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RESEARCH ARTICLE

Evaluation of agro-morphological traits of quinoa (*Chenopodium quinoa* Willd.) under different environmental conditions

Borisz Czékus[1], Mirela Matković Stojšin[2*], Zorica Jovanović[3], Veselinka Zečević[4], Ivana Radović[3], Milena Marjanović[3], Dejan Cvikić[4], and Slađana Savić[5]

[1]Public enterprise “Vojvodinašume”, Preradovićeva 2, 21131 Petrovaradin, Serbia.
[2]Tamiš Research and Development Institute, Novoseljanski put 33, 26000 Pančevo, Serbia.
[3]University of Belgrade, Faculty of Agriculture, Nemanjina 6, 11080 Belgrade, Serbia.
[4]Institute for Vegetable Crops Smederevska Palanka, Karađorđeva 71, 11420 Smederevska Palanka, Serbia.
[5]Institute for Plant Protection and Environment, Teodora Drajzera 9, 11040 Belgrade, Serbia.
[*]Corresponding author (matkovic.stojsin@institut-tamis.rs).
Received: 21 May 2024; Accepted: 9 August 2024, doi:10.4067/S0718-58392025000100003

ABSTRACT

Quinoa (*Chenopodium quinoa* Willd.) exhibits remarkable adaptability to different agroecological conditions, but there are still challenges in introducing it to new environments, especially those in northern latitudes. This study investigates the impact of genotype, season, sowing density (5 and 10 cm between plants), and their interaction on agro-morphological traits of quinoa cultivars (Puno and Titicaca). Seasonal variations, primarily influenced by precipitation, significantly affected all analyzed traits (plant height, number of side branches and flower branches, biomass and grain yield per plant) with the highest values recorded in a favorable season. The season factor had the greatest influence in the variation of grain yield, with a share of 89.7% in the total variation. Grain yield per plant was 31.41 g in the favorable season compared to 14.64 g in the less favorable season. The significance of the Genotype × Season interaction in variation of plant height, number of side branches and biomass production per plant, as well as the significance of the Season × Sowing density interaction in biomass production, highlighted the importance of these factors to optimize cultivation practices and increase quinoa productivity in different environmental conditions. Principal component analysis (PCA) highlighted the interrelationships among agro-morphological traits, where in less favorable environments grain yield was most closely related to biomass, number of side branches and number of flower branches. Lower sowing density (10 cm between plants) may be more favorable for achieving high values across all analyzed traits, particularly increasing the number of flower branches (16.75 at lower density and 14.61 at higher density). The ‘Puno’ genotype stands out with a pronounced adaptability to less favorable environmental conditions, especially at lower sowing density. In contrast, the ‘Titicaca’ genotype stands out for its high biomass production, especially in the second season (74.9 g).

Key words: Adaptability, genotype, quinoa, PCA, season, sowing density.

INTRODUCTION

In recent decades, an increase in temperature has been recorded on Earth, which threatens agricultural production, and therefore the food supply. The threat to food security is compounded by the twin challenges of population growth and decreasing rainfall. Projections based on statistical analyses for cereals indicate potential yield declines ranging from 3.1% to 7.4% for every 1 °C increase in temperature, highlighting the urgent need for breeders to develop innovative crop varieties specifically adapted to thrive in warmer environments (Zhao et al., 2017). The expected increase in the frequency and severity of extreme weather events, especially drought, extends across different regions, including areas in the Mediterranean, South-East Europe, Central Europe and even traditionally wet zones such as North-West France and South-East England (European Environment Agency, 2017). This disturbing trend poses a significant threat to agricultural productivity. Thus, the important task involves not only addressing the immediate risks, but also introducing into production new crops with enhanced adaptability to challenging climates.

Addressing this challenge, our study explores the potential of quinoa (*Chenopodium quinoa* Willd.) as a resilient and adaptable crop in the face of changing environmental conditions. Quinoa is a pseudocereal distinguished by its significant content of inherent antioxidants, flavonoids, and anthocyanins (Ain et al., 2023). These compounds have potential protective mechanisms in plants against both biotic and abiotic stressors (Razzaghi et al., 2020). Numerous investigations, including those by Präger et al. (2018) and Afzal et al. (2022) consistently confirm its pronounced ability to thrive under varying temperature, altitude, water and nutrient availability. Consequently, quinoa has emerged as a crop that can potentially be cultivated in regions beyond its original center of origin, the Andean Altiplano (Bazile et al., 2016; Matías et al., 2021), especially as an alternative for marginal agricultural land (Jacobsen, 2015). Also, its high resistance to various abiotic stresses and adaptability to various agroecological and soil conditions make quinoa a suitable crop for sustainable cultivation (Ain et al., 2023). In addition to its adaptability, quinoa has rich nutritional profile, including high protein content and all essential amino acids. Notably, quinoa seeds generally surpass the total protein content of common grains, although they fall below the levels found in oilseeds and legumes (Elsohaimy et al., 2015). This nutritional richness, together with its gluten-free nature, highlights the importance of quinoa in improving the nutritional composition of gluten-free food products (Craine and Murphy, 2020). Recognizing the significance of quinoa, there has been a steady rise in production and consumption over the past decades, with a noticeable exponential increase by 2013, designated as the International Year of Quinoa (Bazile et al., 2016).

