429 + 1.17576 \times W - 2.3382 \times 10^{-3} \times W^2 + 0.14725 \times F + 2.41165 \times 10^{-4} \times WF - 1.95825 \times 10^{-4} \times F^2$	0.513
NUE (kg kg^{-1})	$-144.064 + 1.27509 \times W - 1.5429 \times 10^{-3} \times W^2 + 1.26612 \times F - 4.4187 \times 10^{-4} \times WF - 1.16903 \times 10^{-3} \times F^2$	0.429

Note: W and F stand for irrigation and fertilization, respectively. TY, NI, WP, TNA, and NUE stand for tuber yield, net income, water productivity, total nitrogen accumulation, and nitrogen use efficiency, respectively.

Table 10. Irrigation amount and fertilization rate corresponding to optimal potato TY, NI, WP, TNA, and NUE.

Dependent Variable	Irrigation Amount (mm)	Fertilization (N-P-K) Rate (kg ha^{-1})	TY (kg ha^{-1})	NI (CNY ha^{-1})	WP (kg m^{-3})	TNA (kg ha^{-1})	NUE (kg kg^{-1})
Optimal TY (kg ha^{-1})	290	185.45-92.73-231.82	42,658.75	36,772.45	16.00676	116.7305	372.2581
Optimal NI (CNY ha^{-1})	286	180-90-225	42,615.62	36,830.29	16.17222	116.6314	372.141
Optimal WP (kg m^{-3})	210	187.27-93.64-234.09	36,736.64	29,953.65	17.74388	106.344	349.8706
Optimal TNA (kg ha^{-1})	280	200-100-250	42,249.05	36,066.94	16.26278	117.3544	366.6843
Optimal NUE (kg kg^{-1})	340	172.73-86.36-215.91	39,892.03	33,470.5	13.10728	106.7424	377.386

Note: TY, NI, WP, TNA, and NUE stand for tuber yield, net income, water productivity, total nitrogen accumulation, and nitrogen use efficiency, respectively.

Further analysis determined that the confidence interval ≥ 80% of the optimal values of TY, NI, WP, TNA, and NUE was an acceptable optimization range. The overlapping areas of TY, NI, WP, TNA, and NUE expanded as the range of confidence interval expanded. If the optimization confidence interval range continued to expand, the optimization results obtained could severely weaken potato TY, NI, WP, TNA, and NUE. Therefore, a confidence interval range of ≥95% was acceptable. Potato TY, NI, WP, TNA, and NUE simultaneously achieved ≥95% of their optimal values when irrigation varied from 248 mm to 266 mm and fertilization (N-P-K) varied from 149.09-74.55-186.36 kg ha^{-1} to 212.73-106.36-265.91 kg ha^{-1} (Figure 11).

