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Research Article

Variation in Agronomic and Grain Nutritional Traits of Quinoa (*Chenopodium quinoa* Willd.) Cultivars

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Abstract

Quinoa is a potential crop for its use as human food and animal feed due to the high nutritional grain and quality forage. However, quinoa's growth, yield and quality are affected by many factors. The study was aimed to evaluate the variability of eight quinoa cultivars over two years for phenology, yield and attributing traits, and also for nutritional quality of grain. The experiments were arranged in Randomized Complete Block Design with three replications. Significant variations were exhibited among the cultivars for all studied traits. Three cultivars, 5-Red, 40-Red and 45-Red, had the highest potential growth performance, while Cahuil cultivar had the highest grain yield. Both Cahuil and Isluga cultivars exhibited more stable and higher contents of nutrient composition than other cultivars. Significant positive correlation were observed for grain yield with yield attributing traits, and for forage yield with most of the growth traits. No negative correlations among grain quality traits were observed, implying easier improvement for quinoa grain quality. The first two principal components in PCA (principal component analysis) explained 77.39% of the total variability. Based on forage yield, grain yield and nutritional quality over two years, 40-Red cultivar was selected for grain production and forage yield purposes, and Cahuil cultivar was selected for high grain yield and nutritional quality.

Introduction

Quinoa (*Chenopodium quinoa* Willd.) is an annual species belonging to *Amaranthaceae* family. It can grow under diverse agro-ecological zones and is tolerant to a wide range of abiotic stresses (Ruiz et al., 2015). Quinoa, with high nutritional value, is considered as "functional food" and recognized as being significant in world food security (FAO, 2013). Quinoa grain has a high carbohydrate content, mainly consisting of starch and a small percentage of sugars (Filho et al., 2017). It has a higher level of protein than cereal grains such as barley, maize, rice and wheat and contains many essential amino acids, vitamins and important minerals (Bock et al., 2021). In addition to human food use, quinoa can be used as fodder (Asher et al., 2020) because of cellulose and lignin-rich in stem (Temel & Yolcu, 2020) and protein-rich in leaves (Buxton, 1996). Quinoa had higher forage quality than other forage species as oat and alfalfa (Shah et al., 2020). Various studies have been focused on forage of quinoa in aspects of maximizing production (Shah et al., 2020; Tan & Temel, 2022; Carpici et al., 2023)

Quinoa originated in the Andean region of South America and was later introduced to Asia, Europe, Africa and North America during the 20th century (Tan & Temel, 2022). In Asia, particularly for tropical areas, quinoa is still a new crop and not has yet paid attention (Taaime et al., 2023a). In Vietnam, quinoa was first grown in 1986 using HV1 variety with grain yield ranging from 1.4 to 2.6 tons ha^{-1} (Trinh, 2001). According to Bertero et al. (2004), quinoa adapted well to Vietnam's climate and soil condition with higher yields compared to several original regions. Since 2014, quinoa has been considered as a potential crop in different agro-ecological zones in Vietnam (Nguyen, 2016).

Quinoa has great diversity in morpho-phenological characteristics and seed grain and quality (Präger et al.,

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2018; Nguyen & Nguyen, 2021; Sarwar et al., 2023). Environmental factors can affect trait expression and different varieties are always brought distinctive traits adaptable to specific regions (Präger et al., 2018; Bock et al., 2021). There is limited information on quinoa production for different agro-ecological zones in Vietnam in particular and for tropical areas in Asia in general; therefore, this study aimed to assess the variability of various quinoa cultivars over two years for agronomical characters, forage-related yield traits, yield components, grain yield and quality and provided suggestion for selection of cultivars suitable to different utilization purposes.

Materials and Methods

Plant materials and experimental design

The study used eight quinoa cultivars provided by Buenos Aires University Argentina, Wageningen UR the Netherlands and INIA Chile (Table 1).

Table 1. Origin of eight quinoa cultivars

No.	Cultivars	Origin
1	2-Want	Chile x Bolivia
2	30-Test	Chile x Bolivia
3	42-Test	Chile x Bolivia
4	Cahuil	Chile
5	Isluga	Chile
6	5-Red	INIA-Chile
7	40-Red	INIA-Chile
8	45-Red	INIA-Chile

Experiments were conducted in the open field of Vietnam National University of Agriculture, Hanoi, Vietnam (21°00′07.2′′N, 105°55′55.6′′E) from January to May in 2022 and 2023. The field soil properties were determined each year before cultivation (Table 2). Climate data recorded during two experimental years were presented in Figure 1.

Table 2. Chemical properties of the field soil in 2022 and 2023

Year	pH	OM (%)	Total N (%)	Available N (%)	Exchangeable P (mg 100 g^{-1})	Exchangeable K (mg 100 g^{-1})
2022	6.65	2.31	0.085	3.86	14.64	8.62
2023	6.48	2.16	0.125	3.93	12.97	9.58

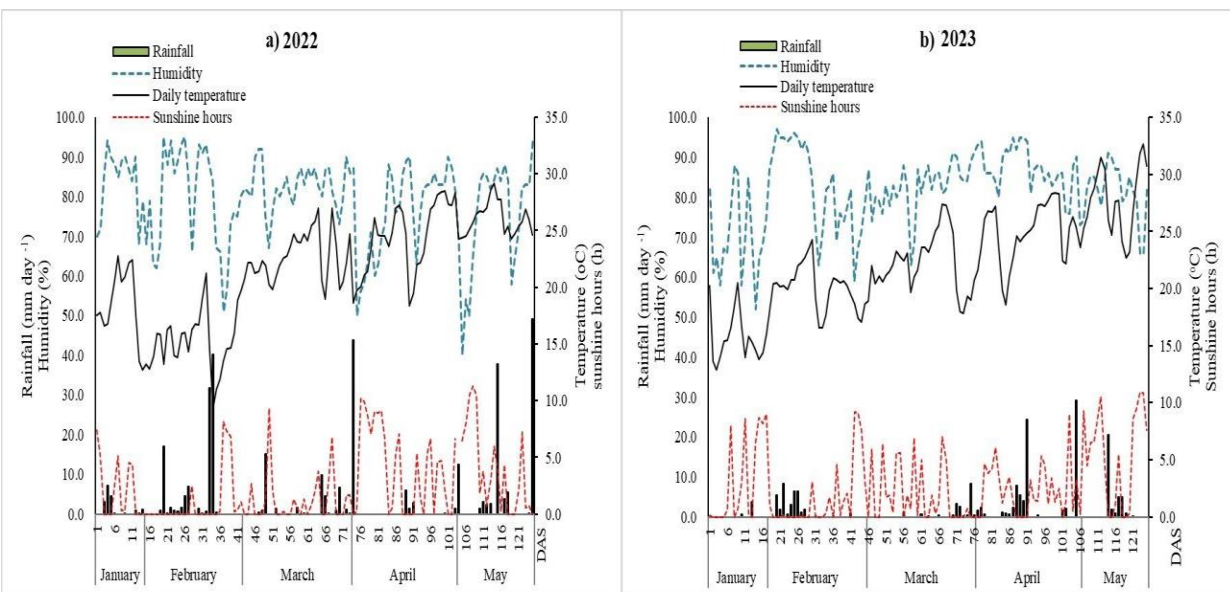

Figure 1. Meteorological conditions of the experimental site during the experiment periods in (a) 2022; (b) 2023. Note: DAS: Days after sowing

