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Evaluation of Quinoa Varieties for Adaptability and Yield Potential in Low Altitudes and Correlation with Agronomic Traits

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Abstract: The research conducted at the Shanxi Agricultural University's Quinoa Experimental Model Base in Jinzhong, Shanxi Province, aimed to assess agronomic traits and their correlation with yield across 32 quinoa varieties. Three distinct yield categories emerged: low ($\leq$1500 kg ha^{-1}), middle (1500–2500 kg^{-1}), and high (>2500 kg ha^{-1}). High-yielding varieties demonstrated notable characteristics, including decreased plant height and increased leaf area per plant at maturity compared to low- and middle-yielding varieties. Moreover, the decline in leaf area per plant and root traits from flowering to maturity was less pronounced in the high-yielding varieties. The high-yielding varieties had a higher hardness of the stem base and middle stem by 12–13.7% and 6.3–11.5% compared to the medium- and low-yield varieties. Furthermore, high-yielding varieties indicated improvements in dry matter accumulation, decreased effective branch number, and increased main ear length and 1000-grain weight. Correlation analysis highlighted significant relationships between grain weight, yield, post-flowering senescence, and root and leaf characteristics. Structural equation model analysis revealed the negative impact of certain root and leaf traits on grain weight and yield, suggesting their importance in determining productivity. Notably, high-yielding varieties exhibited traits conducive to increased grain weight, including shorter plant height, slower root senescence, and enhanced post-flowering leaf resilience. These findings showed that understanding the relationship between agronomic traits and yield potential is crucial for optimizing quinoa production and promoting the sustainable development of this essential crop.

Keywords: quinoa; germplasm resources; yield; agronomic traits; correlation analysis

Citation: Tang, P.; Ren, A.; Jiang, Z.; Wang, R.; Cui, K.; Wu, X.; Sun, M.; Gao, Z.; Anwar, S. Evaluation of Quinoa Varieties for Adaptability and Yield Potential in Low Altitudes and Correlation with Agronomic Traits. *Agronomy* **2024**, *14*, 852. https://doi.org/10.3390/agronomy14040852

Received: 4 March 2024
Revised: 15 April 2024
Accepted: 17 April 2024
Published: 19 April 2024

1. Introduction

Quinoa (*Chenopodium quinoa* Willd.), a revered member of the Amaranthaceae family, predominantly thrives in the Andes of South America [1–3]. This exceptional grain is celebrated for its balanced and comprehensive nutritional profile, outshining traditional grains with its superior protein, amino acid content, and essential vitamins and minerals [4]. It contains all nine essential amino acids, rendering it a complete protein source [5]. Quinoa is rich in dietary fiber, B vitamins, and antioxidants, offering a range of health benefits including improved digestion and reduced risk of chronic diseases [6]. Such nutritional richness has propelled quinoa to global recognition as one of the healthiest foods [1,2].

Despite its numerous advantages, quinoa cultivation faces several challenges. Uneven ripening can complicate harvest times and affect yield [7]. Additionally, its low tolerance to herbicides necessitates extensive manual labor, thus increasing labor costs [8]. Nevertheless, owing to its remarkable ecological resilience, quinoa demonstrates adaptability in various harsh environments, including drought, salinity, and cold and barren conditions, which has spurred its widespread cultivation and acceptance [9,10].

Quinoa was introduced to China in the late 20th century, and by 2010, it had achieved large-scale cultivation in Luliang, Shanxi Province. Since then, its cultivation has expanded to different regions as market demand and prices have continued to rise [11]. Shanxi Province, situated in the Loess Plateau, epitomizes arid or semi-arid areas where soil water scarcity significantly impacts crop yield and quality [12,13].

Plant phenotype serves as a fundamental tool for assessing crop production potential and morphologically associated traits. Understanding genotypic variations requires a comprehensive evaluation of multiple traits and their interactions with the environment [14]. Studies on quinoa germplasm in China have revealed variations in yield, morphology, and physiology, particularly in arid regions. Root development plays a crucial role in arid and semi-arid environments, as it influences plant growth and productivity [15]. Quinoa's performance under drought conditions involves intricate physiological and morphological adaptations, including alterations in the root system that enhance water and nutrient uptake efficiency and yield formation [16]. Leaf area directly impacts plant productivity by facilitating light energy capture and assimilating production [17]. Leaf senescence, a determinant of biomass production, negatively affects yield by limiting nutrient mobilization [18]. To optimize yield, plants redistribute nutrients by adjusting leaf area, lateral branches, and senescence processes during the final developmental stages [19].

Previous studies revealed significant correlations between quinoa yield and agronomic traits, including plant height, stem diameter, branch number, panicle length, and grain weight [20,21]. Lodging, a common phenomenon affecting yield, is influenced by plant height, stem strength, and stem diameter [22,23]. Selecting phenological traits which favor lodging resistance could increase yield by reducing stem displacement and strengthening plant structure [24]. Helena et al. [25] evaluated the phenological and yield relationships in 30 quinoa genotypes and reported that the panicle length, seed weight, and seed diameters were the most influencing traits for a higher yield.

While previous research has identified correlations between quinoa yield and agronomic traits [26,27], few studies have explored trait disparities among quinoa germplasms at various yield levels and their implications for yield [28]. This preliminary study aims to address this gap by comparing and analyzing agronomic traits of different quinoa germplasm varieties in the low-altitude area of Shanxi. By elucidating growth characteristics and underlying post-anthesis root and leaf senescence, this research aims to identify high-yield quinoa germplasm suitable for regional cultivation, providing valuable insights for breeding and variety development.