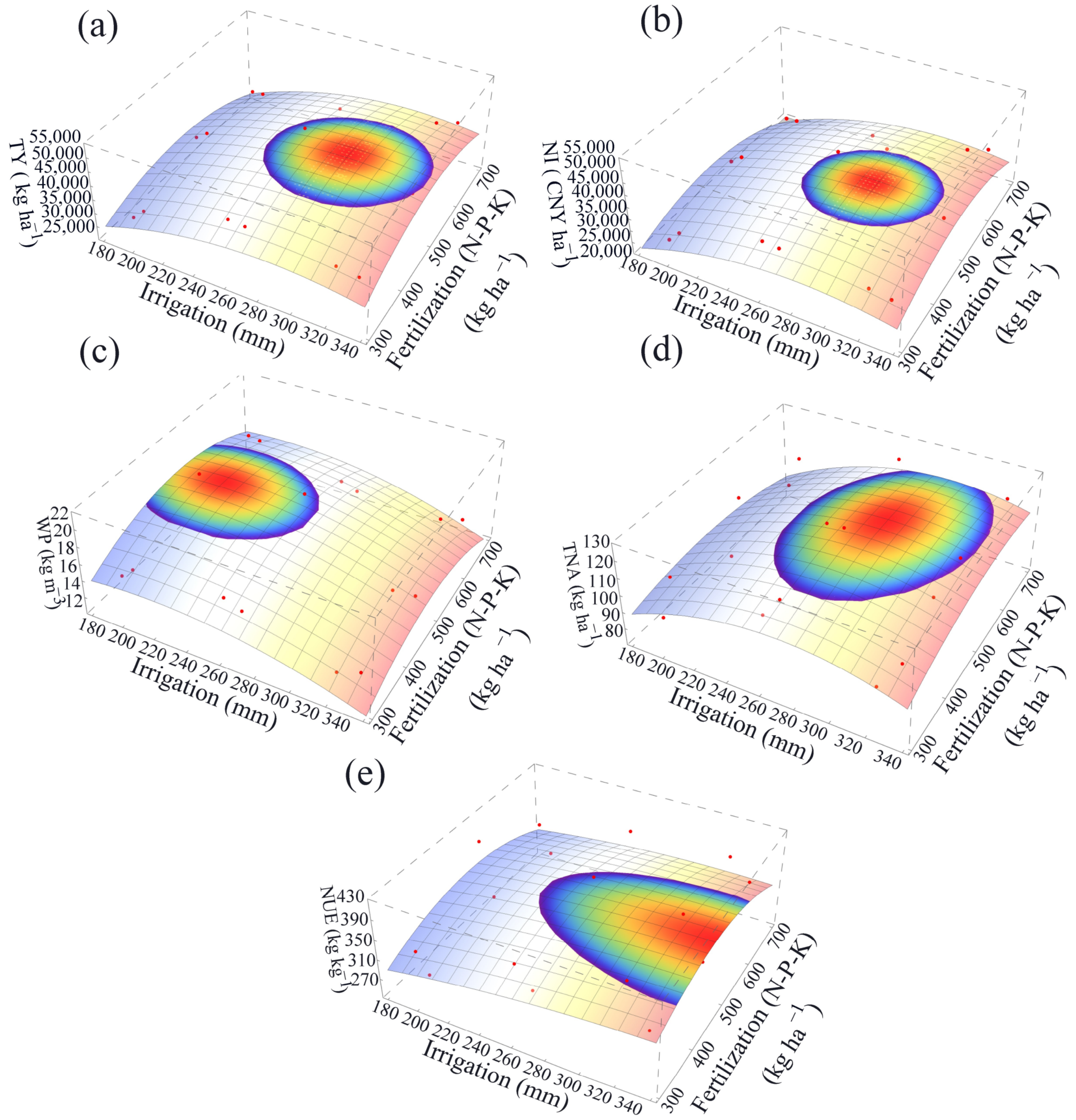

Figure 11. (**a**–**e**) Relationships of potato TY, NI, WP, TNA, and NUE with irrigation amount and fertilization rate. Note: The red dotted points in the figure represent the mean of the measured values in 2021 and 2022. The blue areas indicate the 95% confidence interval for the optimal values of potato TY, NI, WP, TNA, and NUE, respectively. The color in the figure changes from blue to red, indicating that the values are getting closer to the optimal values. TY, NI, WP, TNA, and NUE stand for tuber yield, net income, water productivity, total nitrogen accumulation, and nitrogen use efficiency, respectively.

4. Discussion

4.1. Plant Height, TY and NI

Our study revealed that TY was strongly and positively related with plant height, with a correlation coefficient of 0.55. The Logistic model to fit the dynamic changes in plant height over time for each treatment was excellent, and the plant height showed a "slow-fast-slow" trend with growth time. Deficit irrigation delayed the rapid growth period of plant height, as well as the time when the maximum daily growth appeared, and slowed down the daily maximum growth and average growth rate of plant height, which was not conducive to crop yield formation [29]. This was mainly due to the fact that drought stress impaired leaf stomatal morphology, reduced CO_2 diffusion and intercellular CO_2 concentration, and severely restricted the normal growth and development of crop roots, which affected the growth of the crop [30]. Fertilizer application strongly influenced the dynamic changes in potato plant height across the growth period [31]. The daily maximum growth and average growth rate of plant height were highest at the F1 level. Rational fertilizer management could effectively synchronize the nutrient demand and soil nutrient supply over the entire growing period, thus promoting crop growth [32]. Compared with the traditional water and fertilizer management regimes, drip fertigation effectively promoted crop growth and improved the soil microenvironment [33]. The drip fertigation method could accurately regulate the water and fertilizer demand of the crop during the whole growing period and accurately transport water and fertilizer to the roots, which significantly enhanced resource utilization efficiency [34]. Potato is a shallow-rooted crop, and its root system is extremely sensitive to soil nutrients in the root zone [35]. Fertilizers are converted into available nutrients through various enzymes and physiological and biochemical reactions in the soil, ultimately affecting crop plant height [36], and this conclusion was also proven in this study. Properly increasing irrigation would improve crop metabolic rate and photosynthetic efficiency. Inadequate irrigation could hinder crop development by inhibiting the synthesis of biological enzymes, inducing stomatal closure and disrupting normal growth metabolism [37]. In this study, we observed that plant height was most sensitive to the irrigation amount and deficit irrigation severely inhibited crop growth.

Appropriate irrigation, fertilizer application, and variety selection are essential for optimizing crop yield and economic efficiency. Water is a key factor in driving yield formation. A reasonable water supply promotes crop yield formation, while deficit or excessive irrigation adversely affects crop yield [38]. Water stress severely slowed down crop growth, reducing crop biomass formation, which eventually led to severe yield reduction. When the soil water stress exceeds a certain threshold, the physiological and metabolic activities of the crop will stagnate, inhibiting dry matter accumulation and finally leading to yield reduction [39,40]. However, potato TY and NI were not always positively correlated with irrigation. In this study, there were significant differences in TY and NI among the W1, W2, and W3 treatments ($p < 0.05$). Potato TY and NI first rose and then declined as irrigation increased. When crops suffered from drought stress during the growth period, the antioxidant enzyme system was activated to protect cells from oxidative damage, causing blockage of primary metabolite synthesis pathways and insufficient raw materials for secondary metabolite synthesis, which led to yield reduction [41]. However, reasonable soil moisture increased potato root vigor and enlarged the root–soil contact area, which improved the metabolic rate of the crop [42]. In addition, appropriate irrigation significantly reduced plant canopy temperature, increased environmental humidity, reduced soil moisture loss from evaporation, and alleviated drought stress during the whole growth period, which ultimately promoted crop yield formation [43]. However, excessive irrigation would compress the soil, reduce porosity and oxygen diffusion rate, and lead to abnormal crop respiratory metabolism, thus limiting yield formation [44]. Compared with the no fertilization treatment, increasing fertilizer application during the potato growth period enhanced net photosynthesis rate and LAI, promoted biomass accumulation, and consequently improved yield formation [45]. Utilization of fertilizer showed a favorable correlation with both NI and TY within a certain range. However, when nitrogen application exceeded the critical value, the yield did not increase or even decreased [46]. Our study identified that TY and NI were most sensitive to fertilizer application. TY and NI initially increased and then diminished as fertilization increased. Fertilization is a critical tool for stabilizing crop yield. Although fertilizer application caused many serious environmental impacts, it greatly increased crop yield and net income (average TY and NI for F2 were 21.48% and 21.96% higher than that for F3 in 2021, and 12.88% and 13.40% higher in 2022, respectively). However, increasing fertilizer application severely reduced fertilizer use efficiency [47]. Excessive fertilizer application could inhibit potato tuber formation, reduce crop resistance, prolong fertility, and make crops susceptible to pests and diseases, limiting crop yield [48]. Furthermore, we discovered that V1 and V3 had higher TY and NI. In short, considering only TY and NI, variety V1 and V3 are varieties that can be promoted for cultivation in the northwest of China.