Experiments were arranged in Randomized Complete Block Design (RCBD) with three replications in 2022 and 2023. Seeds were sowed in two rows per plot at spacing of 50 cm × 20 cm with density of 100,000 plant ha^{-1}.

Fertilizers were applied before sowing with 1000 kg ha^{-1} of Quelam 01 microbial organic fertilizer, 500 kg ha^{-1} of lime, and 60 kg ha^{-1} of phosphate, 45 kg ha^{-1} of nitrogen and 30 kg ha^{-1} of potassium. At the panicle initiation stage, the rest of nitrogen and potassium fertilizers with rates of 45 kg ha^{-1} and 30 kg ha^{-1} respectively were applied. Irrigation, weeding and phytosanitary treatments and disease control were monitored to provide favorable conditions for plant growth.

Data collection

Data were recorded for phenology, growth characters, yield components, grain yield and quality. The panicle initiation stage was determined when all plants in a plot had at least 50% of panicle initiation. The harvest stage was determined when the lower part of leaves turned yellow and lower stems started drying, and grains had become hard.

Growth characters were measured at harvest for plant height (PH), number of leaves on main stem (NLMS), number of branches per plant (NBPP) and stem diameter (SD) on 5 plants per plot. Five-plant samples were cut from the base to measure shoot fresh weight (SFW) and shoot dry weight (SDW) at the panicle initiation (SFW-PI and SDW-PI, respectively) and harvest (SFW-H and SDW-H, respectively). Yield components were measured on 5 plants per plot for number of panicles (NP), length of main panicle (LMP), number of seeds on main panicle (NSMP). Panicles were sun-dried for 5 days then threshed and cleaned to determine weight of 1000-seeds (1000-SW). Grain yield (GY) was measured from remaining plants.

Seed was used to determine contents of protein, starch, fat and total sugar. Protein content was determined followed Kjeldahl method with a conversion factor of 6.25 by AOAC method (AOAC International., 2016) using UDK-149 system, Italy. DNS method was used to measure total sugar content (UV-Vis, UV 1900i, Malaysia). Bertrand method was used to determine amount of reducing sugars, then starch content was calculated based on reducing sugars and general sugar content in glucose. Fat content was measured using VELP solvent extractors SER 148/6, Italy with VELP cellulose thimbles 33 x 80 mm for 90 min using petroleum ether with a boiling range of 40-60^{o}C, as the extraction solvent (Eisa et al., 2018).

Data analysis

ANOVA analysis was used to determine effects of cultivars, years and cultivars × years by using Minitab 16. Pairwise comparison between cultivars and years were made with Tukey test at a significance level of 5%. Pearson correlations among growth characters, yield components and yield, and grain quality were performed using Performance Analytics package in R (Peterson et al., 2020). For a comprehensive understanding of variation among eight quinoa cultivars, principal component analysis (PCA) was performed with R ver. 4.3.2 on the analyses of growth characters, yield components, grain yield, and grain quality. Ranking genotypes plot were generated by using metan package in R (Olivoto & Lúcio, 2020).

Results

Phenological and growth characters of studied quinoa cultivars

Quinoa growth stages were recorded at panicle initiation and harvest stages which were significantly different among cultivars, years and cultivars × years (Table 3 & Figure 2). Total growth duration varied from 105.0 – 125.7 days over two years, with more differences among eight cultivars in 2023 (~ 17 days) (Figure 2).

Table 3. ANOVA results for phenological traits, growth characters, yield components, grain yield and quality of eight quinoa cultivars in 2022 and 2023

Source of variation	MS	Sig.	MS	Sig.	MS	Sig.	MS	Sig.	MS	Sig.
	DI		DH		PH		NLMS		NBPP	
Cultivar	49.18	***	248.56	***	343.99	***	15.28	***	44.77	***
Year	5.33	*	44.08	***	108.9	**	21.33	***	18.75	**
Cultivar × Year	2.81	*	8.85	**	32.14	*	3.79	*	4.99	ns
	SD		SDW-H		SFW-H		SDW-PI		SFW-PI	
Cultivar	1.25	ns	384.43	***	4876.9	***	5.92	***	3162.6	***
Year	19.64	***	515.88	***	58610.8	***	6.86	***	463.3	***
Cultivar × Year	0.65	*	14.86	ns	2960.7	ns	0.22	ns	189.7	ns
	NP		LMP		NSMP		1000-SW		GY	
Cultivar	51.08	***	56.95	***	646992	***	0.07	***	0.25	***
Year	13.27	ns	43.82	***	745535	***	0.06	*	0.02	ns
Cultivar × Year	7.95	ns	7.7	*	78646	*	0.03	ns	0.03	ns
	Protein		Starch		Fat		Sugar			
Cultivar	4.68	***	8.7	***	0.79	***	0.19	**		
Year	0.01	ns	0.07	ns	0.29	*	0.27	ns		
Cultivar × Year	0.26	ns	0.27	ns	0.09	ns	0.07	ns		

MS: mean square; Sig.: Significance; *, **, *** significant levels respectively P ≤ 0.05, 0.01, 0.001; ns: not significant.

DI: days to the panicle initiation, DH: days to the harvest, PH: Plant height, NLMS: number of leaves on main stem, NBPP: number of branches per plant, SD: Stem diameter, SFW-PI: shoot fresh weight at the panicle initiation, SDW-PI: shoot dry weight at the panicle initiation, SFW-H: shoot fresh weight at the harvest, SDW-H: shoot dry weight at the harvest, NP: number of panicles, LMP: length of main panicle, NSMP: number of seeds on main panicle, 1000-SW: weight of 1000 seeds, GY: grain yield.