Beyond the grains, quinoa leaves, which exhibit a taste reminiscent of botanical relatives such as Swiss chard and spinach, are also incorporated into the diet. The utilization of both quinoa seeds and leaves in traditional and innovative food products and beverages underscores their versatility (Angeli et al., 2020). Despite of that, quinoa breeding programs have predominantly prioritized the development of varieties with high grain yields (Bazile et al., 2016), with minimal focus on the non-grain-producing elements of the plant, despite the undeniable versatility of quinoa as a multipurpose crop (Shah et al., 2020).

Quinoa shows significant morphological, agronomic and physiological variability, which makes it highly adaptable to different environments (Thiam et al., 2021). Despite its potential, the successful cultivation of quinoa in a specific region requires a comprehensive understanding of environmental factors and cultivation practices. Several studies (De Bock et al., 2021; Dumschott et al., 2022; Dostalíková et al., 2023) across various trials has revealed that environmental factors such as season, localities, water regimes, and sowing density rates exert a significant impact on the morphological characteristics, grain yield, and nutritional quality of quinoa. Therefore, a comprehensive examination of these environmental factors and cultivation practices becomes imperative to ensure successful adaptation and sustainable production of quinoa in a particular region.

Our previous research indicated good nutritional quality of quinoa grains of ‘Puno’ and ‘Titicaca’ grown in Serbian agro-climatic conditions (Czekus et al., 2019; Stikić et al., 2020). This study focuses on investigation of the impact of genotype, growing season, and sowing density, along with their interactions, on the agro-morphological traits of quinoa grown in local agro-climatic conditions in order to provide recommendations for successful quinoa cultivation in this European region, where quinoa present a newly introduced crop.

MATERIALS AND METHODS

Plant material and experimental design

The experiment was established across three growing seasons (2016 – S1, 2017 – S2, and 2019 – S3) and at an experimental field near Subotica (northern part of Serbia, 46°7' N 19°4' E) under rain-fed conditions. Two quinoa (*Chenopodium quinoa* Willd.) cultivars, Puno and Titicaca, sourced from the Quinoa Quality ApS (Regstrup, Denmark), were utilized. The experiment was performed according to split-split plot system with four replicates. The size of the main plot was 12 m². Two sowing densities were implemented: 5 cm between plants in a row (sowing density 1 - SD1) and 10 cm between plants in a row (sowing density 2 - SD2), with distance between rows of 50 cm. The seeds were sown at a depth of 2 cm. Sowing was done in the first half of April, with re-sowing in May during the 2019 growing season due to unfavorable weather conditions. Harvesting was done in the second half of August. Morphological parameters plant height (cm), number of side branches, and number of flower branches were assessed during flowering stage (BBCH 69), and yield parameters biomass per plant and grain yield per plant (g) were evaluated during senescence-full maturity stage (BBCH 99) in accordance with Sosa-Zuniga et al. (2017). These analyses were conducted with a standardized sample size of 10 plants per replicate, ensuring statistical robustness and reliability in the obtained data.

The experiment was conducted on Chernozem soil, characterized by moderate N and humus content, abundant P and K, and a slightly alkaline pH. Agrochemical analyses were performed before and after each growing season, and detailed results are shown in Table 1.

Table 1. Agrochemical analysis of the Chernozem soil conducted before sowing and after harvesting of quinoa within each season of the experiment.

Season	Time of analysis	pH (H_2O)	pH (KCl)	$CaCO_3$	Humus	N	P_2O_5	K_2O
				%	%	%	mg 100 g^{-1}	mg 100 g^{-1}
Season 1	Before sowing	8.20	7.66	12.06	3.19	0.19	34.68	25.42
	After harvesting	8.15	7.58	12.04	3.01	0.18	33.27	22.37
Season 2	Before sowing	8.28	7.77	15.66	2.88	0.18	30.05	20.98
	After harvesting	8.33	7.82	14.34	2.69	0.16	26.45	18.59
Season 3	Before sowing	8.32	7.97	17.32	2.57	0.15	20.42	18.72
	After harvesting	8.27	7.81	16.80	2.55	0.15	20.54	17.21

Meteorological conditions

The climatic conditions in the Subotica region exhibit a continental climate, featuring an average daily air temperature of 11.0 °C and an annual rainfall of approximately 536 mm. Meteorological data for temperature were obtained from the Republic Hydrometeorological Institute of Serbia, more precisely from the hydrometeorological station Palić, located 13 km from the experimental field (RHMZ, 2019), while data on the amount of precipitation were obtained from a rain gauge installed on the experimental field (Figure 1).