2. Materials and Methods

2.1. Seed Material and Experimental Conditions

The experiment was conducted in 2021 at the Nong Valley Quinoa Base of Shanxi Agricultural University (37°42′N, 112°53′E), which belongs to a warm temperate continental climate with an altitude of 791 m, annual sunshine duration of 2500–2600 h, average annual temperature difference of 6 °C, and average annual precipitation of 458 mm. Thirty-two different quinoa varieties were provided by Shanxi Jiaqi Agricultural Technology Co., Ltd, Taiyuan, China (Table 1). Quinoa (*Chenopodium quinoa* Willd.) was sown in mid to late April and harvested in late September. Precipitation and temperature from April to September are shown in Table 2. Soil surface fertility was as follows: organic matter of 12.65 g kg^{-1}, alkali-hydrolyzed nitrogen of 42.56 mg kg^{-1}, available phosphorus of 15.65 mg kg^{-1}, and available potassium of 210.66 mg kg^{-1}.

Table 1. The names and apparent characteristics of different quinoa varieties used in the current study.

Sr. No.	Variety No.	Apical Leaf Color	Spike Color	Sr. No.	Variety No.	Apical Leaf Color	Spike Color
1	JQ-00955	Green	Green	17	JQ-00685	White	Green
2	JQ-00987	Green	White	18	JQ-02259	Green	White
3	JQ-00679	Green	Green	19	JQ-00783	Green	Green
4	JQ-00764	Green	Indipink	20	JQ-00080	White	Green
5	JQ-01347	Green	Green	21	JQ-02267	Lilac	Purple
6	JQ-02284	Green	White	22	JQ-02275	White	Green
7	JQ-01525	Purple	Purple	23	JQ-00984	Purple	Lilac
8	JQ-01778	Green	Green	24	JQ-00174	White	Green
9	JQ-00920	Lilac	Purple	25	JQ-02319	Green	Green
10	JQ-01141	White	White	26	JQ-00623	Lilac	Purple
11	JQ-00988	Green	Green	27	JQ-02307	Lilac	Purple
12	JQ-01961	Green	Green	28	JQ-00317	White	Indipink
13	JQ-00952	Green	Green	29	JQ-00573	White	Green
14	JQ-02342	White	Indipink	30	JQ-00294	Pink	Pink
15	JQ-00740	Green	Green	31	JQ-00425	Green	Green
16	JQ-00927	Green	Green	32	JQ-01238	Green	Indipink

Table 2. Precipitation and temperature at the experimental site in Taigu.

	April	May	June	July	August	September
Precipitation (mm)	10.8	13.9	75.6	79.8	92.0	58.7
Average temperature (°C)	12.78	18.80	23.27	24.16	23.33	21.21

2.2. Seed Sowing and Experimental Design

A randomized complete design (RCBD) with three replications (as blocks) was used in the experiment. The plot area of each replicate was 12 m × 4 m. The seeds were sown on 22 April 2021 and 150 kg ha^{-1} compound fertilizer was applied before sowing. Seeds were sown through a drill and the seeding rate was 5.25 kg ha^{-1}. After germination, thinning was performed to attain an effective plant density of 15 × 10^4 ha^{-1}. Weeds were controlled by hand and field-irrigated at different stages such as the seedling stage, branch stage, ear stage, flowering stage, and filling stage, in the routine control of pests and diseases, and when taking the harvest and yield measurements at the maturity stage.

2.3. Determination of Agronomic Traits

2.3.1. Green Leaf Area Per Quinoa Plant

During each growth stage of quinoa, five uniform quinoa plants were randomly selected. Ten green leaves of different sizes were removed from each plant and a 4 cm^2 area of leaves was clipped using a punch. The whole leaves and leaf blades were dried at 105 °C in an oven for 30 min and then at 75 °C to constant weight. The dry weight of the green leaves per unit area and the total dry weight of the green leaves were recorded to calculate the green leaf area per plant as follows:

$$\text{Green leaf area (cm}^2\text{)} = \text{Dry leaf weight per plant} \times \text{unit green leaf area/dry weight per unit green leaf area}$$

2.3.2. Root System Characteristics

After rinsing with deionized water, quinoa roots were placed on the glass plate of the root scanner. After scanning with the root scanner (EpsonperfectionV850Pro), the images were analyzed using the WinRHIZO2017 root analysis software. The parameters of total root length (TRL), root diameter, root volume (RV), and root tip number (RT) were obtained [29].

2.3.3. Dry Matter Mass

During each growth period, five plants with uniform growth were uprooted and placed in an oven at 105 °C for 30 min, dried at 75 °C to constant weight, weighed to record the dry matter mass of each plant, and then converted into dry matter mass per hectare [30].

2.3.4. Stalk Characteristics

Stalk strength traits were measured using a YYD-1-type stalk strength tester (Zhejiang Topu Yunnong Technology Company, Ltd., Hangzhou, China). The maximum penetrating value (Kpa) of the culm cuticle was recorded from the middle and base of the internode vertically at a constant speed. The node to be measured was placed in the groove of the analyzer, the distance between the two fulcrums was 2 cm, and the node to be measured was aligned with the middle point of the stalk strength tester; then, the pressure was slowly applied to the middle point of the node until it broke and the maximum force to break the stalk was the stem-breaking force of the node.

2.4. Yield and Panicle Architecture

When 80% of the leaves were yellow and senescence started, the yield of the 1 m^2 sample area was harvested. A scythe or cutter was used to cut the stalks 50 cm above the ground. Stems were tied into small bundles. After natural air drying of the grains, the 1000-grain weight and the yield per plant were measured and converted into yield of hectares. Ten panicles were selected from the main axis and the length and width of the panicle were measured using a ruler. Panicle compactness was determined by dividing the number of panicle branches by the panicle length (Table 3).

Table 3. Phenotyping scoring of ear compactness of quinoa.