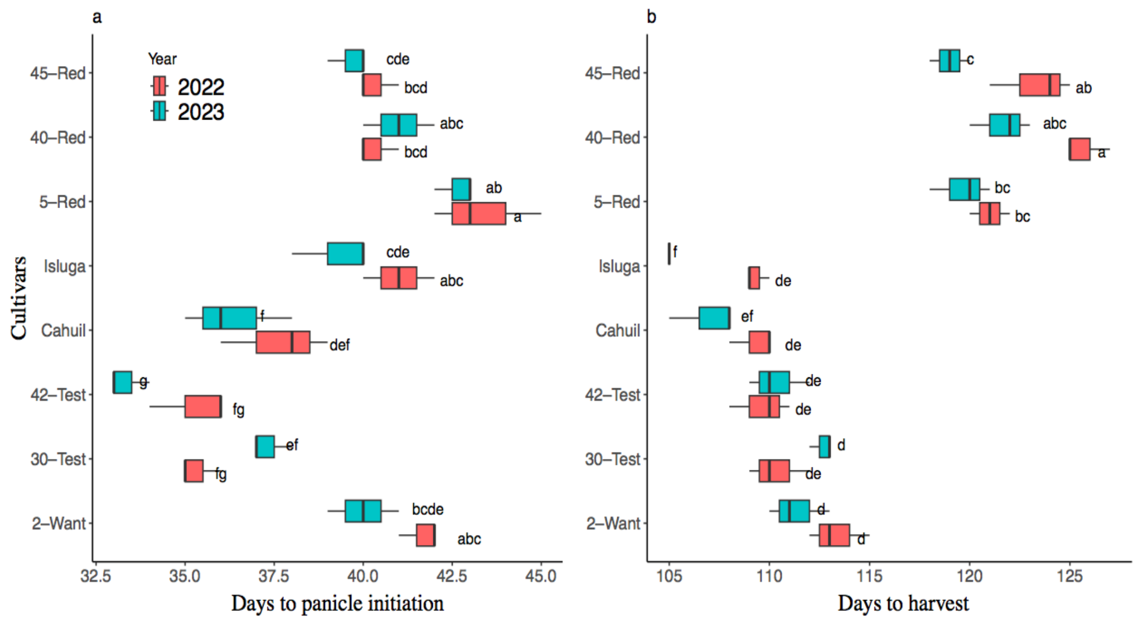

Figure 2. Boxplot showing descriptive statistics for growth stages at (a) the panicle initiation and (b) the harvest of eight quinoa cultivars in 2022 and 2023. Different letters show significant differences at P ≤ 0.05 by Tukey test.

ANOVA results indicated significant differences among cultivars, years and cultivars × years for growth characters, except cultivars × years for NBPP (Table 3). PH of eight cultivars in 2022 varied from 135.67 – 153.20 cm, while those in 2023 varied from 127.13 – 151.40 cm (Table 4). 5-Red, 40-Red and 45-Red were the group having high height plant type (> ~ 140 cm), while others were classified as medium height plant type (~ 130 – 140 cm). NLMS and NBPP over two years were in the range of 38.60 – 45.80 leaves and 27.33 – 37.13 branches, respectively. Most cultivars had NLMS higher than 41 leaves and NBPP higher than 32 branches. SD in 2023 was higher than that in 2022, with the range of 14.80 – 15.87 mm compared to the range of 12.80 – 14.50 mm. Overall, based on the expression of growth characters, there could be three groups of which the first group had the highest potential growth performance with 5-Red, 40-Red and 45-Red, followed by the second group with Cahuil and Isluga, and the third group with 2-Want, 30-Test and 42-Test.

Table 4. Means of PH, NLMS, NBPP and SD of eight quinoa cultivars in 2022 and 2023

Year	Cultivars	PH (cm)	NLMS	NBPP	SD (mm)
2022	2-Want	135.67^{d-f}	41.27^{c-f}	30.30^{d-f}	13.13^{ef}
	30-Test	139.20^{c-e}	38.60^{f}	28.57^{ef}	12.80^{f}
	42-Test	139.53^{c-e}	43.07^{a-e}	27.33^{f}	14.00^{c-f}
	Cahuil	136.20^{d-f}	41.67^{b-f}	34.93^{a-d}	14.30^{b-f}
	Isluga	144.80^{a-d}	40.27^{ef}	33.53^{a-d}	14.13^{b-f}
	5-Red	150.63^{ab}	42.90^{a-e}	32.70^{a-e}	14.37^{b-e}
	40-Red	148.70^{a-c}	44.30^{a-d}	35.87^{ab}	13.90^{d-f}
	45-Red	153.20^{a}	43.80^{a-d}	35.87^{ab}	14.50^{a-e}
2023	2-Want	132.60^{ef}	42.20^{b-e}	32.20^{b-e}	14.87^{a-d}
	30-Test	140.70^{b-e}	41.93^{b-f}	31.07^{c-f}	14.80^{a-d}
	42-Test	127.13^{f}	41.07^{d-f}	30.73^{d-f}	15.13^{a-d}
	Cahuil	134.27^{d-f}	43.27^{a-e}	37.13^{a}	15.53^{a-c}
	Isluga	139.20^{c-e}	42.80^{a-e}	35.53^{a-c}	15.67^{ab}
	5-Red	148.60^{a-c}	44.47^{a-c}	32.83^{a-e}	15.87^{a}
	40-Red	151.40^{ab}	45.00^{ab}	36.07^{ab}	15.20^{a-d}
	45-Red	149.93^{a-c}	45.80^{a}	33.53^{a-d}	14.30^{b-f}

Different letters in the same column show significant differences at P ≤ 0.05 by Tukey test. Hyphen (-) is used for significant differences of more than two letters (e.g. a-c = abc; b-e = bcde ect.).
PH: plant height, NLMS: number of leaves on main stem, NBPP: number of branches per plant, SD: Stem diameter

Significant differences in SFW and SDW among cultivars, years at the panicle initiation and the harvest were observed, but no significant differences were revealed for interaction of cultivar × year (Table 3 & Figure 3). At the panicle initiation, SFW varied from 37.63 – 65.80 g plant^{-1}, and SDW varied from 4.50 – 7.77 g plant^{-1}. At the harvest, SFW varied from 90.37 – 201.3 g plant^{-1}, and SDW varied from 22.43 – 48.74 g plant^{-1}. Over two years, 5-Red, 40-Red and 45-Red had the highest SFW and SDW for both two growth stages. However, no significant differences in SFW and SDW were observed within each cultivar over two years, indicating stability of cultivars.