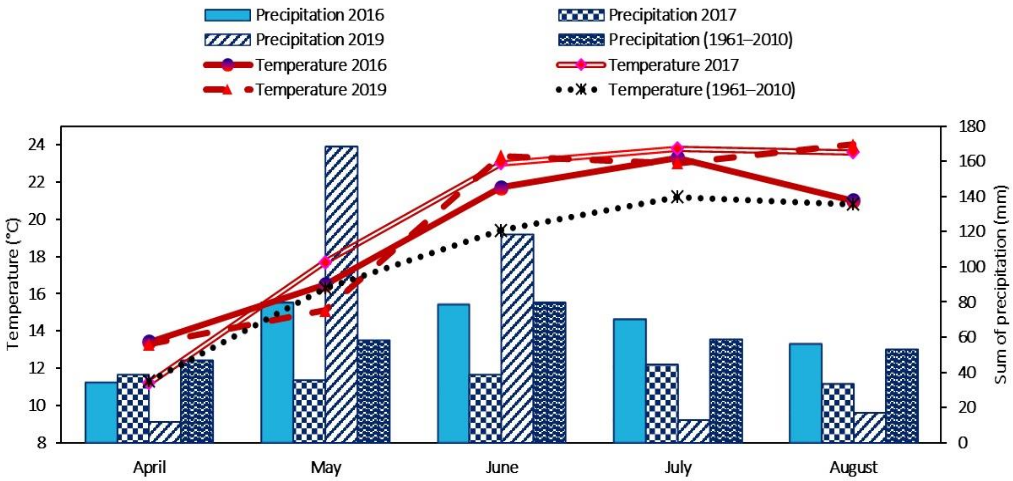


Figure 1. Mean monthly air temperatures and sum of precipitation at the experimental location during the experiment in comparison to the multi-year average.

Across analyzed growing seasons, the mean daily air temperatures were consistent, but significantly higher in relation to the multi-year average of 17.8 °C. However, significant differences between vegetation seasons were observed in terms of precipitation. In 2016 and 2019, total rainfall reached 317 and 328 mm, surpassing the multi-year average by 7.5% and 11.2%, while 2017 experienced a lower-than-average precipitation of 188 mm, representing a 36.2% deficit. Notably, the monthly distribution of precipitation exhibited marked differences among the growing seasons. In 2016 and 2017, precipitation was evenly distributed across the months, ranging from 34 to 79 mm in 2016 and 33 to 44 mm in 2017. In contrast, 2019 witnessed significant monthly fluctuations, with totals ranging from 12 mm in April to a substantial 168 mm in May. The uneven distribution in 2019 is highlighted by the fact that 51% of the total precipitation occurred in just 2 mo (May and June). During July, a crucial phase spanning quinoa's flowering to grain-filling phenophases, the water conditions were more favorable in 2016 and 2017, receiving 54.5 and 44 mm of rainfall, respectively. In contrast, 2019 experienced only 13 mm of rainfall during the third decade of the month (Figure 1). The most favorable year, both in terms of quantity and distribution of precipitation, was 2016, followed by 2017, while 2019 emerged as the least favorable.

