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The Performance of Agronomic and Quality Traits of Quinoa under Different Altitudes in Northwest of China

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Abstract: Quinoa is a resilient crop known for its adaptability to diverse environmental conditions. This study examined the agronomic performance and ecological adaptability of quinoa across four distinct altitudes in the northwestern regions of China. Six quinoa genotypes were assessed for agronomic traits, phenology and yield performances, and nutritional quality characteristics in Yining city, Nilka County, Tekes County and Zhaosu County under varied environmental conditions. Our findings demonstrate significant variations in all measured traits, including agronomic and nutritional quality traits, across the various altitudes and genotypes. In Yining city, a warmer and lower altitude area, genotypes exhibit superior traits for fodder production, including increased branches, longer panicles, robust stems, and high seed protein content. Genotypes Jinli 1 and Beijing 2 achieve yields exceeding 3 tons per hectare (t/ha), highlighting the region's productivity. The Nilka and Tekes counties boasted the shortest quinoa crop cycles, with Jinli 1 yielding 4.05 t/ha seeds in Tekes County, exhibiting high protein and fat content alongside low saponins, making it a prime location for yield production. Zhaosu County, with its cooler climate and fertile chernozem soil, elicited high 1000 seed weight and more robust protein response than Nilka and Tekes counties, illustrating the impact of soil fertility on nutritional composition. Correlation analyses further elucidated that the plants characterized by shorter flowering times, crop cycles, compact inflorescence, and taller heights exhibited superior seed yields. Our study contributes significant insights into the ecological adaptability and nutritional dynamics of quinoa, with implications for sustainable crop production and food security in diverse agroecosystems.

Keywords: quinoa; agronomic traits; quality characters; altitude; genotype; location

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1. Introduction

Quinoa (*Chenopodium quinoa* Willd.), an annual species of the Amaranthaceae family that originates from the Andean region of South America, has been cultivated for around 7000 years [1]. It is a plant that stands out for its excellent nutritional value and has been known since ancient times in the Inca Empire. Despite having cereal characteristics, quinoa is designated as a "pseudo-cereal" as not belonging to the Gramineae family [2]. Quinoa seeds have a higher nutritive value than most cereal grains and contain high-quality protein with the essential amino acid balance, high levels of fatty acids, vitamins, minerals, and dietary fiber. In addition to presenting high nutritional quality, it is also characterized by being gluten-free, which is suitable as a more nutritious food for patients with celiac disease [2,3]. Meanwhile, the genetic variability of quinoa is very plentiful and can be

adapted to a wide range of agroecological conditions, with cultivars of quinoa being grown from sea level to 4000 m above sea level, from 40° S to 2° N latitude, from 40% to 80% humidity, and from a cold, highland climates to subtropical conditions [4]. It has a high tolerance to adverse environmental stress, such as drought, salinity and frost [5]. The above-mentioned characteristics make quinoa a strategic crop for providing nutrition and playing a significant role in food security in the face of climate change, especially the increasing salinization and aridity worldwide [6,7]. To focus world attention on the role that quinoa's biodiversity and nutritional value play in providing food security and nutrition and in poverty eradication, the United Nations declared the year 2013 as "the International Year of Quinoa" (IYQ) [8].

The number of countries growing quinoa has increased rapidly, from 8 in 1980 to 40 in 2010, and to 95 in 2015, which has been introduced in Europe, North America, Asia and Africa [1]. In contrast, the history of quinoa cultivation in China is very short. Although experts from the Chinese Academy of Agricultural Sciences (CAAS) introduced quinoa germplasm in the 1960s, no relevant research was conducted due to a lack of knowledge about this pseudocereal. Until 1988, Tibet Agriculture and Animal Husbandry College introduced three quinoa lines from Bolivia and carried out preliminary planting experiments. However, these works were limited to simple studies of biological characteristics, cultivation and progeny selection [9–11]. Since the turn of the 21st century, increased global research activities on quinoa combined with an explosion in the economic value of the crop have contributed to large-scale quinoa cultivation in Shanxi Province in 2008 and the breeding of some new cultivars adapted to the local environment. Henceforth, the number of provinces growing quinoa has risen rapidly to more than 20. The area under quinoa cultivation and the total output in China has increased from 1300 ha and 2100 t in 2014 to about 16,600 ha and 28,800 t in 2019, which indicates that China has become the third-largest quinoa production country in the world and is only surpassed by the traditional countries of origin: Peru and Bolivia.

There are large differences in quinoa farming systems and cultivation practices in China due to its vast territory, complex terrain and diverse climates. It is important to identify and develop optimally adapted varieties. Meanwhile, study of the corresponding field farming practices is also needed. The objective of this research was to evaluate different introduced quinoa varieties for their main agronomic traits and performance under different altitudes ranging from 670 masl to 2200 masl in Ili State, Xinjiang Autonomous Region, which is located at the northwest frontier of China. In addition, we also investigated the changes in the contents of total starch, protein, fat, ash, phenolic compounds and flavonoids of quinoa seeds harvested from different altitudes.

2. Materials and Methods

2.1. Plant Material and Field Experiment

Six genotypes introduced from different provinces were evaluated in this study: two officially registered varieties named "Longli 1" and "Longli 4" were introduced from Gansu Academy of Agricultural Sciences; two resources named "Beijing 1" and "Beijing 2" were introduced from Chinese Academy of Agricultural Sciences; "Nongli 3" was introduced from Qinghai College of Agriculture and Animal Husbandry; while "Jinli 1" was introduced from Shanxi University. A field experiment was conducted at four different stations of the Ili Institute of Agricultural Science in Yili State, Xinjiang Autonomous Region during the 2017 growing season. Selected planting areas fostered an exceptional natural environment in which disease and insect infestations were minimal. Consequently, during cultivation, no chemical control measures, including the application of pesticides or herbicides, were implemented. Throughout the investigation, manual weeding was conducted as required due to the unavailability of herbicides designed specifically for quinoa. The climatic and environmental characterization of the four locations is shown in Table 1. Before sowing, the soil required a fine preparation (flat, soft, moisture preservation) and adequate sole fertilizer application (300 kg/ha of granular organic fertilizer). The experiment was determined by the randomized

block design of three replications. Each experiment plot consisted of 20 m^2 (5 m long × 4 m wide), 50 cm between rows (9 rows per plot), and 15–20 cm between plants. The crop planting dates in the different locations were all early May in 2017 except the location of Yining city, which was 11 April 2017 (Table 1). The sowing depth was 2–3 cm with artificial ditching. At the seedling stage (4–6 leaves), the final batch of seedlings was made as 1 plant per pot. In the squaring stage, granular organic fertilizer (75 kg/ha) was applied. The temperature and rainfall of each month in the four different locations during the whole growth stage were recorded in the present study (Figure 1).

Table 1. Climatic and environmental characterization of the four locations in Xinjiang Autonomous Region of China.

Location	Longitude	Latitude	Altitude (masl)	Average Temperature (°C)	Precipitation mm yr^{-1}	Frost-Free Period	Soil Type	Preceding Crop	Planting Date
Yining city	81°23′ E	43°55′ N	670	9	240	185	sierozem	peanut	11 April
Nilka county	82°53′ E	43°82′ N	1050	6	402	150	sierozem	maize	5 May
Tekes county	81°81′ E	43°23′ N	1400	5.3	474	130	sierozem	wheat	7 May
Zhaosu county	81°08′ E	43°15′ N	2200	3	459	110	chernozem	cabbage	9 May