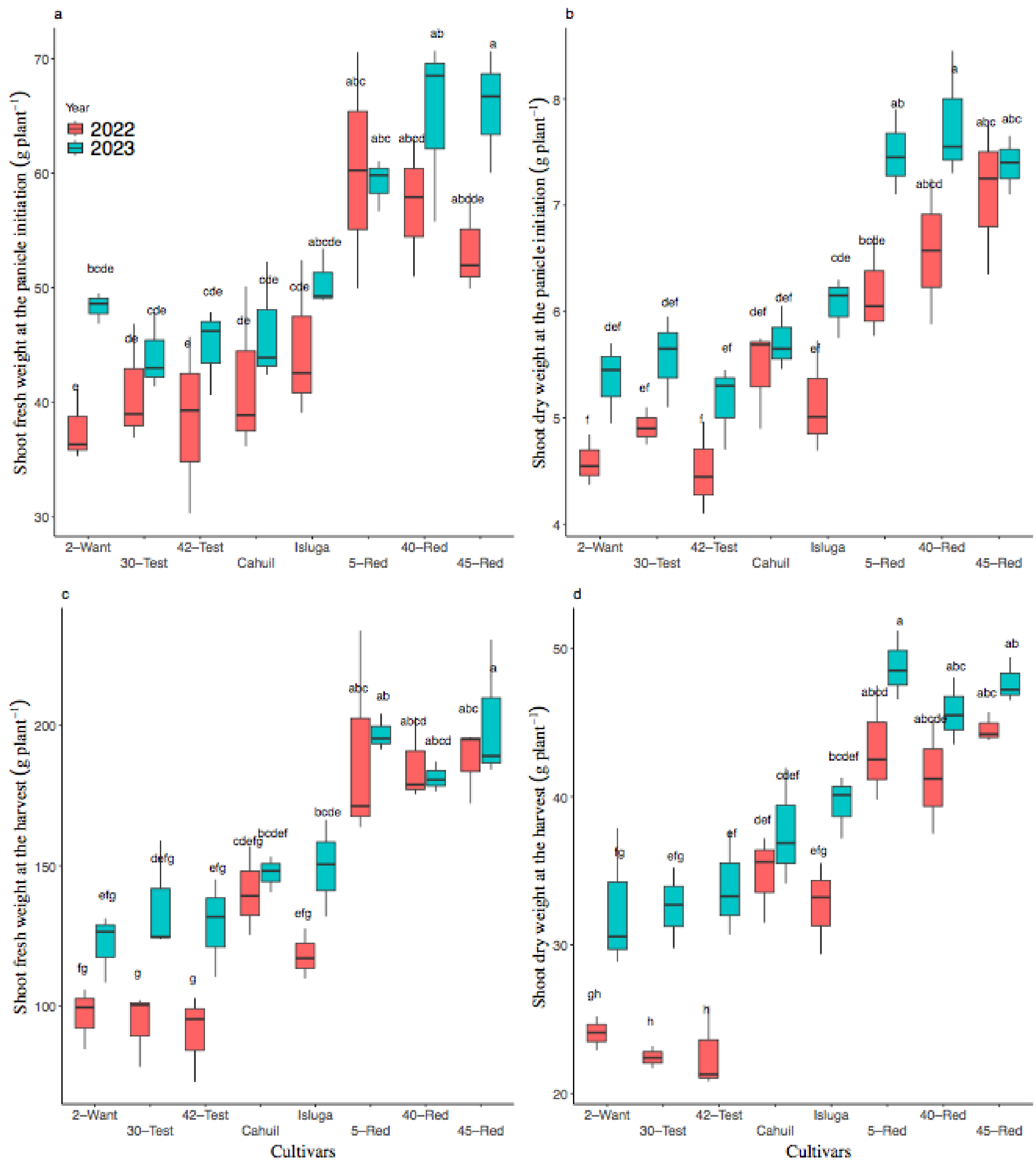

Figure 3. Boxplot showing descriptive statistics for (a) SFW and (b) SDW at the panicle initiation; and (c) SFW and (d) SDW at harvest in 2022 and 2023. Different letters show significant differences at P ≤0.05 by Tukey test.

Yield components and grain yield of studied quinoa cultivars

ANOVA showed significant differences among cultivars, years and cultivars × years for LMP and NSMP (Table 3; Figure 4). NP and GY were only significantly different among quinoa cultivars. Significant differences were exhibited among cultivars and years, but not for years × cultivars for 1000-SW.