Assignment	Standard
1	Most dispersive
2	More dispersive
3	Dispersive
4	Tight
5	Tighter
6	Tightest

2.5. Harvest Index (%)

The harvest index was calculated using the following formula:

$$\text{Harvestindex}(\%) = \frac{\text{Grainyield}}{\text{Drymatteraccumulation}} \times 100$$

2.6. Data Analysis

For statistical data processing and visualization, Microsoft Excel 2010 was used. Systematic cluster analysis and mapping were conducted using SPSS 26.0 software. Analysis of variance (ANOVA) was performed for all analyses and significant variance among treatments was tested via the LSD method. Additionally, IBM SPSS 26.0 Amos software was utilized to analyze structural equation models, construct path diagrams, and calculate correlation coefficients and R^2 values. Correlation analysis graphs using the Pearson correlation coefficient were drawn using Origin 2021 software.

3. Results

3.1. Yield Cluster Analysis

The cluster analysis was performed on the grain yield of 32 quinoa varieties. Considering the first and second levels of clustering, the quinoa cultivars were clustered into three categories (Figure 1). Ten varieties in cluster I had yields lower than 1500 kg ha^{-1} and were categorized as low-yielding varieties (LY). The 16 varieties in cluster II with a yield of 1500–2500 kg ha^{-1} were categorized as the medium-yielding variety (MY). Class III consisted of six varieties with a yield higher than 2500 kg ha^{-1} and were categorized as high-yielding varieties (HY).

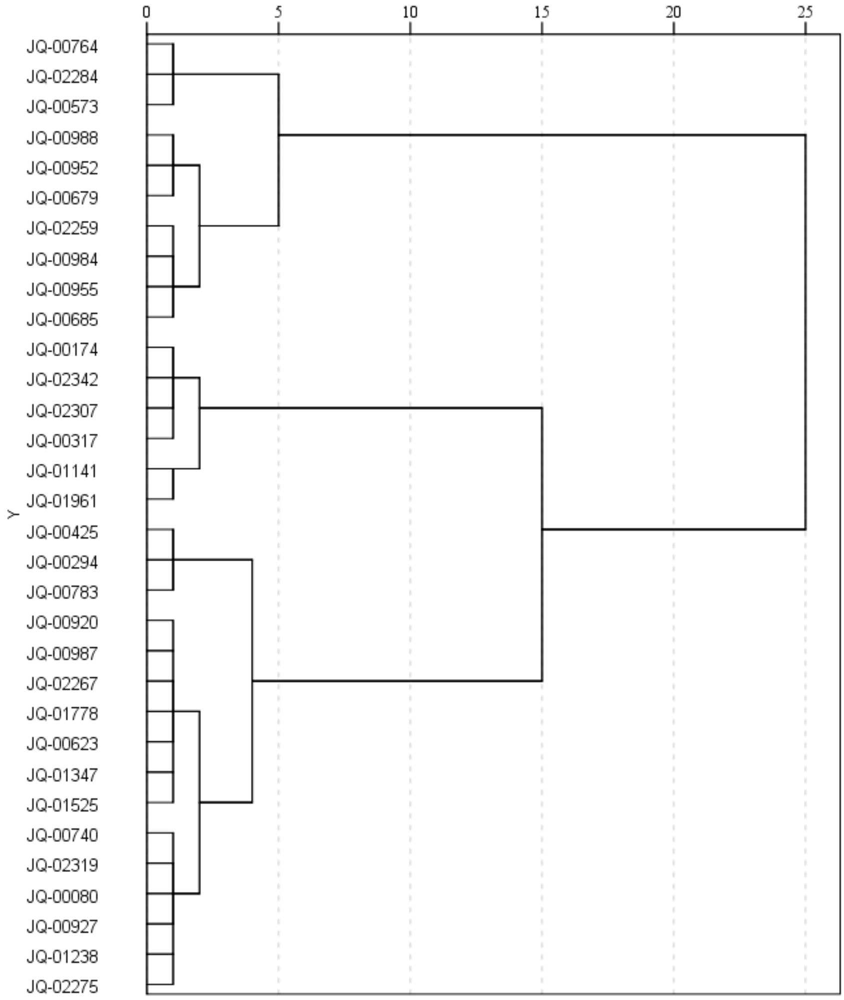

Figure 1. Quinoa yield cluster analysis.

3.2. Differences in Agronomic Traits of Low-, Medium-, and High-Yield Quinoa Cultivars across Growth Stages

3.2.1. Plant Height

With the advancement of the growth process, plant height showed an increasing trend (Figure 2). The plant height of the LY varieties was the highest during all growth stages before flowering. At the flowering stage, the MY variety had the highest plant height, which was 4.4% and 9.7% higher compared with the LY and HY varieties. At maturity, the plant heights of the HY varieties were 24.8% and 22.4%, which were significantly lower compared with the LY and MY varieties. In conclusion, the plant height of high-yielding varieties of quinoa was significantly lower compared with the low and middle varieties during the whole growth period.

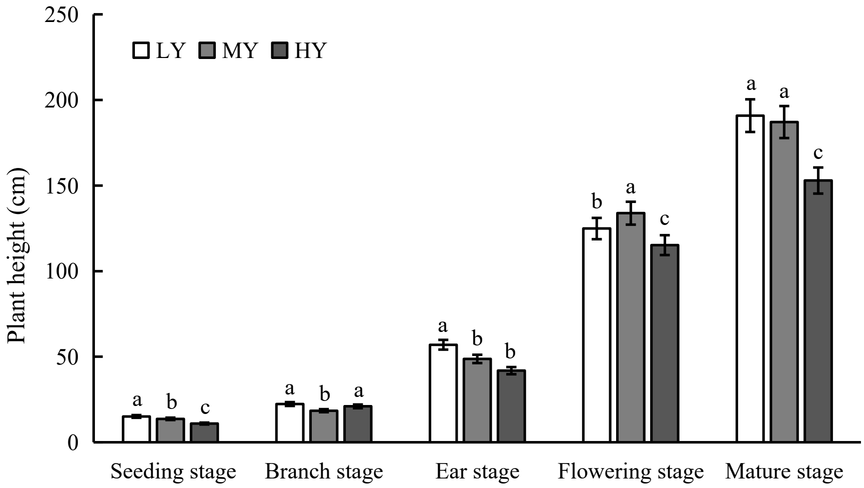

Figure 2. Plant height of quinoa at different yield levels in different periods. The bars indicate means (n = 3 ± standard error) and different lowercase letters on the bars indicate significant differences among the LY, ML, and HY categories at a specific growth stage using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively.