Statistical analysis

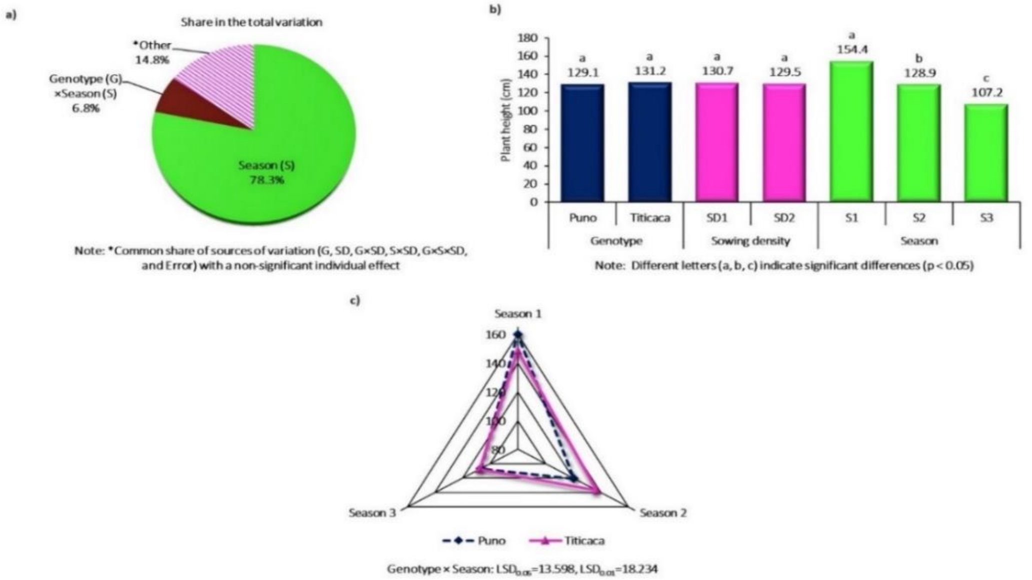
The impact of analyzed factors (genotype, season, and sowing density, as well as their interactions) was assessed through factorial ANOVA model, treating all factors as fixed effects, using the program SPSS Statistics, Trial Version 22.0 (2011) (IBM, Armonk, New York, USA). Post hoc analyses were conducted using the LSD test to examine differences between factor variants, as it is suitable for comparing means when the number of comparisons is relatively small. Significance levels were set at 5% and 1% to determine the statistical significance of observed variations. The principal component analysis (PCA) was applied to express the relationships among morphological traits, biomass and grain yield of quinoa. The data set, structured as a correlation matrix, was subjected to scaling for uniformity before PCA implementation. This scaling ensured that all variables contributed equally to the analysis. The results of the PCA analysis are represented by a biplot, which shows the distribution of traits and genotypes in a space of reduced dimensions, defined by the first two main components (PCA1 and PCA2). The PCA was performed in R version 4.3.2 (R Project for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org/).

RESULTS AND DISCUSSION

Genotype, season, and sowing density effects on agro-morphological traits

One of the significant characteristics of quinoa is its adaptability to a wide range of agro-ecological conditions (Präger et al., 2018; Afzal et al., 2022). However, quinoa was not initially suited to the environmental conditions of northern latitudes or large-scale production, posing distinct challenges for breeders and farmers aiming to introduce it to new growing regions (Hinojosa et al., 2018). Therefore, understanding the impact of genotype, season, and sowing density on the agro-morphological properties of quinoa is crucial for optimizing cultivation practices, and enhancing the overall productivity of quinoa across diverse agricultural environments. The highest share in the variation of quinoa plant height was the season factor (78.3%), followed by the interaction of genotype and season (6.8%), while other factors (genotype and sowing density) and their interactions did not significantly contribute to the phenotypic expression of plant height (Figure 2a, Table 2). Wang et al. (2020) also reported nonsignificant effect of plant density on quinoa height.

Seasonal variations in our research are mostly described by differences in distribution and sum of precipitation. The highest value of plant height was recorded in the Season 1 (S1), 154.4 cm, described as the most favorable in terms of the amount and distribution of precipitation. In contrast, the Season 3 (S3), marked by a dry period during the crucial stages of plant growth, resulted in the lowest plant height at 107.2 cm (Figure 2b). These findings align with observations by Nguyen et al. (2020), emphasizing the positive correlation between available water and vegetative growth, including plant height. The interaction of genotype and season revealed a shift in the rank of genotypes across seasons. For instance, the 'Puno' genotype displayed a higher plant height in Season 1, while the 'Titicaca' genotype surpassed in Season 2. However, nonsignificant differences among genotypes in terms of plant height were found in Season 3. Unfavorable environmental conditions in this season impacted both genotypes, leading to lower stem height values (Figure 2c). Similar to our results, Dumschott et al. (2022) emphasized the impact of water regimes on plant height.



Note: *Common share of sources of variation (G, SD, G×SD, S×SD, G×S×SD, and Error) with a non-significant individual effect

Note: Different letters (a, b, c) indicate significant differences ($p < 0.05$)