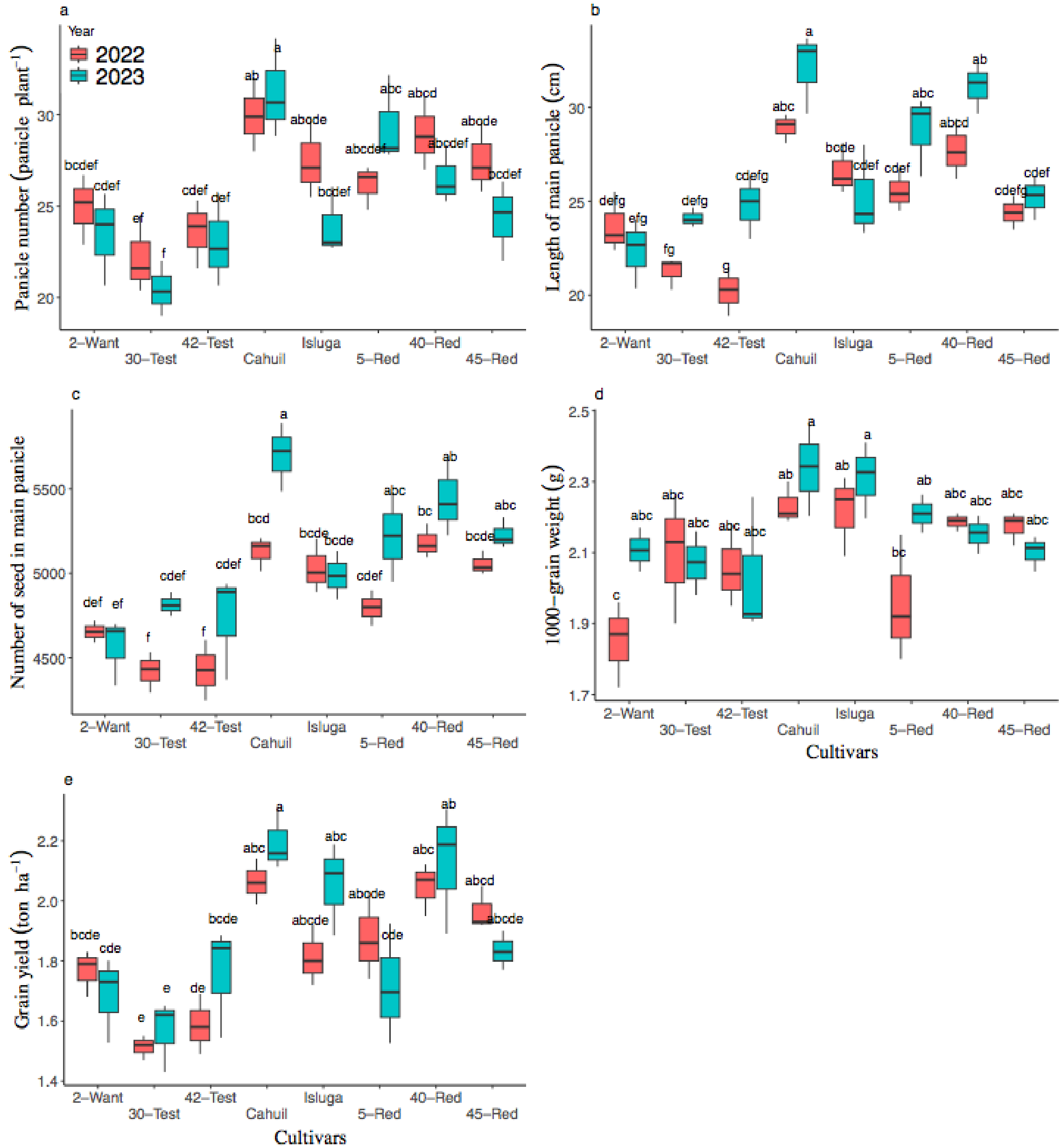

Figure 4. Boxplot showing descriptive statistics of yield components: (a) panicle number, (b) length of main panicle, (c) number of seed in main panicle, (d) 1000-seed grain, and (e) grain yield of eight quinoa cultivars in 2022 and 2023. Different letters show significant differences at P ≤ 0.05 by Tukey test.

NP in 2022 varied from 22.17 – 29.93 panicles, which was lower than that in 2023 with the range of 20.44 – 31.22 panicles. Cahuil, 5-Red and 40-Red were cultivars with high and stable NP over two years. Therein, Cahuil had the highest NP, followed by 5-Red and 45-Red. LMP was the highest for Cahuil. 40-Red and 5-Red had panicles in 2023 longer than in 2022, but similar with those of Cahuil in both years. LMP of 30-Test and 40-Test were similar in size and lower compared to other cultivars.

Generally, most cultivars had NSMP > 4500 seeds, except for 42-Test and 30-Test in 2022. Cahuil, Isluga, 5-Red, 40-Red, 45-Red produced more NSMP than those of 2-Want, 30-Test and 42-Test. For 1000-SW, Cahuil also exhibited the highest values in two years (2.23 and 2.34 g), followed by Isluga and 40-Red.

GY is an important indicator for cultivar selection. Over two years, some cultivars including 2-Want, 5-Red and 45-Red had GY in 2022 higher than those in 2023 while GY of the rest cultivars were vice versa (Figure 4). Cahuil had the highest GY in both 2022 and 2023 (2.06 and 2.20 tons ha^{-1}, respectively), followed by 40-Red (2.05 and 2.13 tons ha^{-1}, respectively) and Isluga (1.81 and 2.05 tons ha^{-1}, respectively). 30-Test expressed the lowest GY in both 2022 (1.51 tons ha^{-1}) and 2023 (1.57 tons ha^{-1}). Results showed that Cahuil was ranked the first, followed by 40-Red and Isluga.

Grain quality of studied quinoa cultivars

Quinoa is known for its high nutrient values in terms of protein, starch, fat and total sugar contents. ANOVA results indicated that these nutrients were significantly influenced by cultivar but not influenced by year of growing, except for fat (Table 3; Figure 5). No differences of all grain quality traits among years × cultivars were revealed. The ranges of protein, starch, fat and total sugar contents respectively fluctuated from 14.81 – 18.77%, 55.90 – 62.50%, 3.74 – 4.73% and 1.26-1.54% over two years (Figure 5). Generally, Cahuil exhibited more stable and higher contents of protein, starch, fat and total sugar, followed by Isluga over two years.