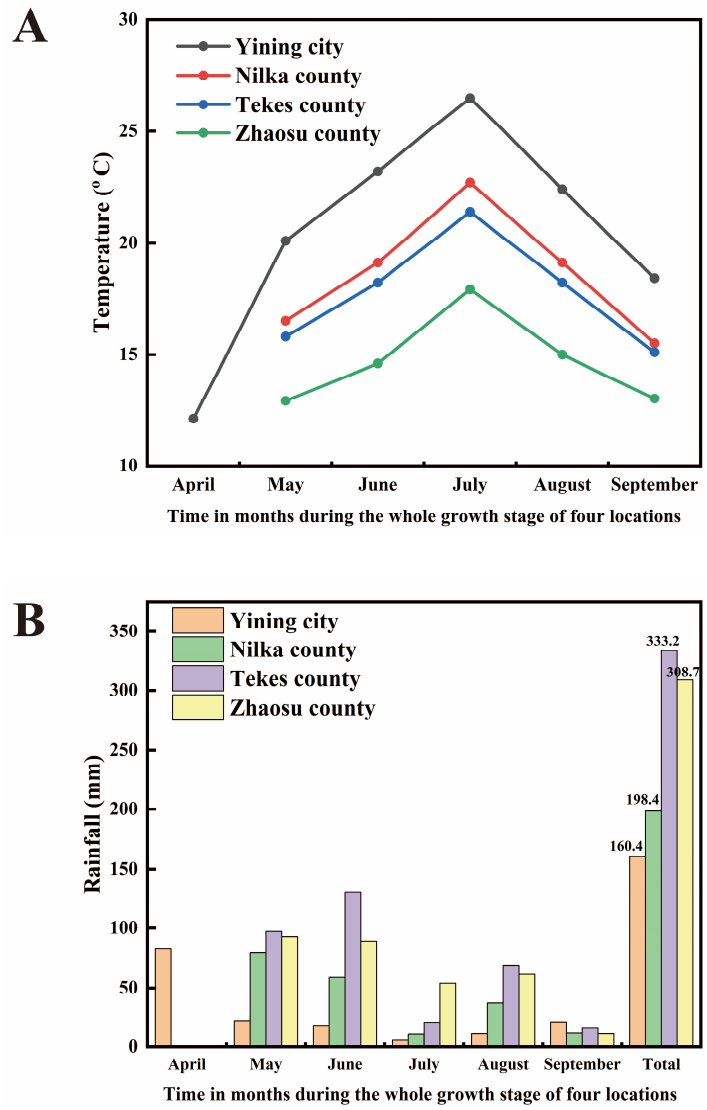

Figure 1. Average monthly temperature (°C) and total monthly rainfall (mm) of each month for the four locations during the whole growth stage of 2017: (**A**) average monthly temperature (°C) for Yining city, Nilka County, Tekes County, and Zhaosu County; (**B**) total monthly rainfall (mm) for Yining city, Nilka County, Tekes County, and Zhaosu County.

2.2. Measurement of Agronomic Traits

The agronomic traits were measured according to the International Descriptor for quinoa [12] with some modifications. Briefly, growth and development stages were recorded as follows: period of seedling, branching, squaring, anthesis, and maturity (50% of the plants show and reach these traits from each plot). Before and after harvest, data on the following traits were measured, plant height (from land to the top inflorescence), stem diameter (basal stem third node), effective branches (the branches with inflorescence), panicle length (the main panicle length), and 1000 seed weight (1000 seed weight during maturity). The crop cycle was calculated as days from emergency to maturity. Harvested seed per plot was weighed and grain yield per hectare was estimated at 12% moisture content.

2.3. Quality Traits Analysis

Before analysis, whole quinoa seeds of each genotype were ground and passed through 60 mesh screens. The compositions of moisture and ash were determined according to the methods of GB5009.4-2016 and GB20264-2006, respectively [13,14]. The protein and fat contents were determined by the Kjeldahl method with a FOSS 2300 type automatic azotometer ((FOSS Ltd., Hillerød, Denmark) [15], and the Soxhlet extraction method [16], respectively. The total starch content was determined by commercially available assays (Megazyme International Ireland Ltd., Wicklow, Ireland).

Total polyphenols and flavonoids were extracted according to our previous study [17]. The total polyphenol content was determined using the Folin–Ciocalteus method, which was expressed as mg of gallic acid equivalents (GAE) per gram of dry weight (r^2 = 0.9931) [18].

The total flavonoid content was analyzed according to a colorimetric assay described by Oomah et al. [19], with some modifications. Briefly, the appropriate dilution of extractions (0.2 mL) was mixed with 2 mL of 0.125% (2-aminoethyl) diphenylborate solution. The mixture was incubated at room temperature for 10 min, and the absorbance was measured at 405 nm using the UV/VIS spectrometer. The total flavonoid content was expressed as mg of quercetin equivalents (QE) per gram of dry weight (r^2 = 0.9955).

The extraction of total saponins was performed according to a previous method with some modifications [20]. Briefly, a 1 g sample was extracted with 40 mL of methanol at 60 °C under reflux for 3 h. Then, the solution was centrifuged at 2500× *g* for 10 min to separate the supernatant. The total saponin content was determined as described previously, with some modifications [21]. The supernatant (1 mL) or oleanolic acid standard solution (0.1–0.5 mg/mL) was mixed with 0.8 mL of 5% (*w*/*v*) vanillin in acetic acid and 3.2 mL of 72% perchloric acid. After being incubated in a water bath at 50 °C for 10 min, the mixture was then cooled by circulating water. The absorbance was measured at 560 nm using the UV/VIS spectrometer. The total saponin content was expressed as mg of oleanolic acid equivalents (OAE) per gram of dry weight (r^2 = 0.9972).

2.4. Statistical Analysis

Results are expressed as means ± standard deviations of triplicate determinations. ANOVA and Tukey's test were performed using IBM SPSS Statistics version 22.0 software. Statistical significance was established at $p < 0.05$.

3. Results

The influence of different elevations on both the agronomic and quality characteristics of quinoa in the four northwestern parts, including Yining city, Nilka County, Tekes County and Zhaosu County of Xinjiang Autonomous Region of China, was evaluated. By conducting a thorough analysis, the effects of elevation on the performance of six genotypes of quinoa (Nongli 3, Beijing 1, Longli 4, Beijing 2, Longli 1, and Jinli 1), with a particular emphasis on agronomic attributes and quality metrics, were determined.

3.1. Agronomic Traits of Quinoa Genotypes in Various Altitudes

The agronomic traits of different quinoa genotypes at various altitudes in Xinjiang Autonomous Region were significantly different (Table 2). The average height of all six genotypes was highest in Zhaosu County, measuring 189.38, followed by Yining city with a height of 179.35 (Figure 2A). Jinli 1 and Beijing 2 achieved unprecedented heights in Zhaosu County and Yining city, surpassing the 200 mark (Table 3). The stem diameter did not significantly vary between altitudes, with the exception of Zhaosu County, where Jinli 1 recorded a diameter of 2.12 cm (Figure 2B; Table 3). With a mean of 23.43 and no discernible genotypic variations, Yining city had the highest branch number; nevertheless, the Beijing 2 genotype had the highest branch number (26.00), followed by Beijing 1, respectively. Nilka County had the lowest branch number among the four zones, with a mean of 9.43 across the genotypes (Figure 2C; Table 3). The length of the panicles for each genotype in Zhaosu and Nilka counties were not statistically different from one another; however, the longest panicle was found in Yining city, with a mean length of 62.44 cm, and genotype Longli 4 recorded 64.78 cm, the longest, followed by Beijing 1 (Figure 2D; Table 2). The correlation analysis unveiled a significant positive correlation between plant height and stem diameter (r = 0.39, p <0.000). Additionally, a strong positive correlation (r = 0.59, p < 0.000) was observed between the number of branches and panicle length, underscoring the relationship between branch development and the length of the panicle (Figure 3).

Table 2. Mean sum of squares of variation and level of significance explained by genotype (G), Location (L), and G × L interaction for phenological, agronomic, and nutritional quality traits of six quinoa genotypes in Xinjiang Autonomous Region.

	Genotypes		**Locations**		**G × L**	
	Sum of Square	***p* Value**	**Sum of Square**	***p* Value**	**Sum of Square**	***p* Value**
Flowering (Day)	2553.28	<0.001	5763.22	<0.001	2706.61	<0.001
Crop cycle (Day)	3913.17	<0.001	3014.00	<0.001	639.50	<0.001
Plant height (cm)	8383.59	<0.001	2897.91	<0.001	3695.85	0.031
Stem diameter (cm)	0.78	0.053	0.39	0.13	1.08	0.38
Branches (#)	96.41	0.002	2082.40	<0.001	456.90	<0.001
Panicle length (cm)	307.29	0.32	3854.70	<0.001	2226.98	0.002
1000 seed weight (g)	3.37	<0.001	4.97	<0.001	1.66	0.01
Seed yield (t/ha)	12.18	<0.001	3.14	<0.001	4.81	<0.001
Fat (%)	15.66	<0.001	14.16	<0.001	3.39	<0.001
Protein (%)	15.43	<0.001	84.22	<0.001	13.38	<0.001
Ash (%)	2.48	<0.001	0.96	<0.001	2.07	<0.001
Total starch (%)	184.63	<0.001	94.82	<0.001	151.1	<0.001
Total polyphenol (mg/g)	0.87	<0.001	0.24	<0.001	2.30	<0.001
Total flavonoids (mg/g)	0.23	<0.001	0.09	<0.001	0.24	<0.001
Total saponins (mg/g)	14.16	<0.001	13.09	<0.001	11.03	<0.001

Table 3. Agronomic traits of six quinoa genotypes grown in four various locations in Xinjiang Autonomous Region.