3.2.2. Green Leaf Area Per Plant

The green leaf area per plant increased first and then decreased with the growth period (Table 4). In the branching stage, the green leaf area per plant was the highest for the MY varieties with 15.6% and 3.1% higher green leaf area than the LY and HY varieties, respectively. In the ear and flowering stages, the number of green leaves per plant was the highest in the LY varieties in which the increase in green leaf area per plant from the ear to the flowering stage was 310.4 cm^2, which was significantly higher than that in the HY varieties.

Table 4. The green leaf area (cm^2) at different yield levels and growth stages of quinoa.

Type	Seeding Stage		Branch Stage		Ear stage		Flowering Stage		Maturity Stage	
	Average	**CV**	**Average**	**CV**	**Average**	**CV**	**Average**	**CV**	**Average**	**CV**
LY	35.36 a	5.55%	72.11 b	8.43%	144.57 a	18.26%	454.98 a	16.16%	128.42 b	16.19%
MY	38.19 a	7.62%	85.41 a	6.31%	133.05 b	17.05%	434.81 ab	16.69%	156.53 ab	12.08%
HY	37.11 a	4.31%	82.75 a	9.47%	143.58 a	13.66%	410.70 b	11.12%	181.80 a	11.03%

Different lowercase letters following means indicate significant differences among the LY, ML, and HY categories using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively. CV refers to the coefficient of variation.

At maturity, the green leaf area per plant was reduced compared to the flowering stage and the reduction in green leaf area of the HY varieties was 34% and 30.4% lower than that of the LY and MY varieties.

The variation coefficient of the three quinoa categories increased first and then decreased with the growth period. Compared with the other growth stages, the variation coefficient was the highest in the heading stage, showing high genetic variability. With time, the variation coefficient of the MY and HY varieties decreased. The HY varieties had a relatively smaller coefficient of variation and high genetic stability compared to the LY and MY varieties.

3.2.3. Root Characteristics

The total root length, root diameter, and root volume increased first and then decreased with the advancement of the growth period, while the number of root tips showed an increasing trend (Figure 3). The total root length showed a rapid increase from the ear to the flowering stage. The HY varieties showed the maximum increment in root length from the ear to the flowering stage. The increase in root length of the LY, MY, and HY varieties was 283.96 cm, 278.73 cm, and 329.26 cm from the ear to the flowering stage, respectively. At maturity, the total root length of the HY varieties was higher than that of the LY and MY varieties.

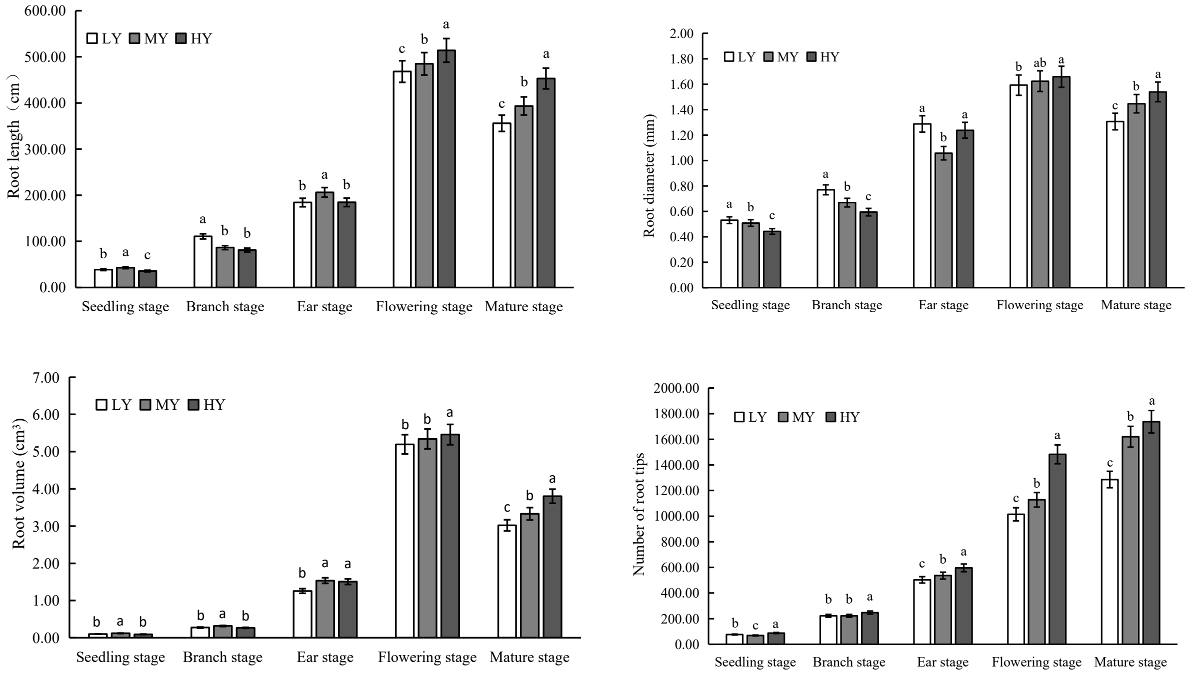

Figure 3. Root characteristics of quinoa at different yield levels in different periods. The bars indicate means (n = 3 ± standard error) and different lowercase letters on the bars indicate significant differences among the LY, ML, and HY categories at a specific growth stage using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively.