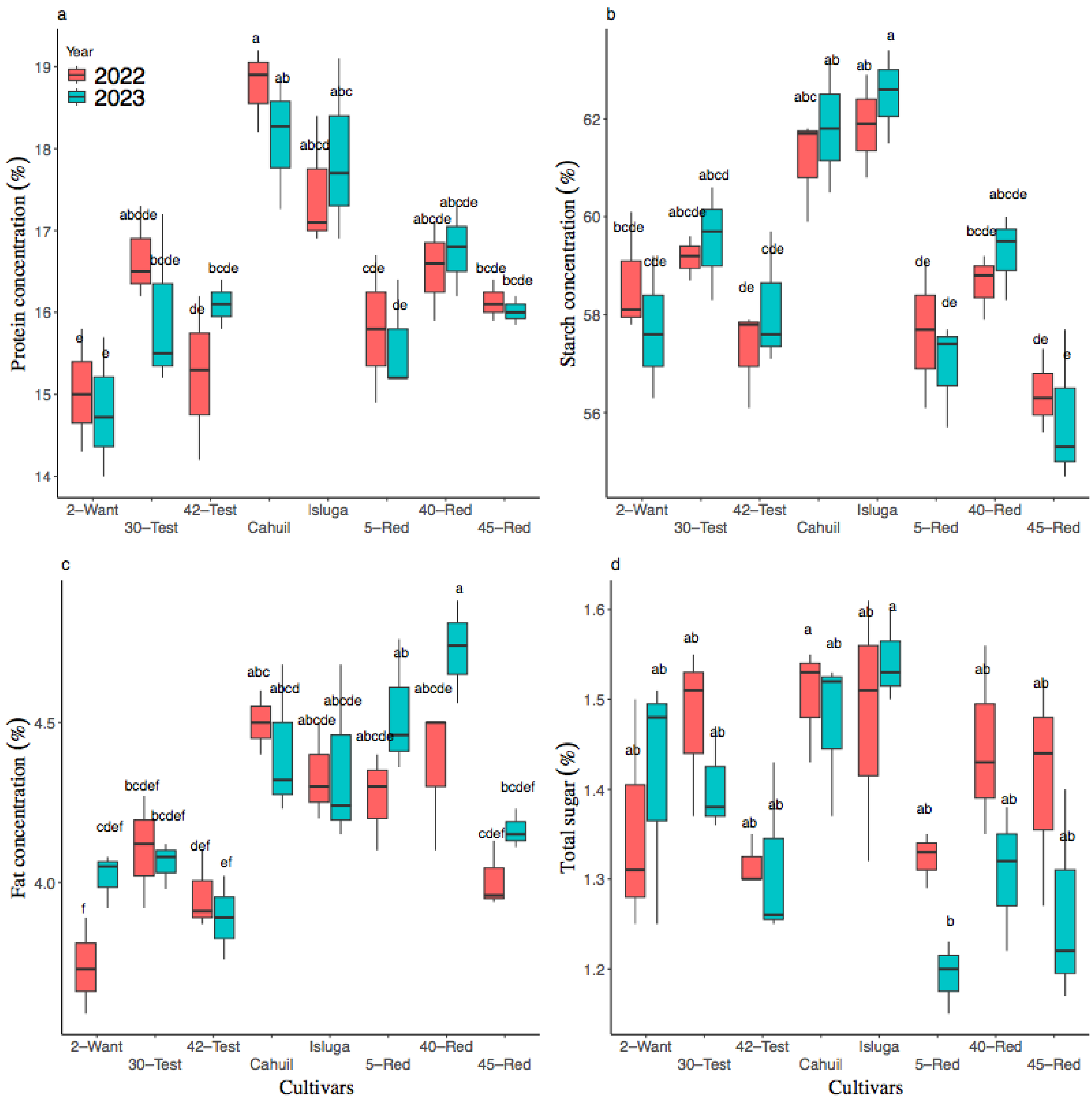

Figure 5. Boxplot showing descriptive statistics of (a) protein, (b) starch, (c) fat and (d) total sugar contents of eight quinoa cultivars in 2022 and 2023. Different letters show significant differences at P ≤ 0.05 by Tukey test.

Correlation among traits and Principal component analysis

Various significant correlations between measured parameters were exhibited (Figure 6). Noticeably, GY was significantly positive correlated with all yield component traits, with some growth characters such as NBPP and SFW-H and SDW-H. However, GY was not correlated with seed quality, PH, NLMS, SFW-PI and SDW-PI. In addition, forage yield (SFW-H and SDW-H) had positive and significant correlations with PH, NLMS, NBPP.

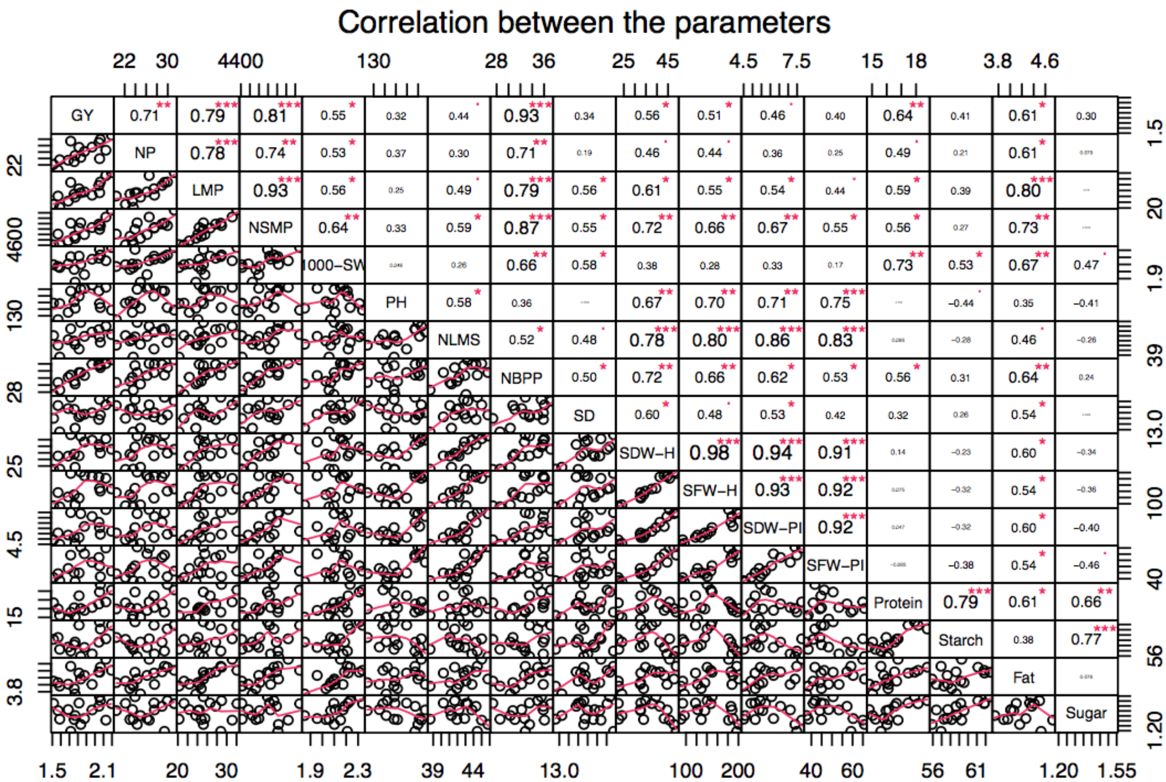

Figure 6. Pearson correlation between measured parameters including growth characters, yield components, grain yield and grain quality.

*, **, *** significant levels respectively P ≤ 0.05, 0.01, 0.001.

GY: grain yield, NP: number of panicles, LMP: length of main panicle, NSMP: number of seeds on main panicle, 1000-SW: weight of 1000 seeds, PH: plant height, NLMS: number of leaves on main stem, NBPP: number of branches per plant, SD: Stem diameter, SFW-PI: shoot fresh weight at the panicle initiation, SDW-PI: shoot dry weight at the panicle initiation, SFW-H: shoot fresh weight at the harvest, SDW-H: shoot dry weight at the harvest.

Grain quality was also significantly related to various parameters depending on cases. For example, protein content was positively correlated with 1000-SW and NP. Starch and sugar contents were only positively significant correlated with 1000-SW. Fat content had many positively significant correlations with other parameters. Interestingly, pairwise correlations of seed quality traits were all positive.