	Location	**Nongli 3**	**Beijing 1**	**Longli 4**	**Beijing 2**	**Longli 1**	**Jinli 1**	**Mean**	***p* Value**
Plant height (cm)	Yining city	153.33 ± 6.05 b	187.11 ± 3.95 ab	174.33 ± 3.40 ab	202.33 ± 5.01 a	176.22 ± 15.03 ab	182.78 ± 4.75 ab	179.35 ± 4.41	0.013
	Nilka county	144.27 ± 11.59 b	176.10 ± 5.22 ab	166.97 ± 3.42 ab	184.17 ± 6.11 a	188.57 ± 5.49 a	185.63 ± 11.79 a	174.28 ± 4.59	0.017
	Tekes county	152.93 ± 7.79 b	175.07 ± 4.31 ab	171.57 ± 2.44 ab	188.30 ± 7.47 a	171.17 ± 4.81 ab	181.63 ± 4.50 a	173.44 ± 3.27	0.013
	Zhaosu county	184.90 ± 1.31 bc	183.43 ± 4.28 bc	177.633 ± 3.88 c	185.53 ± 1.75 bc	196.97 ± 4.57 ab	207.83 ± 2.11 a	189.38 ± 2.68	<0.001
Stem diameter (cm)	Yining city	1.72 ± 0.26 a	1.91 ± 0.75 a	1.72 ± 0.16 a	2.14 ± 0.13 a	1.80 ± 0.36 a	1.45 ± 0.19 a	1.79 ± 0.09	0.403
	Nilka county	1.61 ± 0.04 a	1.67 ± 0.24 a	1.43 ± 0.09 a	1.69 ± 0.13 a	1.62 ± 0.07 a	1.63 ± 0.09 a	1.61 ± 0.05	0.748
	Tekes county	1.70 ± 0.09 a	1.86 ± 0.15 a	1.60 ± 0.03 a	1.80 ± 0.05 a	1.69 ± 0.12 a	1.79 ± 0.17 a	1.74 ± 0.04	0.671
	Zhaosu county	1.78 ± 0.13 ab	1.84 ± 0.12 ab	1.41 ± 0.07 b	1.86 ± 0.14 ab	1.72 ± 0.10 ab	2.12 ± 0.02 a	1.79 ± 0.06	0.011
Branches	Yining city	18.89 ± 2.11 a	25.56 ± 1.28 a	23.67 ± 1.76 a	26.00 ± 1.64 a	23.44 ± 0.80 a	23.00 ± 2.83 a	23.43 ± 0.85	0.175
	Nilka county	7.67 ± 0.96 b	9.37 ± 1.13 ab	12.43 ± 0.43 a	7.93 ± 1.27 b	11.27 ± 0.93 ab	7.90 ± 0.35 b	9.43 ± 0.54	0.012
	Tekes county	11.20 ± 0.49 bc	10.33 ± 0.87 bc	12.20 ± 1.33 b	17.47 ± 0.27 a	8.77 ± 0.39 c	10.70 ± 0.55 bc	11.78 ± 0.71	<0.001
	Zhaosu county	12.40 ± 0.67 b	11.63 ± 1.08 b	8.43 ± 0.30 b	10.63 ± 0.88 b	20.67 ± 0.68 a	12.90 ± 1.82 b	12.78 ± 0.99	<0.001

Table 3. *Cont.*

	Location	Nongli 3	Beijing 1	Longli 4	Beijing 2	Longli 1	Jinli 1	Mean	*p* Value
Panicle length (cm)	Yining city	49.89 ± 2.44 b	62.00 ± 1.17 a	64.78 ± 1.09 a	60.44 ± 1.16 a	59.56 ± 2.35 a	62.44 ± 1.49 a	59.85 ± 1.29	0.001
	Nilka county	38.87 ± 1.84 a	37.77 ± 2.84 a	35.40 ± 2.96 a	41.97 ± 2.13 a	45.87 ± 3.67 a	46.13 ± 1.99 a	41.00 ± 1.33	0.069
	Tekes county	46.03 ± 3.66 b	45.63 ± 2.60 b	42.77 ± 1.13 b	62.97 ± 2.56 a	39.87 ± 6.79 b	53.93 ± 1.28 ab	48.53 ± 2.24	0.006
	Zhaosu county	43.17 ± 6.17 a	45.27 ± 5.60 a	54.87 ± 6.89 a	38.63 ± 10.07 a	42.70 ± 2.05 a	33.70 ± 6.99 a	43.06 ± 2.79	0.404
1000 seed weight (g)	Yining city	3.08 ± 0.09 a	2.38 ± 0.03 b	3.01 ± 0.04 a	2.93 ± 0.17 a	2.38 ± 0.15 b	2.89 ± 0.07 a	2.78 ± 0.08	0.001
	Nilka county	2.43 ± 0.03 b	2.47 ± 0.03 b	2.70 ± 0.10 ab	2.87 ± 0.09 a	2.57 ± 0.03 ab	2.83 ± 0.09 a	2.64 ± 0.05	0.003
	Tekes county	2.53 ± 0.23 b	2.77 ± 0.20 ab	3.00 ± 0.06 ab	3.30 ± 0.12 a	2.70 ± 0.00 ab	3.23 ± 0.09 a	2.92 ± 0.08	0.013
	Zhaosu county	3.60 ± 0.12 a	2.93 ± 0.07 b	3.40 ± 0.12 a	3.60 ± 0.06 a	2.93 ± 0.07 b	3.60 ± 0.06 a	3.34 ± 0.08	<0.001
Seed yield (t/ha)	Yining city	2.20 ± 0.07 c	2.32 ± 0.10 bc	2.30 ± 0.06 bc	3.06 ± 0.09 a	2.59 ± 0.08 b	3.34 ± 0.08 a	2.63 ± 0.11	<0.001
	Nilka county	1.79 ± 0.62 e	2.29 ± 0.07 d	3.36 ± 0.05 a	2.40 ± 0.06 cd	2.59 ± 0.04 c	3.02 ± 0.04 b	2.58 ± 0.12	<0.001
	Tekes county	2.31 ± 0.07 d	2.79 ± 0.08 c	2.67 ± 0.07 c	3.38 ± 0.06 b	3.46 ± 0.09 b	4.05 ± 0.07 a	3.11 ± 0.14	<0.001
	Zhaosu county	2.11 ± 0.07 e	2.37 ± 0.11 de	2.87 ± 0.06 bc	2.56 ± 0.07 cd	3.14 ± 0.11 ab	3.28 ± 0.07 a	2.72 ± 0.10	<0.001

Mean values for grain yield and agronomic yield components of six quinoa genotypes in four locations. The values are the means for each genotype of three replicates per block from a total of three blocks in each location. Means followed by the same letter were not significantly different at $p = 0.05$ by the Tukey-b test.