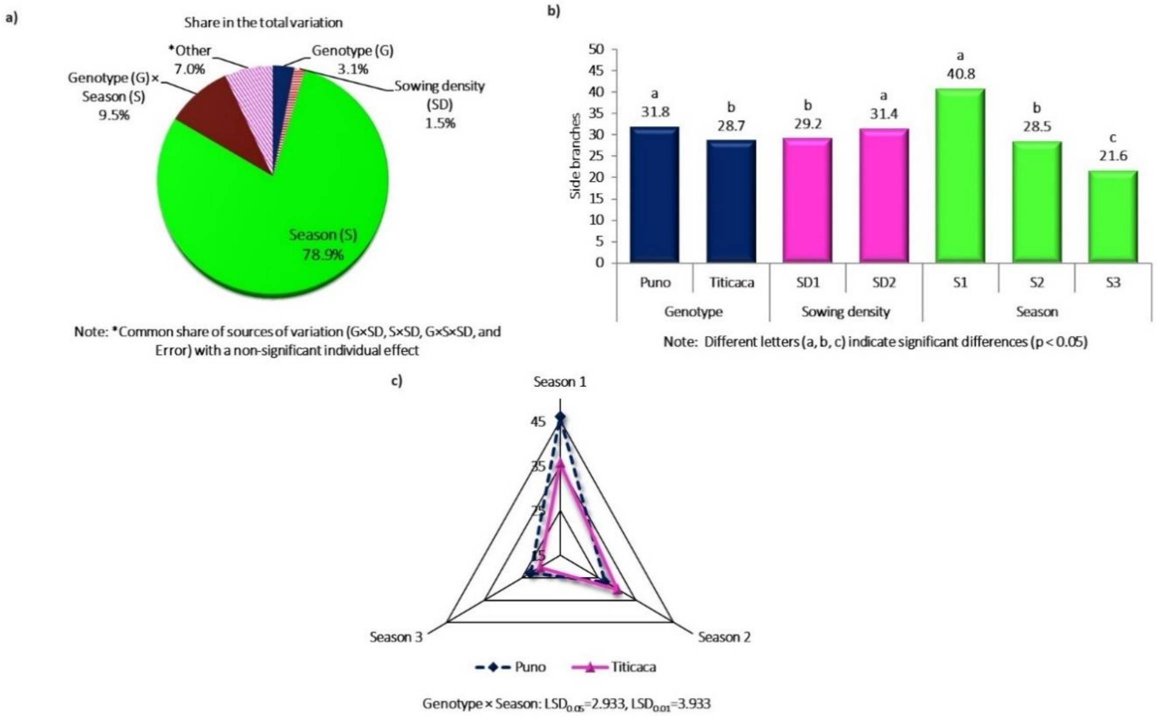
Genotype × Season: $LSD_{0.05}=13.598$, $LSD_{0.01}=18.234$

Figure 2. Analysis of the main factors and their interaction contributing to plant height variation in quinoa during the experiment: Share of the analyzed factors and their interaction in the total trait variation (a), mean values of plant height in two genotypes ('Puno' and 'Titicaca') grown at two sowing densities (SD) during three seasons (b), and mean values of plant height through the interaction of genotype and season (c).

Table 2. ANOVA for plant height, number of side branches, number of flower branches, biomass per plant, and grain yield per plant in quinoa cultivars ('Puno' and 'Titicaca') sown at two sowing densities over three seasons. df: Degrees of freedom; MS: mean squares; F: F-statistic (F-value); Sig.: significance level (p-value); Sd: standard deviation (n = 48); CV: coefficient of variation (n = 48); ^{ns}nonsignificant; $^{**}p < 0.01$; $^{*}p < 0.05$.

	Genotype (G)	Sowing density (SD)	Season (S)	G × SD	G × S	SD × S	G × SD × S	Error	Total
df	1	1	2	1	2	2	2	36	47
Plant height, cm									
MS	51.05	16.92	8933.55	5.67	779.16	35.42	1.15	89.91	
F	0.568^{ns}	0.188^{ns}	99.358**	0.063^{ns}	8.666	0.395	0.013		
Sig.	0.456	0.667	0.000	0.803	0.001**	0.676^{ns}	0.987^{ns}		
Mean: 130.15; Sd: 22.03; CV: 16.93%									
Number of side branches									
MS	118.75	59.18	1512.57	36.92	182.78	29.20	10.83	4.18	
F	28.385	14.147	361.541	8.826	43.689	6.980	2.588		
Sig.	0.000**	0.001**	0.000**	0.054^{ns}	0.000**	0.051^{ns}	0.089^{ns}		
Mean: 30.26; Sd: 9.03; CV: 29.84%									
Number of flower branches									
MS	45.29	54.68	83.19	4.79	8.79	6.18	8.37	3.43	
F	13.214	15.950	24.269	1.399	2.565	1.802	2.443		
Sig.	0.001**	0.000**	0.000**	0.245^{ns}	0.091^{ns}	0.180^{ns}	0.101^{ns}		
Mean: 15.68; Sd: 3.06; CV: 19.51%									
Biomass per plant, g									
MS	1040.95	228.68	996.81	0.349	1172.3	499.58	116.06	39.51	
F	26.348	5.788	25.23	0.009	29.673	12.645	2.938		
Sig.	0.000**	0.021*	0.000**	0.926^{ns}	0.000**	0.000**	0.066^{ns}		
Mean: 51.78; Sd: 13.26; CV: 25.61%									
Grain yield per plant, g									
MS	1.460	56.05	1264.69	0.007	18.81	28.408	1.488	3.757	
F	0.388	14.91	336.611	0.002	5.006	7.561	0.396		
Sig.	0.537^{ns}	0.000**	0.000**	0.965	0.057	0.051	0.676		
Mean: 21.32; Sd: 7.74; CV: 36.30%									