From the ear to the flowering stage, the root diameter of the LY, MY, and HY varieties increased by 0.31 mm, 0.57 mm, and 0.42 mm, respectively. At the flowering and maturity stages, the root diameter was the highest for the HY varieties, but the decrease in the root diameter from the flowering to the maturity stage was 141% and 49.6% lower for the HY variety than that of the LY and MY varieties, respectively.

The ear to flowering stage was the rapid growth period for root volume. The root volume in the flowering and maturity stages was the highest for the HY varieties. The root volume was reduced at maturity compared to the flowering stage and the root volume reduction was lower for the HY varieties than that of the LY and MY varieties.

The root tip number was the highest for the HY varieties in the whole growth period. The root tip number from the heading to the flowering stage was 42.3% and 37.3% higher for the HY variety than that of the LY and MY varieties, respectively. Similarly, the root tip number at the maturity stage was significantly higher for the HY variety than that of the LY and MY varieties.

3.2.4. Dry Matter Accumulation

The dry matter accumulation per plant increased gradually with the growth period (Table 5). In the seeding and heading stages, the dry matter of the LY varieties was the highest. After the heading stage, the highest dry matter was accumulated by the HY varieties and was significantly higher than for the varieties in the other yield categories. The dry matter accumulation of the HY varieties at the maturity stage was 46.64% and 15.67% higher than that for the LY and MY varieties. The coefficient of variation of dry matter accumulation increased first, reaching its highest in the flowering stage, and then decreased at maturity. The coefficient of variation was lower for the HY variety than that of the LY and MY varieties at the flowering and maturity stages. It can be seen that the dry matter accumulation of the HY varieties was higher in the late growth stage.

Table 5. The difference in dry matter accumulation (kg ha^{-1}) of quinoa at different yield levels and growth stages.

Type	Seeding Stage		Branching Stage		Ear Stage		Flowering Stage		Maturity Stage	
	Average	CV	Average	CV	Average	CV	Average	CV	Average	CV
LY	64.50 a	3.06%	632.50 a	10.49%	2088.00 c	22.19%	5647.50 c	28.95%	9736.50 c	15.73%
MY	55.50 b	4.92%	477.00 c	15.61%	2194.50 b	16.37%	7489.50 b	17.03%	15388.50 b	16.83%
HY	54.00 b	3.11%	545.50 b	10.30%	2512.50 a	11.41%	9736.50 a	12.52%	18247.50 a	10.61%

Different lowercase letters following means indicate significant differences among the LY, ML, and HY categories using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively. CV refers to the coefficient of variation.

3.3. Stem Strength and Yield Traits of Low-, Medium-, and High-Yield Quinoa Cultivars at Maturity

3.3.1. Stem Characteristics

The stem diameter, hardness of the stem base, and the hardness of the middle part of the stem were the highest for the HY varieties (Table 6). Compared with the LY and MY varieties, the hardness of the stem base of the HY varieties was 12% and 13.7% higher, and the hardness of the middle part of the stem was 11.5% and 6.3% higher. The stem-breaking force of the MY variety was higher, reaching 11.52 N, which was 20.40% higher compared with the LY varieties.

Table 6. Differences in culm characteristics of quinoa at maturity at different yield levels.

Type	Stem Thickness (mm)		Stem Base Hardness (Kpa)		Mid-Stem Hardness (Kpa)		Stress Value of Stem Section (N)	
	Average	CV	Average	CV	Average	CV	Average	CV
LY	9.65 a	19.75%	346.22 b	16.79%	268.63 b	12.11%	9.17 c	19.14%
MY	10.13 a	7.48%	339.71 b	35.68%	284.34 b	6.66%	10.82 b	9.05%
HY	10.72 a	12.60%	393.59 a	12.73%	303.35 a	5.96%	11.52 a	4.17%

Different lowercase letters following means indicate significant differences among the LY, ML, and HY categories using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively. CV refers to the coefficient of variation.

The coefficient of variation of the stem diameter was the lowest (7.48%) for the MY variety, followed by the HY variety, while the highest was for the LY variety, and both the LY and HY varieties were greater than 10%. The coefficient of variation of stem base hardness was greater than 10% for all yield categories, showing high genetic variation. The coefficient of variation of hardness in the middle of the stem and the coefficient of variation of stem-breaking force decreased gradually with the increase in yield. It can be seen that the high-yield varieties have thicker stems and high hardness and lodging resistance.

3.3.2. Panicle Characteristics

The average main stem ear length was significantly higher for the HY varieties, which was 20.3% and 13.8% higher compared with the LY and MY varieties, respectively. The main ear width was the highest for the LY varieties, which increased by 20.6% and 27.7% compared with the MY and LY varieties, respectively (Table 7). The degree of ear compactness was the highest in the HY varieties, followed by MY, and the lowest in the LY varieties. The coefficient of variation gradually decreased with the increase in yield. The coefficient of variation was the highest for the main stem panicle length and lowest for panicle compactness. The variation coefficient of the main stem panicle width was the lowest for the HY variety. It can be seen that the HY varieties have longer main stem panicles, more compact panicles, and low variation.

Table 7. Differences in ear traits of quinoa at maturity at different yield levels.

Type	Main Stem Ear Length (cm)		Main Stem Ear Width (cm)		Panicle Compactness	
	Average	CV	Average	CV	Average	CV
LY	34.28 c	18.14%	16.47 a	15.34%	3.17 c	5.25%
MY	37.08 b	13.33%	13.07 b	10.58%	4.25 b	4.01%
HY	43.04 a	11.91%	11.91 c	5.62%	5.10 a	2.85%

Different lowercase letters following means indicate significant differences among the LY, ML, and HY categories using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively. CV refers to the coefficient of variation.