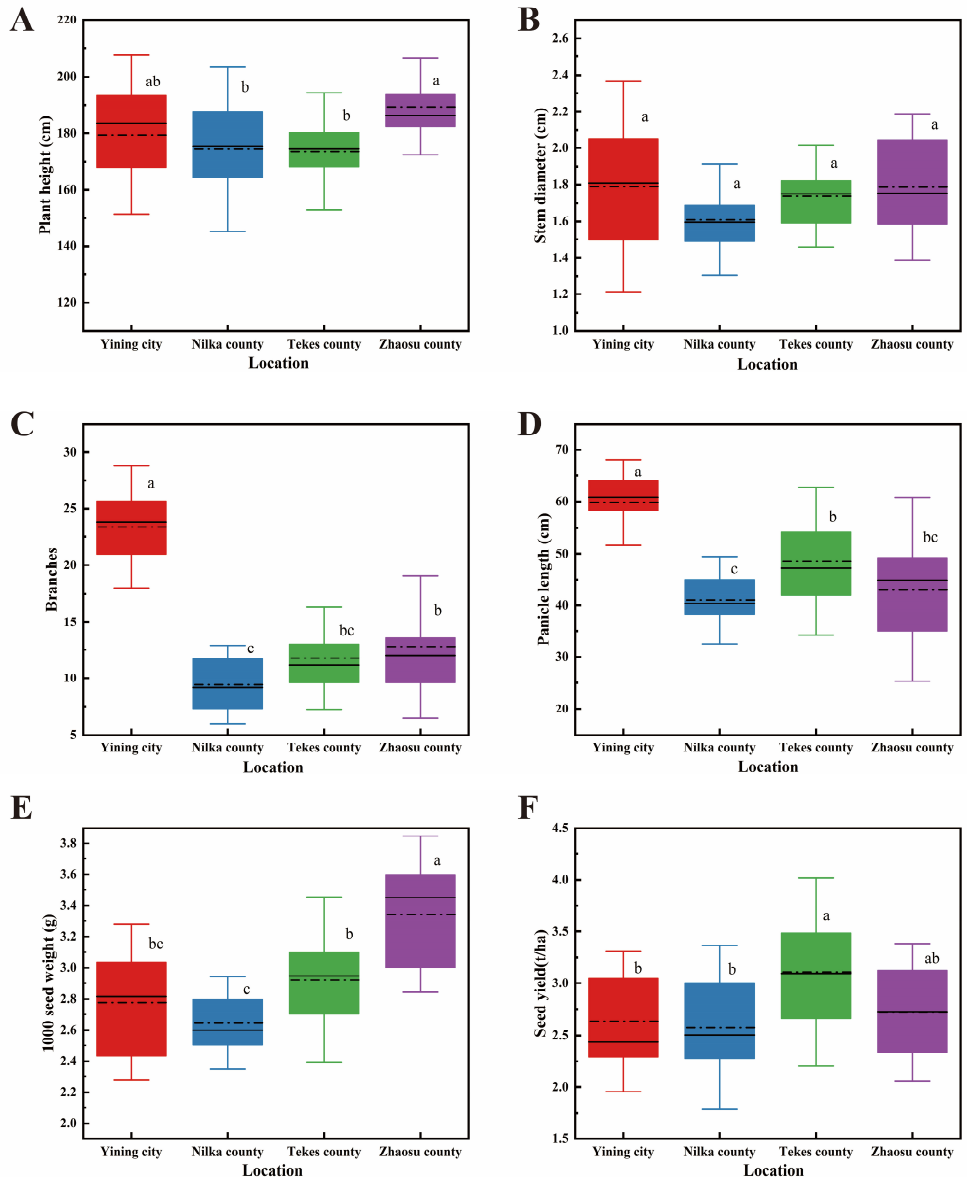

Figure 2. Effect of different location (altitude) on agronomic traits. (**A**) Plant height; (**B**) Stem diameter; (**C**) Branches; (**D**) Panicle length; (**E**) 1000 seed weight; (**F**) Seed yield. Different lowercase letters indicate significant difference ($p < 0.05$).

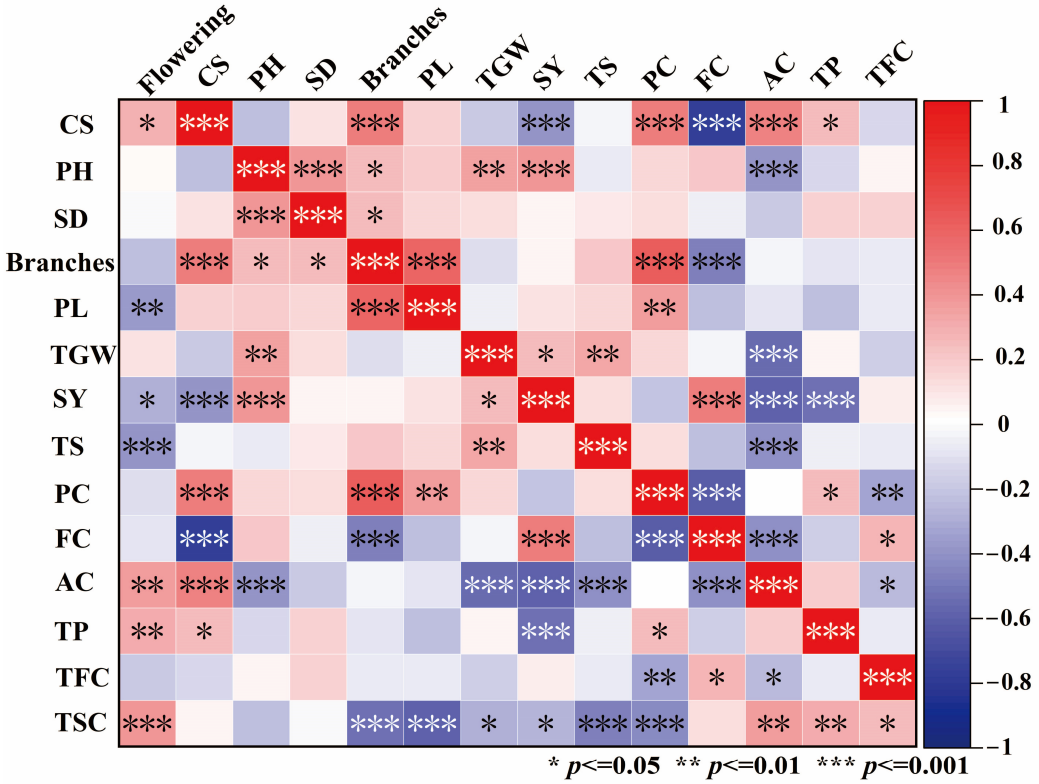

Figure 3. Correlation analysis for agronomic traits and quality traits of quinoa genotypes grown at four different stations with different altitude. Agronomic traits included as crop cycle (CS), plant height (PH), stem diameter (SD), branches, panicle length (PL), 1000 seed weight (TGW) and seed yield (SY). Nutritional quality traits included as total starch (TS), protein content (PC), fat content (FC), ash content (AC), total polyphenol (TP), total flavonoids content (TFC) and total saponins content (TSC) in grains.

3.2. Yield Performances and Phenology for All Tested Varieties by Site

The yield performances, including 1000 seed weight (g) and seed yield (t/ha), as well as phenology, including flowering days and crop cycle of all the examined genotypes exhibited considerable variations across different sites. The genotype and location displayed significant statistical differences, as did the genotype by location interaction ($p < 0.001$; Tables 2 and 3).

3.2.1. Yining City

Among the genotypes examined in Yining city, it was noted that the average time for flowering among the tested genotypes was remarkably fast, with an average of 80 days. This length was the shortest among the four unique altitudes being studied. Beijing 2 had the earliest blossoming, followed closely by Longli 4. Conversely, Longli 1 had a longer flowering period, needing roughly 100 days to reach the flowering stage. The crops with the shortest growth cycles were Longli 4, Beijing 2, and Jinli 1, which took a total of 125.33, 127.67, and 128.00 days to mature, respectively (Table 4). As shown in Table 2, Jinli 1 and Beijing 2 showcased remarkable performance in seed yield, surpassing all other quinoa varieties with recorded yields of 3.34 and 3.06 t/ha, respectively. However, it is noteworthy that the 1000 seed weight for Beijing 1 and Longli 1 was significantly lower compared to the other genotypes.

Table 4. Phenological traits (Flowering time and crop cycle) of six quinoa genotypes grown in four various locations in Xinjiang Autonomous Region.

	Location	Nongli 3	Beijing 1	Longli 4	Beijing 2	Longli 1	Jinli 1	Mean
Flowering time (Day)	Yining city	78.67 ± 0.88 c	94.00 ± 0.58 b	68.67 ± 0.88 de	67.67 ± 0.67 e	99.33 ± 0.67 a	71.67 ± 0.88 d	80.00 ± 3.02
	Nilka county	101.67 ± 0.33 a	87.33 ± 0.67 b	87.33 ± 0.67 b	77.33 ± 0.67 c	98.67 ± 2.19 a	76.00 ± 1.16 c	88.06 ± 2.37
	Tekes county	91.00 ± 0.58 a	71.00 ± 0.58 c	80.33 ± 0.33 b	79.00 ± 3.00 b	84.00 ± 0.58 b	82.00 ± 0.58 b	81.22 ± 1.52
	Zhaosu county	108.67 ± 0.33 a	101.33 ± 0.88 c	99.00 ± 0.58 c	101.00 ± 0.58 c	104.00 ± 0.58 b	101.00 ± 0.58 c	102.5 ± 0.79
Crop Cycle (Day)	Yining city	145.00 ± 0.58 a	136.00 ± 0.58 b	125.33 ± 1.45 c	127.67 ± 0.67 c	134.33 ± 0.67 b	128.00 ± 0.58 c	132.72 ± 1.64
	Nilka county	130.00 ± 0.00 a	115.00 ± 0.58 c	114.00 ± 0.58 c	109.00 ± 0.58 d	123.00 ± 0.58 b	105.33 ± 0.88 e	116.06 ± 2.02
	Tekes county	133.00 ± 0.58 a	113.67 ± 0.67 b	108.00 ± 0.58 c	112.67 ± 0.67 b	132.00 ± 0.58 a	109.00 ± 0.58 c	118.06 ± 2.53
	Zhaosu county	132.67 ± 0.33 a	124.33 ± 0.88 c	116.00 ± 0.58 e	120.00 ± 0.58 d	129.00 ± 0.58 b	121.00 ± 0.58 d	123.83 ± 1.38

Mean values for grain yield and agronomic yield components of six quinoa genotypes in four locations. The values are the means for each genotype of three replicates per block from a total of three blocks in each location. Means followed by the same letter were not significantly different at $p = 0.05$ by the Tukey-b test.

3.2.2. Nilka County

All investigated genotypes showed statistically significant variations in phenological and seed yield parameters in Nilka County, according to the research. Among the genotypes, Jinli 1 and Beijing 2 illustrated the lowest blossoming time and crop cycle (Table 4). Similarly, Jinli 1 and Beijing 2 had significantly higher 1000 seed weights of 2.87 and 2.83 g, respectively, indicating their superior performance, while Longli 4 and Jinli 1 were particularly notable among all the genotypes, as they exceeded a yield of 3 t/ha (Table 3).