Soil microbial population significantly promoted crop yield formation. Previous studies have shown that soil microorganisms promoted crop yield formation by decomposing organic matter into inorganic matter through catabolism, releasing large amounts of inorganic nitrogen, phosphorus, and potassium for plant growth and metabolic utilization [49]. Our study reached a similar conclusion, and a significant positive correlation was found between TY and SFQ.

4.2. WP and NUE

In arid regions with scarce rainfall, optimizing WP and NUE are critical for sustainable agricultural development [50]. Among all treatments, the maximum ET was 305.94 mm in 2021 and 307.19 mm in 2022. It was observed that the greatest ET was observed at the tuber enlargement stage. Wang et al. [51] found that ET was positively associated with irrigation and continued to increase as irrigation increased. Our study illustrated that ET was most affected by irrigation. Increasing irrigation during the growth period rapidly increased the soil moisture, and appropriate soil moisture environment would accelerate crop water metabolism, open leaf stomata through signal transmission, increase crop transpiration, and increase water consumption [52]. Kaur et al. [53] revealed that crop ET first rose and then declined with increasing fertilizer application, obtaining the largest value at 150 kg ha^{-1} nitrogen application. Our study reached similar conclusions. WP is another reflection of crop yield and water consumption dynamics. WP was most affected by the irrigation and declined with increasing irrigation. Appropriate irrigation might boost agricultural productivity and growth while optimizing the use of resources. However, irrigation was not always positively correlated with yield (the average yield of W1 was 2.74% and 0.55% lower than that of W2 in 2021 and 2022, respectively). Excessive irrigation caused the plant to be greedy and delayed maturity, prolonged crop nutrient growth, shortened reproductive growth, and affected the transfer of nutrients from source to sink, resulting in reduced yield [54]. Within a certain range, increasing fertilizer application significantly improved WP, with the highest WP at the F2 level. When fertilizer application elevated from F3 to F2, the increase rate of yield (the average TY of F2 was 21.48% and 12.88% higher than that of F3 in 2021 and 2022, respectively) was greater than that of ET (the average ET of F2 was 2.17% and 1.08% higher than that of F3 in 2021 and 2022, respectively) and ultimately increased WP. When fertilizer application elevated from F2 to F1, excessive fertilization significantly increased soil salt concentration [55]. Severe salt stress would disrupt the normal growth and metabolism of potato, elevate inefficient water consumption, affect yield formation, and ultimately lead to reduced WP [56]. Our study found significant differences in WP among the three varieties, with variety V2 significantly lower than V1 and V3. Therefore, we recommend that variety V1 and V3 should be selected for potato cultivation in northwest China. Soil microorganisms mediated a large number of soil metabolic activities, which improved soil aggregate structure and enhanced soil aeration and water retention capacity, which ultimately increased WP [57]. WP and SAQ had a positive correlation, which our investigation verified.

Reasonable nitrogen metabolism through the entire growing period would improve crop quality and yield [58]. Severe water shortage reduced TNA, which eventually caused a reduction in crop yield and fertilizer use efficiency [59]. We discovered that TNA initially grew and then declined as irrigation increased, peaking at the W2 level. Rational application of nitrogen fertilizer could enhance TNA (peaking at the F2 level), which might be due to the fact that appropriate nitrogen fertilizer input reduced the residue of available nutrients at the maturity. Significant variations were seen in TNA and NUE across several crop varieties. Our study obtained the lowest TNA and highest NUE in variety V3. This difference might be related to the growth rate, root structure and nutrient utilization efficiency of the variety [60]. NUE is an important indicator for plant nutrient uptake and utilization capacity [61]. NUE had a parabolic trend when irrigation and fertilizer increased. Unreasonable water and fertilizer input caused an imbalance in the pH value of the root zone soil, affecting soil microbial population and nutrient availability, ultimately leading to reduced yield and NUE [62]. Our analysis demonstrated that NUE was negatively associated with TNA, with a correlation coefficient of −0.49. The reasons for this phenomenon were as follows. First, different potato types may have different nitrogen use efficiency. These differences probably arise from the genetic characteristics of potato, including genes related to nitrogen absorption, translocation, and utilization. Furthermore, in the context of over-applied nitrogen fertilizer or plants subjected to limiting growth factors, nitrogen uptake by the plants might lead to nitrogen wastage after absorption [63].