PCA revealed that 77.39% of the total variability was explained by the first two principal components (PC) (Figure 7). PC1 accounted for 52.09% of variation and was highly related to GY, NP, NSMP, NBPP, LMP, and fat content (Figure 7). PC2 explained 25.30% of total variation and was related to grain quality except fat (Figure 7). Other parameters, viz., 1000-SW, PH, NLMS, SFW and SDW were explained by both PC1 and PC2. Cultivars with higher GY, yield components tended to be located far on the left-hand side of graph such as Cahuil and 40-Red. Cultivars with higher PH, NLMS, SFW and SDW were located upper on the left-hand side of graph as 5-Red, 40-Red and 45-Red.

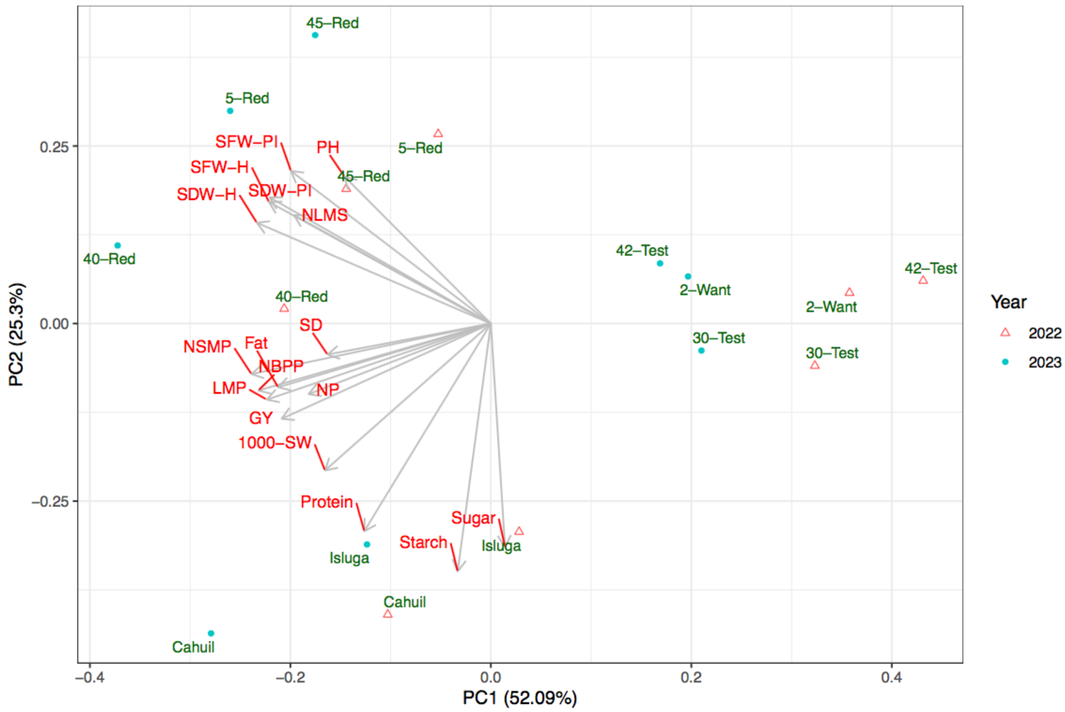

Figure 7. PCA plot of the first and second components of eight quinoa cultivars and seventeen attributes (for growth parameters, yield components, grain yield and seed quality) in 2022 and 2023 by points.
GY: grain yield, NP: number of panicles, LMP: length of main panicle, NSMP: number of seeds on main panicle, 1000-SW: weight of 1000 seeds, PH: plant height, NLMS: number of leaves on main stem, NBPP: number of branches per plant, SD: Stem diameter, SFW-PI: shoot fresh weight at the panicle initiation, SDW-PI: shoot dry weight at the panicle initiation, SFW-H: shoot fresh weight at the harvest, SDW-H: shoot dry weight at the harvest.

Based on GY of quinoa cultivars in two years, 40-Red and Cahuil were selected as they were located in the small circle with a pointing arrow showing the highest yield in two years. Additionally, 40-Red, 45-Red and 5-Red having the highest SDW in both years, which were located in the small circle, were suitable for the forage purpose (Figure 8).

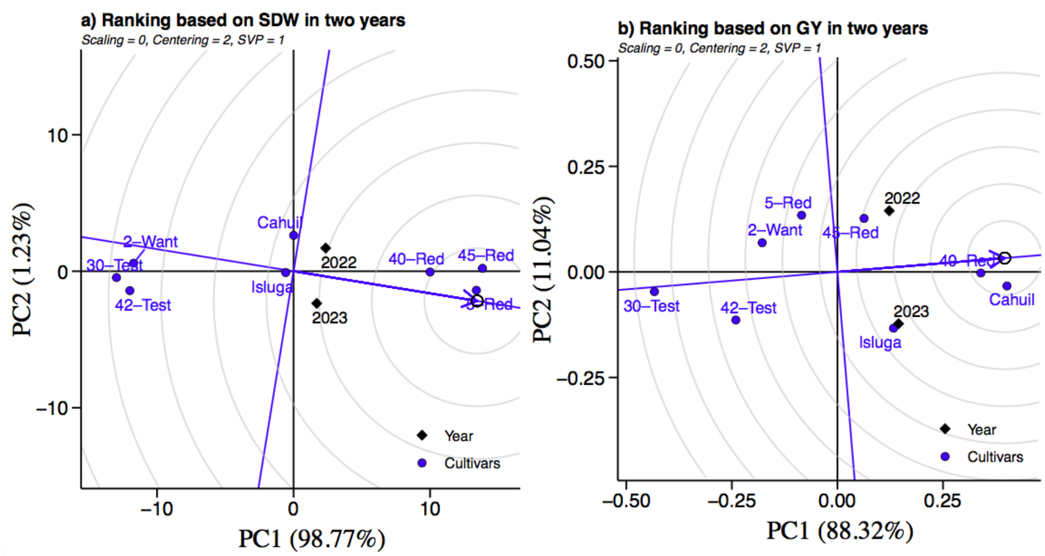

Figure 8. Ranking of eight quinoa cultivars for (a) shoot dry weight (SDW) at the harvest and (b) grain yield (GY) by using collected data in 2022 and 2023 for Genotype-vs-Environment interaction model analysis. Scaling = 0 for no scaling, Centering = 2 for environment-centered, SVP (Singular Value Partitioning) = 1, The singular value is entirely partitioned into the genotype eigenvectors, also called row metric preserving. PC1: principal component 1, PC2: principal component 2. The small circle with an arrow pointing shows the region containing the ideal genotype with the highest SDW and GY in all environments

Discussion

Phenological character of eight quinoa cultivars indicated they are categorized as earliness with days to maturity < 130 days according to Oustani et al. (2023). Total growth period reported in this study was in the ranges reported by Shams (2018), but shorter than that reported by Voronov et al. (2023). Growth duration of quinoa cultivars in this study was slightly shorter in 2023, which could be due to warmer temperature and less humidity and rainfall at vegetative stage in 2023 compared to 2022. It was agreed with previous studies, which showed shorter growing period of quinoa under drier air (Oustani et al., 2023) and higher temperature (Maamri et al., 2022).