The number of side branches and flower branches are indicative of quinoa's reproductive potential. These traits are crucial determinants of the crop's ability to produce seeds, influencing overall grain yield (Dao et al., 2020). The predominant factor influencing the number of side branches is the growing season, accounting for 78.9% of the variation, followed by the interaction of Genotype × Season (9.5%), genotype (3.5%), and sowing density (1.5%), (Figure 3a, Table 2). The average value of the number of side branches in Season 1 was 40.8 and significantly differed from the values obtained in Season 2 (28.5) and Season 3 (21.6). Also, 'Puno' exhibited a higher number of side branches compared to 'Titicaca' (31.8 and 28.7, respectively) (Figure 3b). Consistent with prior research by Shams (2018), the number of side branches in quinoa varies depending on the genotype and season. In Season 1, both quinoa cultivars experienced favorable conditions, allowing them to express their genetic potential. This resulted in more pronounced differences between genotypes, highlighting the significance of the Genotype × Season interaction (Table 2). Specifically, in Season 1, 'Puno' exhibited a significantly higher value compared to 'Titicaca' (Figure 3c).



Note: *Common share of sources of variation (G×SD, S×SD, G×S×SD, and Error) with a non-significant individual effect

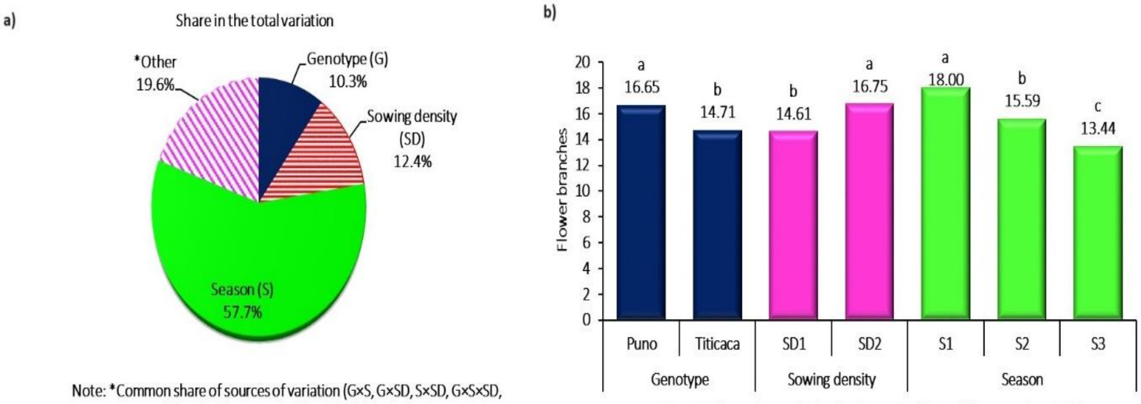
Note: Different letters (a, b, c) indicate significant differences ($p < 0.05$)

Genotype × Season: $LSD_{0.05}=2.933$, $LSD_{0.01}=3.933$

Figure 3. Analysis of the main factors and their interaction contributing to the number of side branches variation in quinoa during the experiment: Share of the analyzed factors and their interaction in the total trait variation (a), mean values of the number of side branches in two genotypes ('Puno' and 'Titicaca') grown at two sowing densities during three seasons (b), and mean values of the number of side branches through the interaction of genotype and season (c).

Additionally, a sowing density with a spacing of 10 cm (SD2) contributed to an increase in the number of side branches (Figure 3b). Dao et al. (2020) found, for 'Titicaca', that a lower sowing density resulted in a better development of the branching system compared to a higher sowing density. This aligns with the adaptive capability of quinoa to compensate for greater spacing between plants by modifying its agro-morphological branch structure (Jacobsen, 2015).

The number of flower branches is significantly influenced by the main factors ($p < 0.01$), with the dominant factor being the season, which accounts for 57.7% of the total trait variation (Table 2, Figure 4a). The genotype factor contributes to the variation with 10.3% (Figure 4a), revealing a significantly higher average value for 'Puno' (16.55) compared to 'Titicaca' (14.71) (Figure 4b). Additionally, lower sowing density (SD2) led to a greater number of flower branches compared to the higher sowing density (SD1) (16.75 and 14.64, respectively) (Figure 4b). Spehar and Santos (2005) reported that quinoa plants at low density had a higher number of lateral branches and flowers, similar to the results obtained in this study. The highest values of flower branches were achieved in the first season (18.0), and the lowest in the third (13.4) (Figure 4b). The interaction of the analyzed factors did not significantly ($p > 0.05$) contribute to the trait variation. The lack of significance of Season × Sowing density can be explained by the results obtained by Nguyen et al. (2018), where the number of flower branches is not affected by plant density in conditions without stress. Also, the analyzed genotypes were consistent in the values achieved across the analyzed seasons and sowing densities, where there was no change in their ranking.