3.2.3. Tekes County

The county of Tekes displayed significant variability in both phenological and seed yield indices. The Beijing 1 genotype had a significantly shortened blooming period, finishing the process in a mere 71.00 days (Tables 2 and 4). In addition, Longli 4 and Jinli 1 had the shortest crop cycles overall, with durations of 108.00 and 109.00 days, respectively. Considering Jinli 1′s noteworthy accomplishment of having the shortest crop cycle, it substantiated its excellence by yielding a tremendously impressive 4.05 t/ha, surpassing all other evaluated genotypes at various altitudes. Furthermore, Longli 1 and Beijing 2 ranked 2nd and 3rd in Tekes County and showed notable seed production, with yields of 3.46 and 3.38 tons per hectare, respectively, closely tracking Jinli 1 (Table 3).

3.2.4. Zhaosu County

The blooming period in Zhaosu County was the longest compared to the various latitudes. Comparatively, Nongli 3 and Longli 1 showed the longest flowering and crop cycles. Among them, the shortest crop cycle was observed by Longli 4 with 116 days (Table 4). Despite having the longest crop cycle in Zhaosu County, all the quinoa genotypes displayed a relatively high 1000 seed weight (g) at the tested elevation sites. Jinli 1 emerged as the highest achiever, surpassing all other varieties and yielding an impressive 3.28 t/ha of seeds. Closely behind, Longli 1 also demonstrated commendable performance, yielding 3.14 t/ha (Table 3).

The correlations between the seed yield and agronomic traits revealed that seed yield was not associated with stem diameter and branches, but it was negatively associated with crop cycle ($r = 0.40$, $p < 0.001$) and positively correlated with plant height ($r = 0.40$, $p < 0.001$). The 1000 seed weight showed no correlation with either agronomic or phenological traits (Figure 3). An affirmative correlation was detected between the duration of the crop cycle and the number of days in which flowering occurs ($r = 0.29$, $p < 0.05$), suggesting that a greater length of time for blooming generally corresponds to a longer overall duration of the crop cycle. On the other hand, there was a strong positive association ($r = 0.48$, $p < 0.001$) between the number of branches and the crop cycle.

3.3. Nutritional Quality Analysis

The nutritional metrics, encompassing indicators such as total starch, protein, fat, ash, total polyphenol, total flavonoids, total saponins showcased significant variations across the various examination sites (Table 2). In Zhaosu County, no substantial differences were detected in total starch content among the various genotypes (Table 5). However, Longli 4 stood out with the highest total starch content of 62.04% and 57.27% in both Yining city and Nilka County compared to the other quinoa genotypes, but among the seeds in Tekes County, the Beijing 2 genotype substantially indicated the greatest concentration of total starch (59.13%). The Longli 1 genotype consistently displayed the lowest overall starch content at three distinct altitudes, with recorded values of 52.23%, 51.65%, and 55.66% in Yining city, Nilka County, and Tekes County, respectively. The Jinli 1 genotype demonstrated the highest protein content in two distinct altitudes and climates, with recorded values of 17.21% in Yining city and 15.22% in Nilka County. Nevertheless, under the most frigid environments and at the greatest elevation in Zhaosu County, Nongli 3, Beijing 2, and Jinli 1 exhibited notably increased protein concentrations in their seeds, measuring 15.72%, 15.52%, and 15.46%, respectively. Significant variations in fat content were detected across the different genotypes and altitudes, notably, Beijing 1 in Nilka County and Zhaosu County, while Jinli 1 across all altitudes emerged as an exceptional performer with the highest fat reserves of (6.55%, 7.41%, 7.61%, and 6.79%) in its seeds. Statistically significant variations in ash percentage were observed across different genotypes and altitudes. Statistically significant variations in ash percentage were observed across different genotypes and altitudes. Precisely, Longli 1 exhibited an ash percentage of 3.50% in Yining city, whereas both Longli 1 and Nongli 3 recorded values of 3.52% and 3.46% in Nilka County. In Tekes County, Nongli 3 presented the highest ash percentage, reaching 3.68%. Furthermore, in Zhaosu County, Beijing 1 and Longli 1 demonstrated ash percentages of 3.29% and 3.19%, respectively.

Total polyphenol was highest in Nongli 3 in Nilka County and Tekes County, with recorded values of 2.36 and 2.21 mg/g, respectively. In Yining city, Beijing 2 and Jinli 1 had the lowest total polyphenol content, recording values of 1.89 mg/g and 1.82 mg/g, respectively. Conversely, in Zhaosu County, during the evaluation of six genotypes conducted in Xinjiang at four various elevations, Nongli 3, Beijing 2 and Jinli 1 exhibited higher total polyphenol values of 2.43 mg/g, 2.37 mg/g, and 2.50 mg/g, respectively. Beijing 2 had exceptional performance in both Yining city and Zhaosu County, with reported values of 0.90 mg/g and 0.72 mg/g, respectively, surpassing all other genotypes in terms of total polyphenol content. On the other hand, Beijing 1 had the greatest total flavonoid levels at all elevations, with the exception of Yining city, at 0.78 mg/g, 0.91 mg/g, and 0.74 mg/g, respectively. Significantly low saponin content was observed in various genotypes in various altitudes. In Yining city, genotype Jinli 1, Beijing 2, and Longli 3 revealed the lowest saponin content, measuring 3.83 mg/g, 4.26 mg/g and 4.02 mg/g. Similarly, in Nilka County and Tekes County, Beijing 2 had significantly low amounts of saponin, with recorded values of 6.34 mg/g and 4.29 mg/g, respectively. Among the genotypes studied, Longli 4 had the lowest saponin content in Zhaosu County.

The relationships between nutritional, agronomic, and phenological traits yielded interesting insights. As shown in Figure 3, the total starch demonstrated no association with most of the traits, except for a negative association with flowering days ($r = 0.39$, $p < 0.001$) and a positive association with 1000 seed weight ($r = 0.33$, $p < 0.001$). The protein content of quinoa seeds showed a positive correlation with both the crop cycle ($r = 0.49$, $p < 0.001$) and the number of branches ($r = 0.63$, $p < 0.001$), whereas fat content displayed the opposite pattern and showed a negative correlation with both variables ($r = 0.77$, $p < 0.001$; $r = 0.48$, $p < 0.001$). A significant strong positive relationship was displayed between ash and total polyphenol with flowering days and crop cycle, while both were negatively associated with seed yield. Moreover, total flavonoids detected no relationship with agronomic and phenological traits, while a strong negative association was observed with protein ($r = 0.33$, $p < 0.001$). Total saponin exhibited strong negative correlation with several traits, including

branches (r = 0.53, $p < 0.001$), panicle length (r = 0.59, $p < 0.001$), total starch (r = 0.48, $p < 0.001$), and protein (r = 0.42, $p < 0.001$). Conversely, it presented a positive correlation with ash (r = 0.37, $p < 0.001$) and total polyphenol (r = 0.31, $p < 0.001$).

Table 5. Nutritional quality traits of six quinoa genotypes grown in four various locations in Xinjiang Autonomous Region.