4.3. Multi-Objective Optimization of Water and Fertilizer Management Strategies

It is challenging to account for potato TY, NI, WP, TNA, and NUE simultaneously under the same treatment. However, comprehensive analysis based on multiple indicators would effectively overcome the problem, thus making the research results more scientific and objective [64]. High TY and NI are the goal pursued by farmers, and high WP and NUE is the core of sustainable development of modern agriculture. To enhance the applicability of field management practices, multiple regression analysis and spatial modeling were employed to determine reasonable irrigation and fertilizer application intervals to meet different production goals. This method has been extensively employed in agricultural production and presented a scientific basis for crop production [65–67]. Our study found that potato TY, NI, WP, TNA, and NUE were simultaneously optimized (achieved ≥95% of their maximum values) when irrigation and fertilization (N-P-K) were 248~266 mm and 149.09-74.55-186.36~212.73-106.36-265.91 kg ha^{-1}, respectively.

5. Conclusions

The Logistic model accurately described how different treatments affected potato plant height growth. Plant height under 100% ETc and 80% ETc increased by 28.34% and 22.38%, respectively, compared to the average height in 60% ETc, while 120-60-150 kg ha^{-1} (N-P-K) plants were notably shorter than those in 240-120-300 kg ha^{-1} and 180-90-225 kg ha^{-1}. The irrigation, fertilization, and variety significantly influenced the tuber yield, net income, and water productivity. Increased fertilizer use initially boosted these indicators, along with total nitrogen accumulation and nitrogen use efficiency, but they later declined. The best results for tuber yield, net income, and nitrogen accumulation were seen at the 80% ETc level. Water productivity and irrigation had a negative correlation, while evapotranspiration and nitrogen use efficiency had a positive correlation. Variety Feiurita and Qingshu9 had markedly greater tuber yield, net income, water productivity, and nitrogen use efficiency than Longshu7. Fertilization notably increased soil bacteria quantity, soil fungi quantity, and soil actinomycetes quantity, which then decreased with higher irrigation levels. Soil microbial population was closely linked to tuber yield, net income, evapotranspiration, water productivity, total nitrogen accumulation, and nitrogen use efficiency. Ultimately, achieving optimal potato yield, net income, and water and nitrogen use efficiency (≥ 95% of their maximum values) required irrigation and fertilization (N-P-K) of 248~266 mm and

149.09-74.55-186.36~212.73-106.36-265.91 kg ha^{-1}, respectively—key for sustainable potato farming in northwest China.

Author Contributions: F.Z. and Y.X. (Yingying Xing); methodology, F.Z.; software, F.Z. and M.C.; validation, M.C., Y.Z. and Y.X. (Yunxia Xie); formal analysis, F.Z.; investigation, M.C., Y.Z. and Y.X. (Yunxia Xie); resources, Y.X. (Yingying Xing); data curation, Y.X. (Yingying Xing); writing—original draft preparation, F.Z.; writing—review and editing, F.Z. and Y.X. (Yingying Xing); visualization, F.Z.; supervision, Y.X. (Yingying Xing); project administration, Y.X. (Yingying Xing); funding acquisition, Y.X. (Yingying Xing). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (NO. 52169014, 42107379).

Data Availability Statement: The data sets supporting the conclusions of this article are included within the article.