3.3.3. Yield and Component Factors

The effective branch number was the lowest for the HY varieties, which was 37.8% and 14.2% lower than that of the LY and MY varieties, respectively (Table 8). The 1000-grain weight was the highest for the HY variety, which was 36% and 16% higher than that of the LY and MY varieties, respectively. The yield of the LY, MY, and HY varieties significantly varied and was 932.6 kg ha^{-1}, 1853.9 kg ha^{-1}, and 2781.6 kg ha^{-1}, respectively. The harvest index of the HY varieties was significantly higher than that of the LY and MY varieties, reaching 13.15%. The coefficient of variation decreased first and then increased with the increase in yield and was the lowest for the MY variety. It can be seen that high-yield varieties have fewer effective branches and higher 1000-grain weight, which is more conducive to a high yield.

Table 8. Differences in yield and yield components of quinoa at different yield levels.

Type	Effective Branching Number		Thousand Seed Weight (g)		Yield (kg ha^{-1})		Harvest Index (%)
	Average	CV	Average	CV	Average	CV	
LY	37.05 a	6.42%	1.90 c	17.35%	932.56 c	30.85%	8.77 c
MY	30.69 b	2.73%	2.49 b	2.49%	1853.78 b	6.94%	10.93 b
HY	26.88 c	5.93%	2.96 a	8.32%	2781.61 a	12.17%	13.15 a

Different lowercase letters following means indicate significant differences among the LY, ML, and HY categories using the LSD test ($p < 0.05$). LY, MY, and HY indicate low-, medium-, and high-yielding genotypes, respectively. CV refers to the coefficient of variation.

3.4. Correlation Analysis between Yield and Agronomic Traits

The correlation analysis was performed between yield, plant height, stem-breaking force, main stem ear length, main stem ear width, dry matter accumulation, effective branch number, and 1000-grain weight at maturity stage, and the reduction in total root length, root diameter, root volume, and green leaf area per plant from the flowering to the maturity stage (Figure 4). The yield showed a significant positive correlation with the 1000-grain weight, dry matter weight, spike length of the main stem, and the stem-breaking force. On the other hand, it showed a significant negative correlation with the effective branch number, root diameter reduction range, and leaf area reduction. Thousand-grain weight was significantly positively correlated with the dry matter accumulation, significantly positively correlated with stem-breaking force value, significantly negatively correlated with effective branch number and reduction in green leaf area per plant and root diameter, and significantly negatively correlated with reduction in total root length and root volume. The number of effective branches was significantly positively correlated with the reduction in root diameter and green leaf area per plant, and significantly negatively correlated with the reduction in total root length, dry matter accumulation, stress value of stem breaking, and the length of main stem spike. There was a significant positive correlation between dry matter weight and stem-breaking force value, and a significant negative correlation between dry matter weight and root diameter, total root length reduction, and green leaf area reduction per plant.

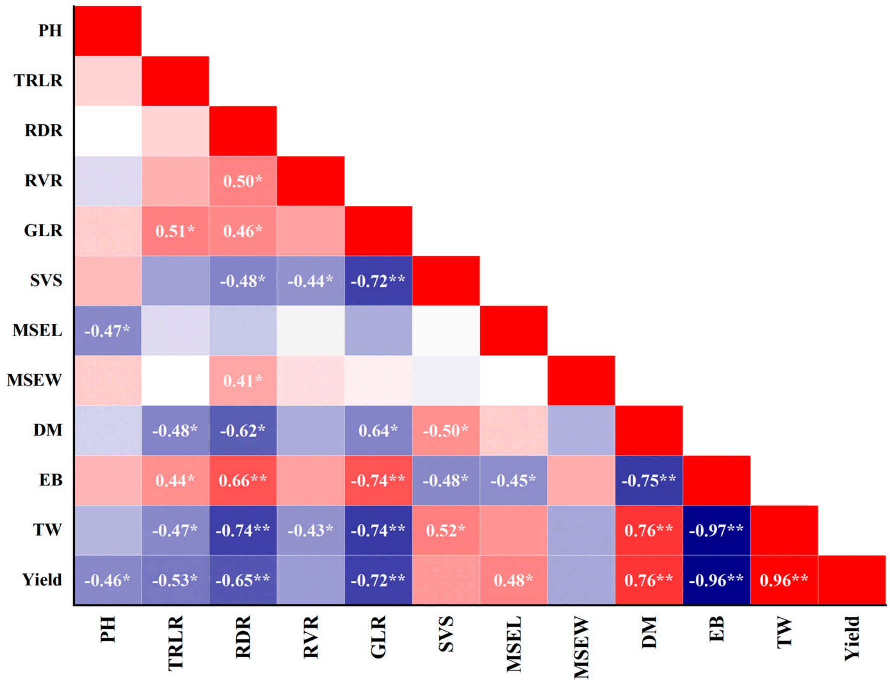

Figure 4. Correlation analysis between yield and agronomic characteristics of quinoa. GLR: green leaf area reduction; DM: dry matter accumulation; EB: effective branch number; MSEL: main stem ear (panicle) length; MSEW: main stem ear (panicle) width; PH: plant height; RDR: root diameter reduction; RVR: root volume reduction, SVS: stress value of stem; TW: thousand-grain weight; TRLR: total root length reduction. * indicates significant level ($p < 0.05$); ** indicates very significant level ($p < 0.01$).

3.5. Structural Equation Modeling of Yield and Agronomic Traits

The relationship between yield and main agronomic traits was analyzed using the structural equation model (Figure 5). The results showed that the reduction in total root length had a significant positive effect on plant height. The reduction in green leaf area per plant was positively affected by plant height, total root length reduction, and root diameter reduction. The reduction in green leaf area per plant had a significant positive effect on the number of effective branches. The 1000-grain weight and yield were negatively affected by the reduction in total root length, the reduction in root diameter, the reduction in green leaf area per plant, and the number of effective branches.