	Location	Nongli 3	Beijing 1	Longli 4	Beijing 2	Longli 1	Jinli 1	Mean
Total starch (%)	Yining city	59.16 ± 0.28 ab	55.54 ± 0.07 bc	62.04 ± 1.63 a	57.58 ± 0.33 b	52.23 ± 0.74 c	56.41 ± 1.32 b	57.16 ± 0.80
	Nilka county	55.98 ± 0.01 ab	54.17 ± 1.06 b	57.27 ± 0.09 a	56.04 ± 0.00 ab	51.65 ± 0.52 c	51.47 ± 0.41 c	54.43 ± 0.57
	Tekes county	56.20 ± 0.17 bc	56.94 ± 0.51 bc	57.95 ± 0.46 ab	59.13 ± 0.04 a	55.66 ± 0.88 c	57.78 ± 0.02 ab	57.28 ± 032
	Zhaosu county	54.42 ± 2.03 a	53.66 ± 2.21 a	57.65 ± 0.19 a	56.37 ± 0.05 a	55.05 ± 0.18 a	58.66 ± 0.72 a	55.97 ± 0.61
Protein (%)	Yining city	16.72 ± 0.02 b	16.47 ± 0.17 b	15.95 ± 0.05 c	16.58 ± 0.01 b	15.23 ± 0.03 d	17.21 ± 0.07 a	16.36 ± 0.15
	Nilka county	14.04 ± 0.11 bc	13.58 ± 0.20 c	13.87 ± 0.11 bc	14.47 ± 0.27 b	13.50 ± 0.18 c	15.22 ± 0.12 a	14.11 ± 0.16
	Tekes county	14.49 ± 0.06 a	13.44 ± 0.05 bc	13.74 ± 0.23 b	13.20 ± 0.00 cd	12.79 ± 0.19 d	13.14 ± 0.01 cd	13.47 ± 0.14
	Zhaosu county	15.72 ± 0.05 a	13.50 ± 0.06 c	14.70 ± 0.01 b	15.52 ± 0.00 a	14.75 ± 0.05 b	15.46 ± 0.23 a	14.94 ± 0.19
Fat (%)	Yining city	4.56 ± 0.03 e	6.17 ± 0.08 b	5.43 ± 0.04 d	5.70 ± 0.08 c	6.03 ± 0.08 b	6.55 ± 0.04 a	5.74 ± 0.16
	Nilka county	6.28 ± 0.09 c	7.26 ± 0.02 a	6.82 ± 0.03 b	6.59 ± 0.05 bc	6.34 ± 0.13 c	7.41 ± 0.07 a	6.78 ± 0.11
	Tekes county	5.73 ± 0.05 d	7.14 ± 0.00 b	6.85 ± 0.02 c	7.07 ± 0.04 b	6.69 ± 0.08 c	7.61 ± 0.02 a	6.85 ± 0.14
	Zhaosu county	5.94 ± 0.13 c	6.81 ± 0.03 a	6.07 ± 0.04 bc	6.23 ± 0.00 b	5.93 ± 0.06 c	6.79 ± 0.03 a	6.30 ± 0.09
Ash (%)	Yining city	3.18 ± 0.03 b	3.12 ± 0.00 bc	3.13 ± 0.06 bc	2.81 ± 0.03 d	3.50 ± 0.03 a	3.02 ± 0.02 c	3.13 ± 0.06
	Nilka county	3.46 ± 0.00 a	3.24 ± 0.00 b	3.03 ± 0.00 c	3.24 ± 0.02 b	3.52 ± 0.03 a	3.02 ± 0.02 c	3.25 ± 0.05
	Tekes county	3.68 ± 0.00 a	2.65 ± 0.03 de	2.87 ± 0.03 c	2.71 ± 0.00 d	3.14 ± 0.00 b	2.59 ± 0.03 e	2.94 ± 0.09
	Zhaosu county	2.97 ± 0.03 b	3.29 ± 0.03 a	3.03 ± 0.00 b	3.02 ± 0.04 b	3.19 ± 0.03 a	2.71 ± 0.00 c	3.03 ± 0.05
Total polyphenol (mg/g)	Yining city	2.07 ± 0.03 ab	2.34 ± 0.07 a	2.25 ± 0.05 a	1.89 ± 0.11 b	2.21 ± 0.09 a	1.82 ± 0.02 b	2.09 ± 0.05
	Nilka county	2.36 ± 0.03 a	2.23 ± 0.04 ab	1.99 ± 0.03 c	2.17 ± 0.04 b	1.98 ± 0.06 c	2.00 ± 0.03 c	2.12 ± 0.04
	Tekes county	2.21 ± 0.01 a	2.07 ± 0.04 ab	1.88 ± 0.06 b	1.87 ± 0.08 b	1.93 ± 0.05 b	1.90 ± 0.02 b	1.98 ± 0.03
	Zhaosu county	2.50 ± 0.05 a	1.88 ± 0.05 b	1.79 ± 0.04 b	2.43 ± 0.03 a	1.72 ± 0.02 b	2.37 ± 0.06 a	2.11 ± 0.08
Total flavonoids (mg/g)	Yining city	0.60 ± 0.03 b	0.69 ± 0.04 b	0.57 ± 0.01 b	0.90 ± 0.02 a	0.67 ± 0.06 b	0.57 ± 0.01 b	0.67 ± 0.03
	Nilka county	0.68 ± 0.02 ab	0.78 ± 0.03 a	0.64 ± 0.01 c	0.61 ± 0.05 c	0.68 ± 0.02 ab	0.64 ± 0.02 c	0.67 ± 0.02
	Tekes county	0.65 ± 0.01 c	0.91 ± 0.02 a	0.74 ± 0.04 bc	0.71 ± 0.03 bc	0.79 ± 0.02 b	0.68 ± 0.01 c	0.75 ± 0.02
	Zhaosu county	0.63 ± 0.01 b	0.74 ± 0.03 a	0.63 ± 0.02 b	0.72 ± 0.01 a	0.63 ± 0.00 b	0.60 ± 0.01 b	0.66 ± 0.01
Total saponins (mg/g)	Yining city	5.07 ± 0.02 a	5.14 ± 0.08 a	4.02 ± 0.18 b	4.26 ± 0.07 b	5.24 ± 0.12 a	3.83 ± 0.09 b	4.59 ± 0.14
	Nilka county	5.83 ± 0.10 b	5.83 ± 0.02 b	5.81 ± 0.13 b	5.03 ± 0.10 c	6.34 ± 011 a	5.73 ± 0.14 b	5.76 ± 0.10
	Tekes county	6.26 ± 0.06 a	6.38 ± 0.17 a	4.91 ± 0.13 b	4.29 ± 0.10 c	6.19 ± 0.18 a	4.52 ± 0.11 bc	5.43 ± 0.22
	Zhaosu county	5.67 ± 0.25 a	5.28 ± 0.09 a	4.54 ± 0.03 b	5.82 ± 0.09 a	5.39 ± 0.04 a	5.25 ± 0.24 a	5.32 ± 0.11

Mean values for grain yield and agronomic yield components of six quinoa genotypes in four locations. The values are the means for each genotype of three replicates per block from a total of three blocks in each location. Means followed by the same letter were not significantly different at $p = 0.05$ by the Tukey-b test.

3.4. Traits across the Study Area

The results demonstrate a complex connection between altitude and different genotypes of quinoa, providing insight into the crop's ability to adapt and respond to a wide range of environmental conditions. The four distinct elevations (Yining city at 650 masl, Nilka County at 1050 masl, Tekes County at 1400 masl, and Zhaosu County at 2200 masl) had a substantial impact on both agronomic traits and nutritional quality traits, as detailed in Tables 1 and 5. The analysis revealed that genotypic variation was not significant for branches and panicle length; however, with the exception of stem diameter, the interaction between locations and genotypes was significant for all agronomic, phonologic, and nutritional traits. From the warmest to the coldest and the lowest altitude to the highest (Figure 1A), there were substantial differences among Yining city, Nilka County, Tekes County, and Zhaosu County, except for stem diameter and total polyphenol (Figures 2 and 3). The warmest city, Yining city, revealed the highest branch number and panicle length. On the other hand, the coldest location, Zhaosu County, followed by Tekes County, recorded the highest 1000 seed weight. However, Tekes County had the maximum seed output per hectare across all genotypes (Figure 2C–F). Variations in nutritional trait content were remarkably dissimilar between the various climates (Figure 4). The warmer climate of Yining city received more protein, less fat, and low saponin in their seeds, followed by the colder, higher altitude region of Zhaosu County (Figure 4B,C,G).