Acknowledgments: We thank 3 anonymous reviewers for their valuable comments.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Qin, R.Z.; Zhang, F.; Yu, C.Q.; Zhang, Q.; Qi, J.G.; Li, F.M. Contributions made by rain-fed potato with mulching to food security in China. *Eur. J. Agron.* **2022**, *133*, 9. [CrossRef]
2. Sampaio, S.L.; Barreira, J.C.M.; Fernandes, A.; Petropoulos, S.A.; Alexopoulos, A.; Santos-Buelga, C.; Ferreira, I.; Barros, L. Potato biodiversity: A linear discriminant analysis on the nutritional and physicochemical composition of fifty genotypes. *Food Chem.* **2021**, *345*, 9. [CrossRef]
3. Cheng, M.H.; Wang, H.D.; Zhang, F.C.; Wang, X.K.; Liao, Z.Q.; Zhang, S.H.; Yang, Q.L.; Fan, J.L. Effects of irrigation and fertilization regimes on tuber yield, water-nutrient uptake and productivity of potato under drip fertigation in sandy regions of northern China. *Agric. Water Manag.* **2023**, *287*, 18. [CrossRef]
4. Yin, J.; Yang, Y.P.; Eeswaran, R.; Yang, Z.; Ma, Z.H.; Sun, F.B. Irrigation scheduling for potatoes (*Solanum tuberosum* L.) under drip irrigation in an arid region using AquaCrop model. *Front. Plant Sci.* **2023**, *14*, 12. [CrossRef] [PubMed]
5. Liu, R.; Yang, Y.; Wang, Y.S.; Wang, X.C.; Rengel, Z.; Zhang, W.J.; Shu, L.Z. Alternate partial root-zone drip irrigation with nitrogen fertigation promoted tomato growth, water and fertilizer-nitrogen use efficiency. *Agric. Water Manag.* **2020**, *233*, 8. [CrossRef]
6. Li, S.; Kupriyanovich, Y.; Wagg, C.; Zheng, F.Z.; Hann, S. Water deficit duration affects potato plant growth, yield and tuber quality. *Agriculture* **2023**, *13*, 2007. [CrossRef]
7. Badr, M.A.; El-Tohamy, W.A.; Salman, S.R.; Gruda, N. Yield and water use relationships of potato under different timing and severity of water stress. *Agric. Water Manag.* **2022**, *271*, 8. [CrossRef]
8. Mthembu, S.G.; Magwaza, L.S.; Mditshwa, A.; Odindo, A. Evaluating drought tolerance of potato genotypes at different growth stages using yield performance and tuber quality traits. *Sci. Hortic.* **2022**, *293*, 11. [CrossRef]
9. Li, F.Q.; Deng, H.L.; Wang, Y.C.; Li, X.; Chen, X.T.; Liu, L.T.; Zhang, H.J. Potato growth, photosynthesis, yield, and quality response to regulated deficit drip irrigation under film mulching in a cold and arid environment. *Sci. Rep.* **2021**, *11*, 16. [CrossRef] [PubMed]
10. Sarker, K.K.; Hossain, A.; Timsina, J.; Biswas, S.K.; Kundu, B.C.; Barman, A.; Ibn Murad, K.F.; Akter, F. Yield and quality of potato tuber and its water productivity are influenced by alternate furrow irrigation in a raised bed system. *Agric. Water Manag.* **2019**, *224*, 11. [CrossRef]
11. Wang, H.; Xiang, Y.Z.; Zhang, F.C.; Tang, Z.J.; Guo, J.J.; Zhang, X.Y.; Hou, X.H.; Wang, H.D.; Cheng, M.H.; Li, Z.J. Responses of yield, quality and water-nitrogen use efficiency of greenhouse sweet pepper to different drip fertigation regimes in northwest China. *Agric. Water Manag.* **2022**, *260*, 13. [CrossRef]
12. Wang, L.; Zhang, H.; Wang, J.; Wang, J.D.; Zhang, Y.C. Long-term fertilization with high nitrogen rates decreased diversity and stability of diazotroph communities in soils of sweet potato. *Appl. Soil Ecol.* **2022**, *170*, 10. [CrossRef]
13. Zheng, X.Q.; Wei, L.; Lv, W.G.; Zhang, H.Q.; Zhang, Y.; Zhang, H.Y.; Zhang, H.L.; Zhu, Z.K.; Ge, T.D.; Zhang, W.J. Long-term bioorganic and organic fertilization improved soil quality and multifunctionality under continuous cropping in watermelon. *Agric. Ecosyst. Environ.* **2024**, *359*, 9. [CrossRef]
14. Grzebisz, W.; Szczepaniak, W.; Bocianowski, J. Potassium fertilization as a driver of sustainable management of nitrogen in potato (*Solanum tuberosum* L.). *Field Crop. Res.* **2020**, *254*, 13. [CrossRef]
15. Dong, J.S.; Xue, Z.; Shen, X.J.; Yi, R.C.; Chen, J.W.; Li, Q.; Hou, X.F.; Miao, H.C. Effects of different water and nitrogen supply modes on peanut growth and water and nitrogen use efficiency under mulched drip irrigation in Xinjiang. *Plants* **2023**, *12*, 3368. [CrossRef]
16. Xu, X.P.; He, P.; Qiu, S.J.; Zhao, S.C.; Ding, W.C.; Zhou, W. Nutrient management increases potato productivity and reduces environmental risk: Evidence from China. *J. Clean. Prod.* **2022**, *369*, 10. [CrossRef]