Note: *Common share of sources of variation (G×S, G×SD, S×SD, G×S×SD, and Error) with a non-significant individual effect

Note: Different letters (a, b, c) indicate significant differences ($p < 0.05$)

Figure 4. Analysis of the main factors and their interaction contributing to the number of flower branches variation in quinoa during the experiment: Share of the analyzed factors and their interaction in the total trait variation (a), mean values of the number of flower branches in two genotypes ('Puno' and 'Titicaca') grown at two sowing densities during three seasons (b).

The variation of biomass per plant was significantly ($p < 0.01$) influenced by the main factors as well as the Genotype × Season and Sowing density × Season interactions (Table 2, Figure 5a). Significantly higher biomass per plant was found in 'Titicaca' (56.44 g) compared to 'Puno' (47.13 g) at the experimental level. Also, in Season 2, a significantly higher value of biomass yield (60.86 g) was recorded compared to the values achieved in Season 1 (46.53 g) and Season 3 (47.94 g) (Figure 5b). Thiam et al. (2021) obtained a large variation in quinoa biomass across trials conducted at five different localities, reflecting diverse agro-ecological environments. Significant differences between genotypes and seasons are the result of the very high biomass yield achieved by 'Titicaca' in the Season 2. A change in the ranking of genotypes by season was observed, with 'Titicaca' achieving a significantly higher value in Season 3, while in Seasons 1 and 2, a higher value was recorded for 'Puno'. This led to the Genotype × Season interaction having the largest share in the total biomass variation. Additionally, 'Titicaca' exhibited the greatest variation in biomass per plant by season, while 'Puno' remained uniform in this regard (Figure 5c). Similar findings were reported by Dumschott et al. (2022), who noted that the quinoa genotype with one of the highest leaf biomasses has also experienced the greatest reduction in shoot biomass in response to reduced water supply. In our experiment, the interaction of Sowing density × Season was highly significant ($p < 0.01$), due to changes in the ranking. In Seasons 1 and 3, the highest biomass per plant values were found in the lower sowing density (SD2), while in Season 2, the higher sowing density (SD1) contributed to a higher biomass value in the analyzed quinoa genotypes (Figure 5d).

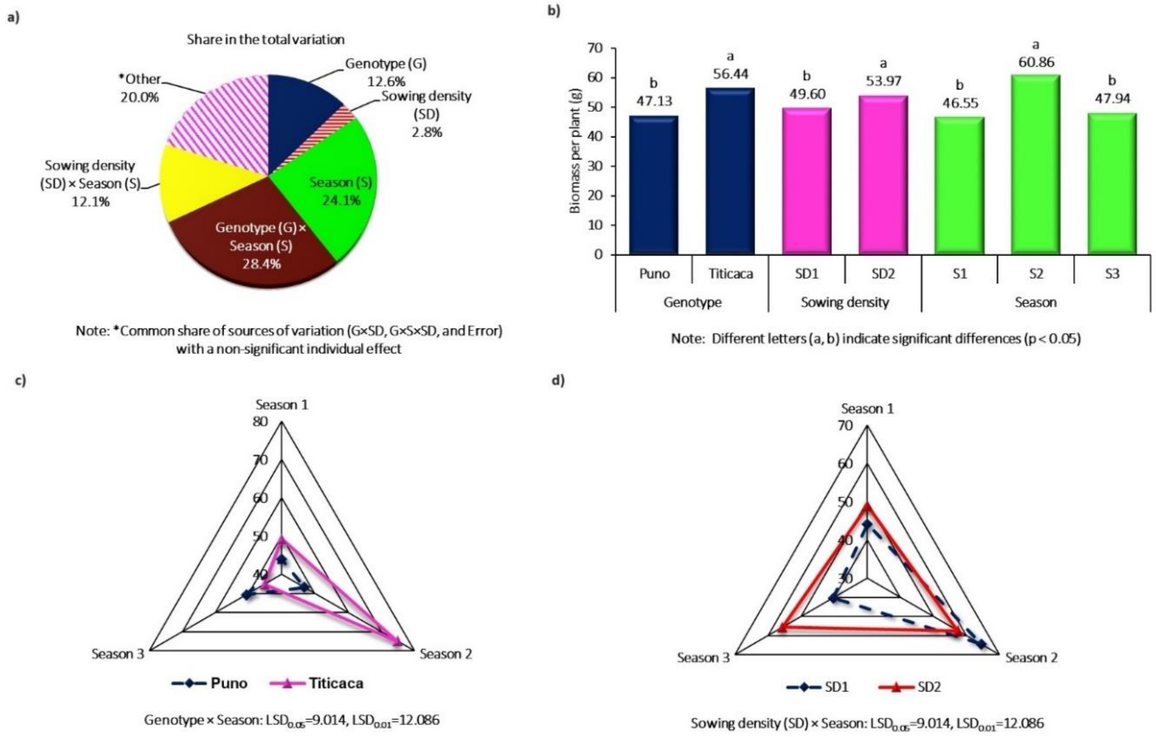
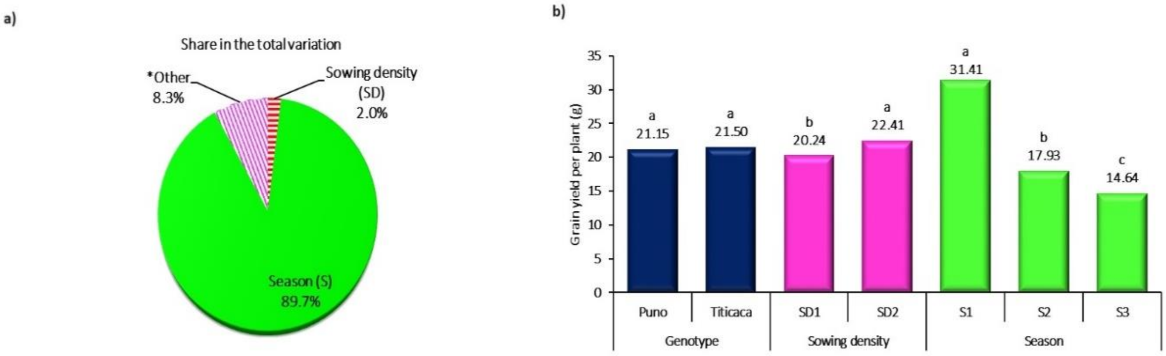