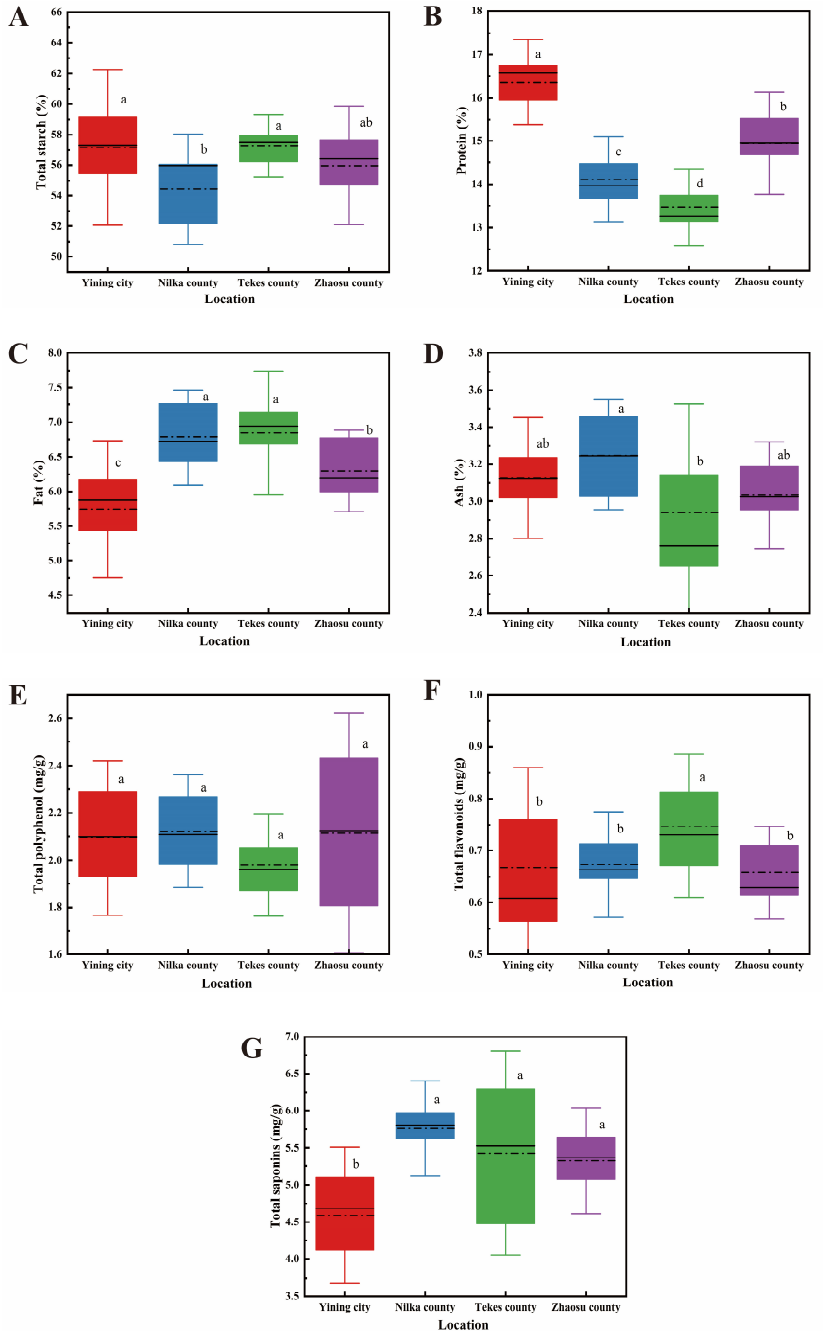

Figure 4. Effect of different location (altitude) on quality traits. (**A**) Total starch; (**B**) Protein; (**C**) Fat; (**D**) Ash; (**E**) Total polyphenol; (**F**) Total flavonoids; (**G**) Total saponins. Different lowercase letters indicate significant difference ($p < 0.05$).

3.5. The Relationship between Seed Yield and Agronomic and Nutritional Traits

A PCA was performed to assess the contribution of the different agronomic and nutritional traits explaining seed yield across genotypes in four locations. The two first principal components explained > 0.47 of the total variation (Figure 5). In principle component 1, seed yield was highly and positively associated with plant height and 1000 grain weight, and positive associations were also found with fat content and total starch, while seed yield was highly associated with ash content and total polyphenol content. However, in principle component 2, seed protein content and branches had negative associations with the total flavonoid content in the grain. In addition, total saponin content in the grain were not associated with any other traits.

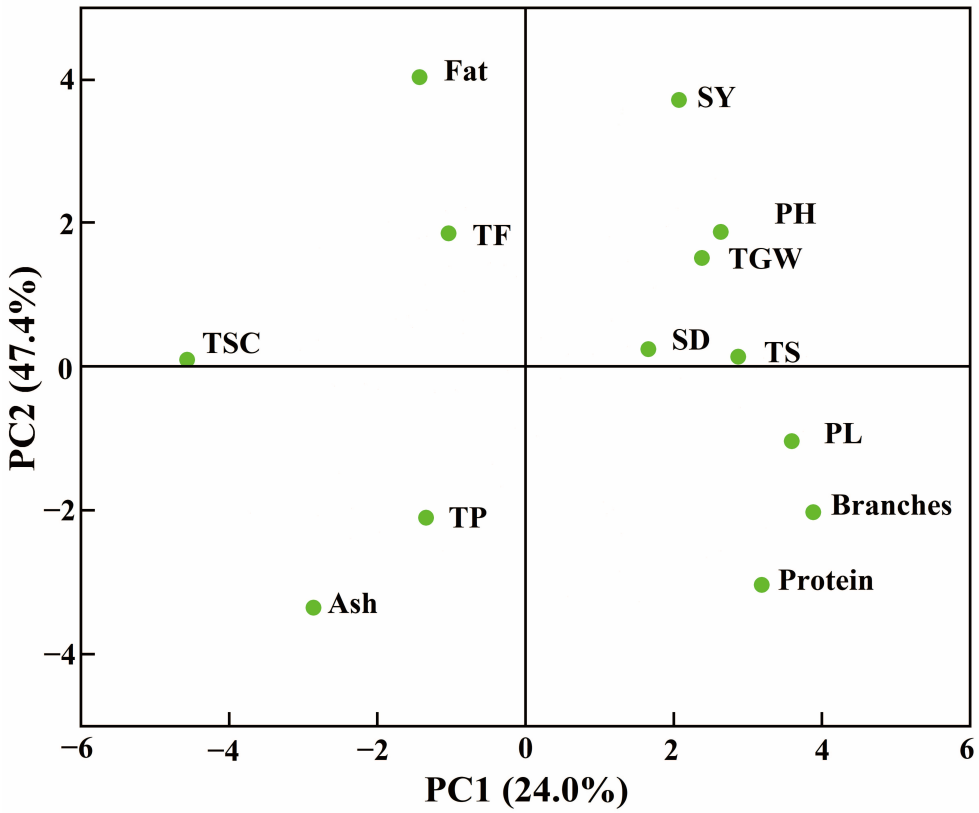

Figure 5. Principal component analysis of seed yield (SY), agronomic and nutritional quality traits for six quinoa genotypes in four locations in Xinjiang Autonomous Region, China. Agronomic traits included as plant height (PH), stem diameter (SD), branches, panicle length (PL), 1000 seed weight (TGW). Nutritional quality traits included as protein content, ash content, total starch (TS), total polyphenol (TP), total flavonoids (TF) and total saponins content (TSC) in grains.

4. Discussion

4.1. Ecological Adaptability of Quinoa in Different Regions

Testing quinoa's ability to thrive in various environmental and geographical conditions is of significant interest due to the rising international demand for the grain, which is boosted by both agricultural development and the Andean export commodity [22–24]. Improvements in crop agronomy for various climates are largely responsible for the rise in quinoa cultivation areas around the world. There has been a recent uptick in the practice of selectively breeding plant types for increased demand in nations with certain environmental requirements [23,25]. Quinoa is an exceptional crop for many parts of the world because of its remarkable adaptability to a wide variety of climates and soil types [26]. Quinoa exhibited remarkable ecological adaptability in various geographical areas, as indicated by the significant variations in phenological, agronomic, and nutritional quality characteristics identified in Xinjiang Autonomous Region, China, focusing on its response to variations in elevation, temperature, soil, precipitation (rainfall), and other environmental factors. The flexibility of quinoa genotypes to respond to varied environmental conditions was reflected in the large variability in agronomic parameters that were noticed between and across different altitudes. Our findings demonstrate quinoa's various environmental adaptations. Quinoa genotypes in colder, higher altitude places like Zhaosu County were taller, possibly to maximize light interception and photosynthesis in low-light situations. It has been observed that, due to shorter daylight hours and lower light intensity, plants in colder temperatures impede plant development but may stimulate taller plants to optimize light interception for photosynthesis [27–29]. In contrast, quinoa plants in lower altitude areas such as Yining city showed increased branch growth and longer panicle lengths, possibly due to less rainfall and the necessity to enhance reproductive success. Nevertheless, Nilka

and Zhaosu County received a significant quantity of rainfall and have much colder climates in comparison to the other two regions, leading to greater 1000 seed weight and seed production per hectare. Similar results were also reported by Lesjak et al. [30].

Although Yining city had the earliest flowering time (80 days), it also had the longest crop cycle (132 days) among the genotypes (Table 4). Yining city's Jinli 1 and Beijing 2 genotypes produced the earliest flowers and the highest seed yields in comparison to other varieties. Jinli 1, Beijing 2, and Longli 4 presented a uniformly shorter crop cycle across all geographical regions, whereas Longli 4 produced the maximum seed yield in Nilka, followed by Jinli 1. It is noteworthy that Jinli 1 exhibited the maximum seed yield in both Zhaosu County and Tekes County when compared to the other genotypes. The genotypes cultivated in Yining city have the highest number of branches, longest panicle length, respectable stem thickness, and plant height, as well as the highest protein content in their seeds, making it a prime area for fodder production. In order to identify cultivars and develop breeding programs that aim to enhance protein quantity and quality, protein-based methodologies have been implemented to characterize storage proteins in quinoa seeds [31,32]. However, it has been proposed that grain yield and grain size, which are predictors of crop commercial quality, are widely utilized as selection criteria for quinoa breeding [33]. Nevertheless, our findings demonstrated diverse responses of the genotypes to changes in the environment. Similar observations were noted by Zurita-Silva [32], who noticed genotype-specific responses to environmental variation and that genotypes performance was primarily impacted by the crop cycle. In this study, quinoa illustrates exceptional resilience and adaptability in spite of diverse climatic conditions, spanning from the comparatively milder and lower altitude regions of Yining city to the colder and higher altitude regions of Zhaosu County.