17. Khalil, T.; Haroon, M.; Miskeen, S.; Sammi, S.; Jahangir, M.; Najeeb, S.; Nisar, K.; Khan, A.; Liaquat, M.; Khan, I.; et al. Potato chip varietal analysis: A comparative evaluation based on potato cultivars. *Potato Res.* **2023**, *16*. [CrossRef]
18. Asnake, D.; Alemayehu, M.; Asredie, S. Growth and tuber yield responses of potato (*Solanum tuberosum* L.) varieties to seed tuber size in northwest highlands of Ethiopia. *Heliyon* **2023**, *9*, 11. [CrossRef]
19. Tiwari, J.K.; Buckseth, T.; Singh, R.K.; Zinta, R.; Thakur, K.; Bhardwaj, V.; Dua, V.K.; Kumar, M. Aeroponic evaluation identifies variation in Indian potato varieties for root morphology, nitrogen use efficiency parameters and yield traits. *J. Plant Nutr.* **2022**, *45*, 2696–2709. [CrossRef]
20. Xiao, G.M.; Zhao, Z.C.; Liang, L.; Meng, F.Q.; Wu, W.L.; Guo, Y.B. Improving nitrogen and water use efficiency in a wheat-maize rotation system in the North China Plain using optimized farming practices. *Agric. Water Manag.* **2019**, *212*, 172–180. [CrossRef]
21. Ma, H.Y.; Li, L.; Liu, S.R.; Shi, W.Q.; Wang, C.; Zhao, Q.F.; Cui, N.B.; Wang, Y.S. Physiological response, phytohormone signaling, biomass production and water use efficiency of the CAM plant Ananas comosus under different water and nitrogen regimes. *Agric. Water Manag.* **2022**, *266*, 11. [CrossRef]
22. Xing, Y.Y.; Zhang, T.; Jiang, W.T.; Li, P.; Shi, P.; Xu, G.C.; Cheng, S.D.; Cheng, Y.T.; Fan, Z.; Wang, X.K. Effects of irrigation and fertilization on different potato varieties growth, yield and resources use efficiency in the Northwest China. *Agric. Water Manag.* **2022**, *261*, 18. [CrossRef]
23. Fan, J.C.; Lu, X.J.; Gu, S.H.; Guo, X.Y. Improving nutrient and water use efficiencies using water-drip irrigation and fertilization technology in Northeast China. *Agric. Water Manag.* **2020**, *241*, 7. [CrossRef]
24. Wang, X.K.; Guo, T.; Wang, Y.; Xing, Y.Y.; Wang, Y.F.; He, X.L. Exploring the optimization of water and fertilizer management practices for potato production in the sandy loam soils of northwest China based on PCA. *Agric. Water Manag.* **2020**, *237*, 14. [CrossRef]
25. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO Rome* **1998**, *300*, D05109.
26. Fandika, I.R.; Kemp, P.D.; Miliner, J.P.; Horne, D.; Roskruge, N. Irrigation and nitrogen effects on tuber yield and water use efficiency of heritage and modern potato cultivars. *Agric. Water Manag.* **2016**, *170*, 148–157. [CrossRef]
27. Liu, K.Y.; Meng, M.L.; Zhang, T.T.; Chen, Y.J.; Yuan, H.T.; Su, T.M. Quantitative Analysis of Source-Sink Relationships in Two Potato Varieties under Different Nitrogen Application Rates. *Agronomy* **2023**, *13*, 1083. [CrossRef]
28. Xing, Y.Y.; Mi, F.Y.; Wang, X.K. Effects of different nitrogen fertilizer types and application rates on maize yield and nitrogen use efficiency in Loess Plateau of China. *J. Soils Sediments* **2022**, *22*, 1938–1958. [CrossRef]
29. Kifle, M.; Gebretsadikan, T.G. Yield and water use efficiency of furrow irrigated potato under regulated deficit irrigation, Atsibi-Wemberta, North Ethiopia. *Agric. Water Manag.* **2016**, *170*, 133–139. [CrossRef]
30. Martínez-Romero, A.; Domínguez, A.; Landeras, G. Regulated deficit irrigation strategies for different potato cultivars under continental Mediterranean-Atlantic conditions. *Agric. Water Manag.* **2019**, *216*, 164–176. [CrossRef]
31. Zhang, R.Y.; Zhang, W.N.; Kang, Y.C.; Shi, M.F.; Yang, X.Y.; Li, H.; Yu, H.F.; Wang, Y.; Qin, S.H. Application of different foliar iron fertilizers for improving the photosynthesis and tuber quality of potato (*Solanum tuberosum* L.) and enhancing iron biofortification. *Chem. Biol. Technol. Agric.* **2022**, *9*, 14. [CrossRef]
32. da Silva, A.; Zotarelli, L.; Dukes, M.D.; van Santen, E.; Asseng, S. Nitrogen fertilizer rate and timing of application for potato under different irrigation methods. *Agric. Water Manag.* **2023**, *283*, 12. [CrossRef]
33. Eissa, M.A. Efficiency of P fertigation for drip-irrigated potato grown on calcareous sandy soils. *Potato Res.* **2019**, *62*, 97–108. [CrossRef]
34. Feng, X.Y.; Pu, J.X.; Liu, H.J.; Wang, D.; Liu, Y.H.; Qiao, S.T.; Lei, T.; Liu, R.H. Effect of fertigation frequency on soil nitrogen distribution and tomato yield under alternate partial root-zone drip irrigation. *J. Integr. Agric.* **2023**, *22*, 897–907. [CrossRef]
35. Wichrowska, D.; Rolbiecki, R.; Rolbiecki, S.; Sadan, H.A.; Figas, A.; Jagosz, B.; Atilgan, A.; Pal-Fam, F. Effect of drip fertigation with nitrogen application on bioactive compounds and the nutritional value of potato tubers before and after their long-term storage. *Agriculture* **2021**, *11*, 1076. [CrossRef]
36. Garg, N.; Choudhary, O.P.; Thaman, S.; Sharma, V.; Singh, H.; Vashistha, M.; Sekhon, K.S.; Sharda, R.; Dhaliwal, M.S. Effects of irrigation water quality and NPK-fertigation levels on plant growth, yield and tuber size of potatoes in a sandy loam alluvial soil of semi-arid region of Indian Punjab. *Agric. Water Manag.* **2022**, *266*, 14. [CrossRef]
37. Hou, J.X.; Liu, X.Z.; Zhang, J.R.; Wei, Z.H.; Ma, Y.Y.; Wan, H.; Liu, J.; Cui, B.J.; Zong, Y.Z.; Chen, Y.T.; et al. Combined application of biochar and partial root-zone drying irrigation improves water relations and water use efficiency of cotton plants under salt stress. *Agric. Water Manag.* **2023**, *290*, 17. [CrossRef]
38. Zhang, J.W.; Xiang, L.X.; Liu, Y.X.; Jing, D.; Zhang, L.L.; Liu, Y.; Li, W.Q.; Wang, X.Y.; Li, T.L.; Li, J.M. Optimizing irrigation schedules of greenhouse tomato based on a comprehensive evaluation model. *Agric. Water Manag.* **2024**, *295*, 18. [CrossRef]
39. Al-Selwey, W.A.; Alsadon, A.A.; Ibrahim, A.A.; Labis, J.P.; Seleiman, M.F. Effects of zinc oxide and silicon dioxide nanoparticles on physiological, yield, and water use efficiency traits of potato grown under water deficit. *Plants* **2023**, *12*, 218. [CrossRef]
40. Liao, Z.Q.; Zhang, K.B.; Fan, J.L.; Li, Z.J.; Zhang, F.C.; Wang, X.K.; Wang, H.D.; Cheng, M.H.; Zou, Y.F. Ridge-furrow plastic mulching and dense planting with reduced nitrogen improve soil hydrothermal conditions, rainfed soybean yield and economic return in a semi-humid drought-prone region of China. *Soil Tillage Res.* **2022**, *217*, 13. [CrossRef]