The results of the cluster analysis on quinoa yield and subsequent analysis of agronomic traits across different yield categories provide valuable insights into the relationship between yield and various plant characteristics. The cluster analysis identified three distinct yield categories based on grain yield: low-yielding (LY), medium-yielding (MY), and high-yielding (HY) varieties. These categories provide a basis for understanding the performance of different quinoa cultivars in terms of yield potential.

Yield components such as effective branch number and 1000-grain weight varied significantly among yield categories. High-yielding varieties demonstrated fewer effective branches but higher 1000-grain weight, suggesting efficient resource allocation towards grain production. This study also found a positive correlation between yield per plant and 1000-grain weight. Previous research has mentioned a positive correlation of yield with seed size, harvest index, and 1000-grain weight [20,31,32]. On the other hand, the number of effective branches at maturity decreased with increasing yield, consistent with the results of Woo et al. [19].

The harvest index (HI) reflects the ability of crop photosynthetic assimilation products to be converted into economic products. A high harvest index indicates that plants have a mechanism for supplying a higher biomass to seeds. In this study, the harvest index of quinoa was low (8.77–13.15%), but the HI increased with the yield, and the HY varieties depicted a higher HI. This suggests that increasing the HI is an important way to increase the yield of quinoa [33]. Therefore, increasing the 1000-grain weight, reducing the branch number, and improving the biomass allocation mechanism can be considered important research directions for increasing quinoa yield.

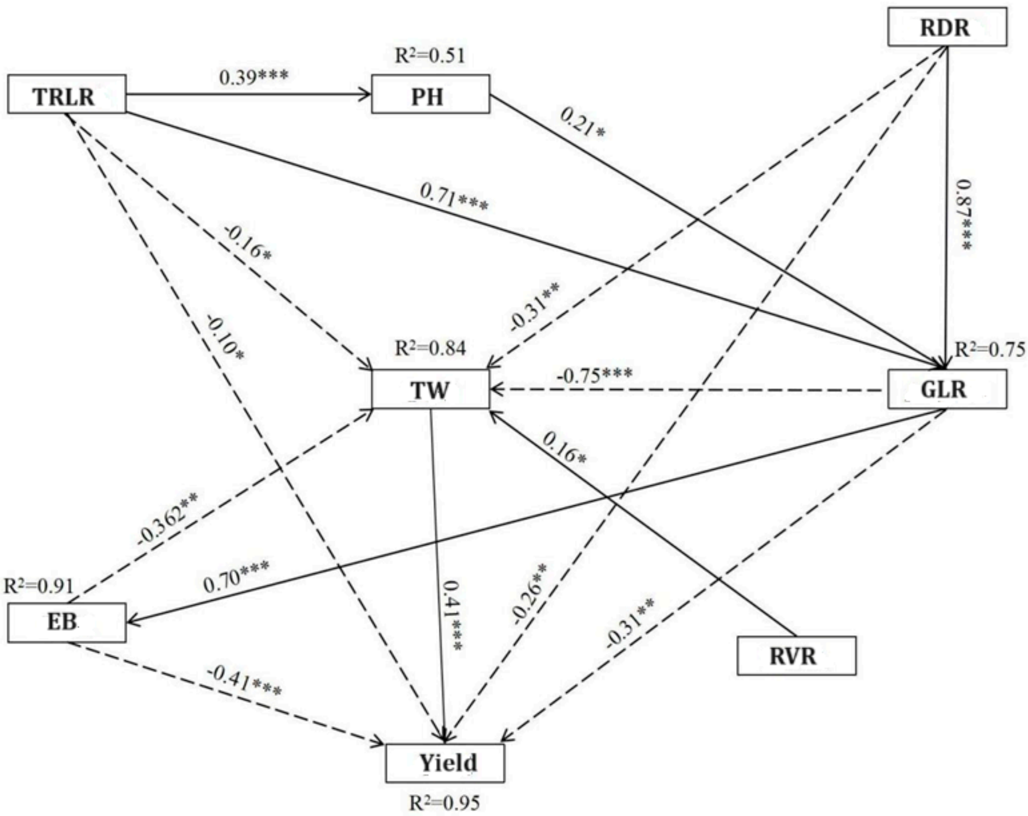

Figure 5. Structural equation modelling to reveal the relationship between quinoa yield and main agronomic traits. GLR: green leaf area reduction; EB: effective branch number; PH: plant height; RDR: root diameter reduction; RVR: root volume reduction, TW: thousand-grain weight; TRLR: total root length reduction. * indicates significant level ($p < 0.05$); ** indicates very significant level ($p < 0.01$); *** indicates very significant level ($p < 0.005$).

Correlation analysis revealed significant relationships between yield and various agronomic traits. Positive correlations were observed between yield and traits such as dry matter accumulation, stem-breaking force, and 1000-grain weight, while negative correlations were observed with traits like effective branch number. These correlations highlight the importance of specific traits in determining yield potential and suggest potential breeding targets for improving quinoa productivity.

The ear (panicle) length of the main stem was found to be significantly higher in the HY varieties, and this increase was positively correlated with yield. On the other hand, the ear width of the main stem at the maturity stage was significantly lower in the HY varieties, and it gradually decreased with increasing yield. The yield was negatively correlated with the ear width and positively correlated with the ear length of the main stem. These findings align with a previous study by Dumschott et al. [7]. However, Manjarres-Hernández et al. [25] reported that quinoa accessions with longer panicle lengths (>57.94 cm) had a lower yield. This discrepancy might be because the maximum average panicle length (43.04 cm) in the present study was lower than the limit referred to by Manjarres-Hernández et al. [25].