4.2. Selection of Agronomic Traits for High-Yield Quinoa

In order to optimize the quinoa yield at varying altitudes, our research emphasizes the significance of selecting suitable agronomic characteristics. Significant variation in yield performance and phenology was observed among quinoa genotypes at various locations. The influence of plant height on the crop performance of quinoa genotypes is elucidated by the existence of a strong positive correlation between seed yield and plant height. Similar conclusions were also reported previously [34,35]. Quinoa genotypes are short-day plants with varying temperature and photoperiod sensitivity [36–38]. Crop longevity is dependent on the length of the basic vegetative phase (BVP) for each cultivar during photoperiods less than a threshold (<11 h). A photoperiod-sensitive phase (PSP) concludes with the initiation of floral buds if conditions are not inductive [38,39]. The inverse relationship between seed yield and phenological parameters, specifically flowering time and crop cycle, can be explained by the fact that both exhibit a negative correlation with seed yield (Figure 3). In general, plants that exhibit reduced reproductive periods and crop cycles demonstrate enhanced productivity. Previous studies emphasized that the days to flowering was identified as the most critical determinant influencing the productivity of quinoa grains in various environmental conditions [33,40,41]. These results suggest that genotypes that demonstrate earlier flowering in each particular environment are associated with an improvement in grain weight. Grain weight determination mostly took place during the post-flowering stage. As a result, genotypes exhibiting extended periods of time until flowering in each natural setting were exposed to detrimental circumstances, including reduced mean temperature and radiation, which might have compromised the processes involved in grain filling [42]. Similarly, quinoa genotypes with short to medium life cycles were capable of evading high temperatures during these crucial phases of development and produced better grain yield than long crop cycle genotypes (Tables 2 and 5). Similar observations were reported by Nanduri et al. [43], suggesting short or medium life cycle genotypes produce a higher yield and completed their life cycle before detrimental environmental circumstances, mainly heat stress.

According to studies, panicles that are longer than shorter ones may produce more grain [35,44]. However, no significant differences were observed for panicle lengths between genotypes at different altitudes except in Tekes County. Compared to Longli 1 and Jinli 1, Beijing 2 has the longest panicle length but lower seed production. Furthermore, in terms of panicle length and seed yields, Longli 4 in Nilka County and Jinli 1 in Zhaosu County exhibited the shortest and most productive, respectively. A large, open inflorescence may be more susceptible to seed loss and evaporate more rapidly after morning dew and precipitation than a small, compact one [1]. Similar findings were also reported by Manjarres-Hernández et al. [45]. Despite the lack of statistical significance in the relationship between panicle length and seed yield, a positive correlation was observed, with the maximum seed yield being produced by panicles of medium length. A medium-sized panicle yielded the best seed output, the same case also be founded in previous study [45]. Genotypes characterized by shorter flowering and crop cycles, as well as taller plant stature, are recommended for cultivation across diverse altitudes.

4.3. Factors Affecting the Quality of Quinoa in Different Regions

The investigation we conducted on the quality indicators of quinoa in different geographical areas illuminates the complex ways in which environmental factors impact nutritional characteristics. The observed discrepancies in nutritional quality underscore the intricate interplay among genetic elements and environmental circumstances, including temperature, altitude, soil, and precipitation (rainfall), in determining the nutritional characteristics of quinoa. Nevertheless, photoperiod and temperature are the two key factors influencing quinoa production [38], and output is typically negligible in areas where temperatures exceed 32 °C [1,46]. However, the performance of a genotype is primarily determined by the genetic makeup of the cultivar, the surrounding environment, and their interaction [33,38,47]. The nutritional characteristics varied between genotypes and altitudes, as indicated by the significant genotypic effects, locations, and genotype–location interactions (G × L) values for all nutritional parameters (Table 2). Genotype, environmental factors, agroecological circumstances, and nitrogen availability in the soil have been suggested to play a role in determining amino acid and protein content [31,48]. The protein content decreased significantly while the fat content increased along a gradient that ran from the lowest to the highest altitude and from the hottest to the coldest places, all of which had the same type of soil (sierozem). Intriguingly, it is worth noting that Zhaosu County, characterized by its chernozem type soil and the highest altitude and lowest temperatures, demonstrated a more favorable response in protein content and a lower fat content in comparison to Nilka County and Tekes County (Figure 4B,C). This discrepancy may potentially be ascribed to the fertile soil composition and nitrogen availability in Zhaosu County. However, the influence of environmental factors on protein and amino acid levels is mostly determined by the genotype [49]. Our study conducted in Yining city revealed that quinoa genotypes displayed the highest protein content and the lowest fat content, suggesting a potential influence of elevated temperatures and the interaction between genotype and environment. These results are consistent with the findings of Matías et al. [48], who examined the effect of temperature on various quinoa cultivars and observed an uptick in protein content when the plant was subjected to thermal stress.

The nutritional composition of quinoa genotypes varies due to the strong genetic variability and environmental differences present in Xinjiang Autonomous Region. Previous studies have documented comparable impacts of agricultural practices, agroclimatic factors, and soil types on the ecotype composition of quinoa [50]. Although all nutritional characteristics (with the exception of total polyphenol) at different altitudes illustrated statistically significant findings, no discernible pattern (except for proteins and fats) in relation to altitude and temperature was noticed in terms of nutritional properties. Saponins, which impart a characteristic bitter flavor to seeds, are secondary metabolites whose concentrations may vary in response to environmental conditions. In Yining city, saponins were found to be the lowest compared to other geographical regions (Figure 4G). this could

be attributed to the lowest rainfall received by Yining city. Granado-Rodríguez et al. [31] observed a similar trend in saponin content during low rainfall in 2019 in their experiment; however, Gómez-Caravaca et al. [20] observed a 45% reduction in saponin concentration during a water deficit experiment carried out in southern Europe. The variability of saponin content is primarily determined by genotype, although it can also be influenced by stressors such as soil salinity or drought [51,52]. A similar trend was observed in our findings: Jinli 1, Beijing 2, and Longli 4 were considered sweet genotypes and showed lower values across the sites except for Zhaosu County, where no significant differences were observed between genotypes except for Longli 4 (Table 5).

Recommended genotypes for each site were identified based on their performance in terms of yield, phenology, and nutritional value. In Yining city, the genotypes Jinli 1 and Beijing 2 are recommended due to their short crop cycles, high seed yields, elevated protein content, and lower saponin levels. In Nilka County, Jinli 1, Longli 4, and Beijing 2 are suggested as they exhibit the shortest crop cycles. Longli 4 and Jinli 1 notably surpass the 3 T/ha seed yield mark. Moreover, Jinli 1 and Beijing 2 seeds boast high protein content and low saponin levels. In Tekes County, Jinli 1, Longli 1, and Beijing 2 produced the greatest seed yield, whereas Nongli 3 had the highest protein content and total saponin. In Zhaosu County, Longli 4, Beijing 2, and Jinli 1 offer the shortest crop cycles. Among these, Beijing 2 and Jinli 1 demonstrate the highest protein content. Longli 4, on the other hand, exhibits the lowest total saponin content compared to other genotypes.

In the province of Xinjiang, quinoa has proven to be truly adaptable and possesses remarkable nutritional value, rendering it a prime contender for prospective cultivation in any location. Breeding initiatives should be undertaken to augment the quality of forage and yield, with an emphasis on lowering saponin levels and increasing protein content, in order to further exploit its potential.

5. Conclusions

In conclusion, this study presents comprehensive insights into the ecological adaptability, agronomic performance and nutritional characteristics of quinoa across various altitudes in the northwestern part of China. Yining city, which is distinguished by its lower altitudes and higher temperatures, appears to offer optimal circumstances for the forage production of quinoa. Due to the superior characteristics exhibited by quinoa genotypes in this region, including longer panicles, increased branch count, sturdy stems, and high seed protein content, making it an ideal location for enhancing livestock feed availability. Additionally, it is worth noting that Nilka and Tekes counties illustrate considerable potential as locations for quinoa seed production due to their comparatively brief crop cycles and substantial yields. The genotype Jinli 1, in particular, demonstrates remarkable yield performance, surpassing 4 tons per hectare (t/ha) in Tekes County, coupled with high protein and fat content and low saponin levels. Interestingly, Zhaosu County, characterized by cooler climates and fertile chernozem soil, illustrates a robust protein response and high 1000 seed weight (g), highlighting the impact of soil fertility on nutritional composition in quinoa. Correlation analyses highlight the significance of agronomic traits in determining seed yield and quality. Plants with shorter flowering times, crop cycles, compact inflorescence, and taller heights tend to exhibit superior seed yields, emphasizing the need for selecting genotypes with optimal agronomic characteristics in order to enhance productivity. Overall, our study contributes significant insights into the ecological adaptability and nutritional dynamics of quinoa, with implications for sustainable crop production and food security in diverse agroecosystems.

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