41. Danso, E.O.; Yakubu, A.; Darrah, Y.O.K.; Arthur, E.; Manevski, K.; Sabi, E.B.; Abenney-Mickson, S.; Ofori, K.; Plauborg, F.; Andersen, M.N. Impact of rice straw biochar and irrigation on maize yield, intercepted radiation and water productivity in a tropical sandy clay loam. *Field Crop. Res.* **2019**, *243*, 11.
42. Yang, Y.P.; Yin, J.; Ma, Z.H.; Wei, X.D.; Sun, F.B.; Yang, Z. Water and nitrogen regulation effects and system optimization for potato (*Solanum tuberosum* L.) under film drip irrigation in the dry zone of Ningxia China. *Agronomy* **2023**, *13*, 308. [CrossRef]
43. Ahmadi, S.H.; Andersen, M.N.; Plauborg, F.; Poulsen, R.T.; Jensen, C.R.; Sepaskhah, A.R.; Hansen, S. Effects of irrigation strategies and soils on field grown potatoes: Yield and water productivity. *Agric. Water Manag.* **2010**, *97*, 1923–1930. [CrossRef]
44. Yan, F.L.; Zhang, F.C.; Fan, X.K.; Fan, J.L.; Wang, Y.; Zou, H.Y.; Wang, H.D.; Li, G.D. Determining irrigation amount and fertilization rate to simultaneously optimize grain yield, grain nitrogen accumulation and economic benefit of drip-fertigated spring maize in northwest China. *Agric. Water Manag.* **2021**, *243*, 12. [CrossRef]
45. Cai, A.D.; Xu, M.G.; Wang, B.R.; Zhang, W.J.; Liang, G.P.; Hou, E.Q.; Luo, Y.Q. Manure acts as a better fertilizer for increasing crop yields than synthetic fertilizer does by improving soil fertility. *Soil Tillage Res.* **2019**, *189*, 168–175. [CrossRef]
46. Liang, G.P. Nitrogen fertilization mitigates global food insecurity by increasing cereal yield and its stability. *Glob. Food Secur. Agric. Policy* **2022**, *34*, 6. [CrossRef]
47. Tuo, Y.; Wang, Z.Y.; Zheng, Y.; Shi, X.L.; Liu, X.N.; Ding, M.J.; Yang, Q.L. Effect of water and fertilizer regulation on the soil microbial biomass carbon and nitrogen, enzyme activity, and saponin content of Panax notoginseng. *Agric. Water Manag.* **2023**, *278*, 11. [CrossRef]
48. Abdelghany, A.E.; Dou, Z.Y.; Alashram, M.G.; Eltohamy, K.M.; Elrys, A.S.; Liu, X.Q.; Wu, Y.; Cheng, M.H.; Fan, J.L.; Zhang, F.C. The joint application of biochar and nitrogen enhances fruit yield, quality and water-nitrogen productivity of water-stressed greenhouse tomato under drip fertigation. *Agric. Water Manag.* **2023**, *290*, 15. [CrossRef]
49. Qin, S.H.; Yeboah, S.; Xu, X.X.; Liu, Y.H.; Yu, B. Analysis on fungal diversity in rhizosphere soil of continuous cropping potato subjected to different furrow-ridge mulching managements. *Front. Microbiol.* **2017**, *8*, 10. [CrossRef]
50. Shrestha, B.; Darapuneni, M.; Stringam, B.L.; Lombard, K.; Djaman, K. Irrigation water and nitrogen fertilizer management in potato (*Solanum tuberosum* L.): A Review. *Agronomy* **2023**, *13*, 2566. [CrossRef]
51. Wang, H.D.; Cheng, M.H.; Zhang, S.H.; Fan, J.L.; Feng, H.; Zhang, F.C.; Wang, X.K.; Sun, L.J.; Xiang, Y.Z. Optimization of irrigation amount and fertilization rate of drip-fertigated potato based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation methods. *Agric. Water Manag.* **2021**, *256*, 18. [CrossRef]
52. Meng, X.P.; Lian, Y.H.; Liu, Q.; Zhang, P.; Jia, Z.K.; Han, Q.F. Optimizing the planting density under the ridge and furrow rainwater harvesting system to improve crop water productivity for foxtail millet in semiarid areas. *Agric. Water Manag.* **2020**, *238*, 11. [CrossRef]
53. Kaur, A.; Singh, K.B.; Gupta, R.K.; Alataway, A.; Dewidar, A.Z.; Mattar, M.A. Interactive effects of nitrogen application and irrigation on water use, growth and tuber yield of potato under subsurface drip irrigation. *Agronomy* **2023**, *13*, 11. [CrossRef]
54. Ierna, A.; Pandino, G.; Lombardo, S.; Mauromicale, G. Tuber yield, water and fertilizer productivity in early potato as affected by a combination of irrigation and fertilization. *Agric. Water Manag.* **2011**, *101*, 35–41. [CrossRef]
55. Zhou, Z.J.; Andersen, M.N.; Plauborg, F. Radiation interception and radiation use efficiency of potato affected by different N fertigation and irrigation regimes. *Eur. J. Agron.* **2016**, *81*, 129–137. [CrossRef]
56. Trost, B.; Prochnow, A.; Meyer-Aurich, A.; Drastig, K.; Baumecker, M.; Ellmer, F. Effects of irrigation and nitrogen fertilization on the greenhouse gas emissions of a cropping system on a sandy soil in northeast Germany. *Eur. J. Agron.* **2016**, *81*, 117–128. [CrossRef]
57. Qin, J.H.; Bian, C.S.; Duan, S.G.; Wang, W.X.; Li, G.C.; Jin, L.P. Effects of different rotation cropping systems on potato yield, rhizosphere microbial community and soil biochemical properties. *Front. Plant Sci.* **2022**, *13*, 14. [CrossRef]
58. Liu, C.A.; Li, F.R.; Zhou, L.M.; Zhang, R.H.; Yu, J.; Lin, S.L.; Wang, L.J.; Siddique, K.H.M.; Li, F.M. Effect of organic manure and fertilizer on soil water and crop yields in newly-built terraces with loess soils in a semi-arid environment. *Agric. Water Manag.* **2013**, *117*, 123–132. [CrossRef]
59. Singh, S.P.; Mahapatra, B.S.; Pramanick, B.; Yadav, V.R. Effect of irrigation levels, planting methods and mulching on nutrient uptake, yield, quality, water and fertilizer productivity of field mustard (*Brassica rapa* L.) under sandy loam soil. *Agric. Water Manag.* **2021**, *244*, 13. [CrossRef]
60. Assunçao, N.S.; Fernandes, A.M.; Soratto, R.P.; Mota, L.; Ribeiro, N.P.; Leonel, M. Tuber yield and quality of two potato cultivars in response to nitrogen fertilizer management. *Potato Res.* **2021**, *64*, 147–166. [CrossRef]
61. Bohman, B.J.; Rosen, C.J.; Mulla, D.J. Relating nitrogen use efficiency to nitrogen nutrition index for evaluation of agronomic and environmental outcomes in potato. *Field Crop. Res.* **2021**, *262*, 13. [CrossRef]
62. Ning, L.Y.R.; Xu, X.P.; Qiu, S.J.; Lei, Q.L.; Zhang, Y.T.; Luo, J.F.; Ding, W.C.; Zhao, S.C.; He, P.; Zhou, W. Balancing potato yield, soil nutrient supply, and nitrous oxide emissions: An analysis of nitrogen application trade-offs. *Sci. Total Environ.* **2023**, *899*, 10. [CrossRef]
63. Tian, X.; Zhang, C.; Ju, X.T. Crop responses to application of optimum nitrogen fertilizers on soils of various fertilities formed from long-term fertilization regimes. *Eur. J. Agron.* **2023**, *148*, 10. [CrossRef]
64. Si, Z.Y.; Liu, J.M.; Wu, L.F.; Li, S.; Wang, G.S.; Yu, J.C.; Gao, Y.; Duan, A.W. A high-yield and high-efficiency cultivation pattern of winter wheat in North China Plain: High-low seedbed cultivation. *Field Crop. Res.* **2023**, *300*, 14. [CrossRef]