Additionally, the dry matter weight at maturity increased with increasing yield. Considering the research by Qi et al. [34], it is evident that quinoa with longer main inflorescence and more branches requires more biomass. In this study, it is speculated that as yield increased, the growth resources were continuously transferred to the panicle, causing a delay in stem growth after flowering. Therefore, breeding high-yield quinoa with dwarf, thick stems, longer main spike length, and strong plants can be considered a promising direction.

Roots serve as the primary interface between plants and the soil [35]. The strength of roots can be determined by various factors such as root number, morphology, and physiological indices [36,37]. This study found that high-yield varieties exhibited the highest values for total root length, root diameter, root volume, and root tip number during the flowering and maturity stages, which aligns with the findings of Sarropoulou et al. [38].

In the present study, the root length and diameter increased consistently with the growth stage until the flowering stage and then growth was slowed or stopped. Previous research on rice roots has demonstrated that slowing down the root growth and delaying the physiological activities of roots after flowering enhances leaf photosynthetic efficiency, promotes grain growth, and increases yield [39,40]. The decrease in total root length, root diameter, and root volume after flowering was found to be associated with increased yield. Specifically, yield was significantly negatively correlated with the decrease in total diameter, total root length, and root volume after anthesis. These findings are consistent with the study by Ma et al. [41]. The quinoa varieties that attained higher root length and diameter at the flowering stage and maintained this until the maturity stage showed enhanced grain weight and yield.

Dry matter accumulation per plant increased with the growth period, with high-yielding varieties accumulating the highest dry matter at maturity. This suggests that high-yielding varieties allocate more resources to biomass production, contributing to increased yield potential. Photosynthesis plays a crucial role in the accumulation of dry matter, which directly impacts crop yield. After flowering, enhancing physiological activity and improving photosynthetic performance can delay the senescence of flag leaves, promote the assimilation of synthesis, and increase grain weight [42]. The findings of this study indicate that high-yield varieties exhibit the highest green leaf area per plant and superior dry matter accumulation during the maturity stage. High-yielding varieties tended to have lower reductions in green leaf area at maturity compared to low- and medium-yielding varieties. Notably, there is a significant negative correlation between yield and the decrease in green leaf area per plant after anthesis. The reduction in green leaf area decrement after anthesis, coupled with an increase in net photosynthetic rate, led to enhanced dry matter accumulation and increased grain yield, aligning with previous research [43,44].

The root distribution of quinoa is shallow and the stem is fragile. During the flowering to maturity period, extreme weather conditions can lead to lodging and stem breakage. Variations in plant height were observed across different yield categories and growth stages. Interestingly, the high-yielding varieties exhibited a shorter plant height compared to the low- and medium-yielding varieties at maturity, suggesting potential trade-offs between plant height and yield [45]. Differences in stem diameter, hardness, and panicle traits were observed among yield categories. High-yielding varieties tended to have thicker stems, higher stem hardness, longer main stem ear length, and more compact panicles, indicating structural characteristics that may contribute to higher yield stability and resistance to lodging [46]. Additionally, the stem diameter, hardness of the middle part of the stem, and stress value of the stem at maturity all increased with increasing yield, which aligns with the results of previous studies [47]. The yield of quinoa is positively correlated with the stress value of the stem. The low and thick stem of quinoa enhances lodging resistance, promoting the accumulation of dry matter and increasing grain weight and yield.

The structural equation model (SEM) analysis provided insights into the complex relationships among different agronomic traits and their effects on yield. The 1000-grain weight and yield were negatively affected by the reduction in total root length, the reduction in root diameter, the reduction in green leaf area per plant, and the number of effective branches. These results highlighted the importance of root characteristics, plant height, and green leaf area in influencing yield, underscoring the multifaceted nature of yield determination in quinoa.

Overall, these results contribute to a better understanding of the factors influencing quinoa yield and provide valuable information for breeding programs aimed at developing high-yielding varieties with improved agronomic traits and yield stability.

4. Conclusions

To summarize, this study categorized the yield of 32 quinoa varieties into three categories in this study. High-yielding varieties exhibited several advantages: They maintained lower plant heights while developing stronger and thicker stems, resulting in increased resistance to lodging. Furthermore, these varieties attained higher dry matter accumulation and possessed extensive root systems characterized by greater length, volume, and number of tips, facilitating water and nutrient absorption. Despite having fewer effective branches, they compensated for yield with significantly heavier grain weights, highlighting their superior yield potential. The structural equation modeling revealed that the higher observed yield could be attributed to the slower senescence of the roots and leaves after anthesis. Consequently, high-yield genotypes exhibited less of a reduction in green leaf area, root diameter, and root length, indicating an improved ability to absorb water and accumulate photosynthate during the grain-filling stage, ultimately enhancing the yield.

Author Contributions: Data curation, A.R.; Funding acquisition, M.S.; Investigation, Z.J. and R.W.; Methodology, K.C. and X.W.; Project administration, Z.G.; Writing—original draft, P.T.; Writing—review and editing, P.T., S.A. and M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is a collaborative innovation center of provincial and ministerial level for high-quality and efficient production Special crops in the Loess Plateau were supported. Science and Technology Assistance Project for Developing Countries (KY202002002), Key Project of Shanxi Province Research and Development Plan (202102140601007), the technology innovation team of China Shanxi Province (No. 201605D131041), the Key Laboratory of Shanxi Province (No. 201705D111007), the "1331" Engineering Key Laboratory of Shanxi Province, and the "1331" Engineering Key Innovation Cultivation Team of Shanxi Province (No. SXYBKY201733).)

Data Availability Statement: The data that support the findings of this study are available from the corresponding author.

Conflicts of Interest: Author Xiangyun Wu from company Shanxi Jiaqi Agricultural Science and Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or finaical relationships that could be construed as a potential conflicts of interests.

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