Results over two years showed significant effects of cultivars, years and cultivars × years on growth, yield responses and grain quality. Dry season seemed to be favorable condition for quinoa in Vietnam, when quinoa cultivars in this study were adapted successfully in spring season from January to May. Nguyen & Nguyen (2021) also concluded that the most suitable season for quinoa cultivation in Central Highland Vietnam was from January to April. Maamri et al. (2022) showed that temperature from 20-25°C may promote quinoa growth and yield. In this study, average temperatures from February to April varied from 15.2 to 24.9°C (Figure 1), which were in the range of appropriate temperature for quinoa.

Some growth characters are considered for forage uses such as PH, SD, NBPP, SFW and SDW (Shah et al., 2020; Carpici et al., 2023). These forage traits were significantly different among genotypes (Yilmaz et al., 2021; Voronov et al., 2023). Genotypes possessing thick stems, more branches and moderate PH produced more forage (Shah et al., 2020). In this study, PH, NLMS, NBPP, SFW and SDW of 5-Red, 40-Red and 45-Red were greater than those of other cultivars. As in agreement with previous studies on criteria for selecting genotypes for forage use (Shah et al., 2020; Voronov et al., 2023), 5-Red, 40-Red and 45-Red have potential for forage yield.

Various studies revealed variation in yield components and GY of quinoa cultivars (Shah et al., 2020; Nguyen & Nguyen, 2021; Oustani et al., 2023). The ranges of yield components and GY in this study were in the ranges reported in previous studies of Bock et al. (2021), Nguyen et al. (2022), Oustani et al. (2023). Cahuil and 40-Red showed significantly greater GY than other cultivars for two years, which could be due to higher NBPP and PN, longer LMP and higher NSMP. Shah et al. (2020) suggested that genotypes having more branches and more compact main inflorescences provided higher GY. Compared with Nguyen & Nguyen (2021), Cahuil and Isluga grown in the Central Highland of Vietnam had lower GY than those in this study. That might be due to the response of genotypes to environmental factors (Präger et al., 2018; Oustani et al., 2023) and cultivation conditions (Asher et al., 2020; Taaime et al., 2023b). Similarly, Präger et al. (2018) and Bock et al. (2021) showed quinoa GY different between cultivars and years. On the other hand, Oustani et al. (2023) showed significant differences of GY between genotypes but insignificant differences between two years and for year × cultivar. In this study, GY was only significantly different among cultivars, but not for years and cultivar x year.

Nutritional grain traits are determined primarily by genes (Cepková et al., 2022; Oustani et al., 2023), environmental (Temel & Yolcu, 2020), cultivation conditions as plant density (Eisa et al., 2018; Asher et al., 2020), fertilizer application (Taaime et al., 2023a). Contents of grain protein, starch, and fat of eight cultivars were in the range reported by previous studies of Präger et al. (2018), Bock et al. (2021), Rodríguez Gómez et al. (2021), while total sugar contents were lower compared to those in the studies of Chen et al. (2023) and Pereira et al. (2019). Our study also revealed that concentrations of protein, starch, fat and total sugar were significantly different among cultivars, but insignificantly different for year (except fat content) and cultivar × year. According to Präger et al. (2018), Nguyen et al. (2022), variability of grain protein depended highly on cultivar and year when quinoa was grown in the same agro-ecological zone. In contrast, Rodríguez Gómez et al. (2021) reported insignificant differences among varieties for grain protein. Starch content was significantly different among cultivars and varied between different years and different countries, with large variation from 44-85% (Cepková et al., 2022). However, Nguyen & Nguyen (2021) showed that starch contents were not significant differences among cultivars and seasons. Similarly, fat contents can be significantly different among cultivars (Nguyen et al., 2022) or insignificantly different over growing years and for cultivar × year (Präger et al., 2018). In contrast, Bock et al. (2021) detected significant variety × year interaction for fat content. According to Pereira et al. (2019), there were insignificant variations between quinoa varieties for grain sugar content. Differences in those reported results can be explained by use of different quinoa varieties, distinct geographical regions, and different grain extraction methodologies (Pereira et al., 2019).

Correlation and PCA analysis revealed significantly positive correlation of GY with growth parameters which is similar to Shah et al. (2020). This suggests criteria that can be used directly or indirectly to select high grain yielding potential cultivars. However, our study indicated no significant correlation between GY and PH, which was in contrast to Shah et al. (2020). Additionally, these growth parameters are often regulated and affected by agronomical practices such as irrigation and fertilization (Ali et al., 2023). Thus, further study is required to determine suitable cultivation practices for these eight quinoa cultivars to maximize yield potential. Interestingly, no negative correlations among grain quality traits were observed which obviously makes improvement of quinoa grain quality easier. This is because there is no compensation when increasing any grain nutrient components as often the case when increasing protein content resulted in decreasing lipid or starch content (Rodríguez Gómez et al., 2021). Additionally, similar to growth characters, grain nutrient contents are also affected by growing locations (Rodríguez Gómez et al., 2021; Oustani et al., 2023) and fertilizer application (Ali et al., 2023). These again suggest further studies on effects of agronomical practices on grain quality of these eight quinoa cultivars. Overall, Cahuil was selected for high potential grain yields and grain quality, while 40-Red was selected for both grain production and forage yield purposes.

Conclusion

Results of this study indicated that variability was significant among quinoa cultivars for all traits. Cultivars having more branches, more panicles, and greater number of seeds on main panicle achieved higher grain yields, while cultivars possessing thick stems, more branches and taller plant height produced more forage. Based on the performance of cultivars over two experimental years, 40-Red is recommended cultivar for both grain production and forage yield purposes, and Cahuil is selected cultivar having both high potential grain yield and quality.

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