65. Zhang, S.H.; Fan, J.L.; Zhang, F.C.; Wang, H.D.; Yang, L.; Sun, X.; Cheng, M.H.; Cheng, H.L.; Li, Z.J. Optimizing irrigation amount and potassium rate to simultaneously improve tuber yield, water productivity and plant potassium accumulation of drip-fertigated potato in northwest China. *Agric. Water Manag.* **2022**, *264*, 13. [CrossRef]
66. Lai, Z.L.; Fan, J.L.; Yang, R.; Xu, X.Y.; Liu, L.J.; Li, S.E.; Zhang, F.C.; Li, Z.J. Interactive effects of plant density and nitrogen rate on grain yield, economic benefit, water productivity and nitrogen use efficiency of drip-fertigated maize in northwest China. *Agric. Water Manag.* **2022**, *263*, 11. [CrossRef]
67. Gao, R.P.; Pan, Z.H.; Zhang, J.; Chen, X.; Qi, Y.L.; Zhang, Z.Y.; Chen, S.Q.; Jiang, K.; Ma, S.Q.; Wang, J.L.; et al. Optimal cooperative application solutions of irrigation and nitrogen fertilization for high crop yield and friendly environment in the semi-arid region of North China. *Agric. Water Manag.* **2023**, *283*, 13. [CrossRef]