Figure 5. Analysis of the main factors and their interaction contributing to biomass per plant variation in quinoa during the experiment: Share of the analyzed factors and their interaction in the total trait variation (a), mean values of biomass per plant in two genotypes ('Puno' and 'Titicaca') grown at two sowing densities during three seasons (b), mean values of biomass per plant through the interaction of genotype and season (c), and mean values of biomass per plant through the interaction of sowing density and season (d).

The ultimate goal of quinoa cultivation is often focused on achieving high grain yields (Shah et al., 2020). Therefore, understanding the influence of factors that contribute to variations in grain yield, such as season and seeding density, enables the development of strategies to increase productivity. The grain yield per plant is predominantly influenced by the vegetation season, accounting for 89.7% of the variation, with sowing density contributing 12.4%. Conversely, the genotype and the interaction of analyzed factors did not show significant contributions to grain yield variation ($p > 0.05$) (Table 2, Figure 6a). During Season 1, the highest grain yield per plant was achieved (31.41 g), significantly differing from the values observed in Season 2 (17.93 g) and Season 3 (14.64 g) (Figure 6b). The lowest quinoa grain yield in Season 3 can be attributed to minimal precipitation in July and August, critical periods encompassing flowering, grain filling, and ripening. Previous studies by Gámez et al. (2019) and Hinojosa et al. (2018) underscore the sensitivity of quinoa's flowering and grain filling stages to drought, designating them as crucial phases for yield determination. Dumschott et al. (2022) reported a reduction in quinoa grain yield under reduced irrigation during flowering and grain filling. Similar findings were reported by Maliro et al. (2017), where they found that irrigated conditions resulted in higher quinoa grain yields compared to rain-fed conditions. An increase in sowing density resulted in a decrease in grain yield per plant, with the higher density (SD1, 40 plants m^{-2}) and a grain yield of 20.24 g, compared to the lower density (SD2, 20 plants m^{-2}) with a yield of 22.41 g (Figure 6b). Some studies suggest that low density may also be detrimental. In the northern region of Vietnam, Nguyen et al. (2018) reported an increase in quinoa yield as density increased. Similarly, in Iran, studies assessing the influence of sowing density on quinoa grain yield revealed that the highest yield was observed at a density of higher (Ahmadi et al., 2019). According to Dao et al. (2020), the optimal density for achieving high yield in 'Titicaca' is 200 000 plants ha^{-1} (20 plants m^{-2}). Studies indicate that sowing density ranging from 10 to 20 plants m^{-2} could enhance quinoa yield under nonirrigated conditions (Isobe et al., 2015; Parwada et al., 2020). The yields obtained in this research align with those observed in the European climate (Präger et al., 2018). However, it is worth noting that with the application of irrigation and fertilization, yields could probably be significantly higher, potentially making quinoa production even more economically viable. A previous cost-benefit analysis indicated that cultivating quinoa 'Puno' and 'Titicaca' in the agro-ecological conditions of Serbia would be highly successful (Savić et al., 2021). This suggests the potential for quinoa cultivation to be not only environmentally sustainable but also economically lucrative when optimal practices, including irrigation and fertilization, are implemented.



Note: *Common share of sources of variation (Genotype (G), G×S, G×SD, S×SD, G×S×SD, and Error) with a non-significant individual effect

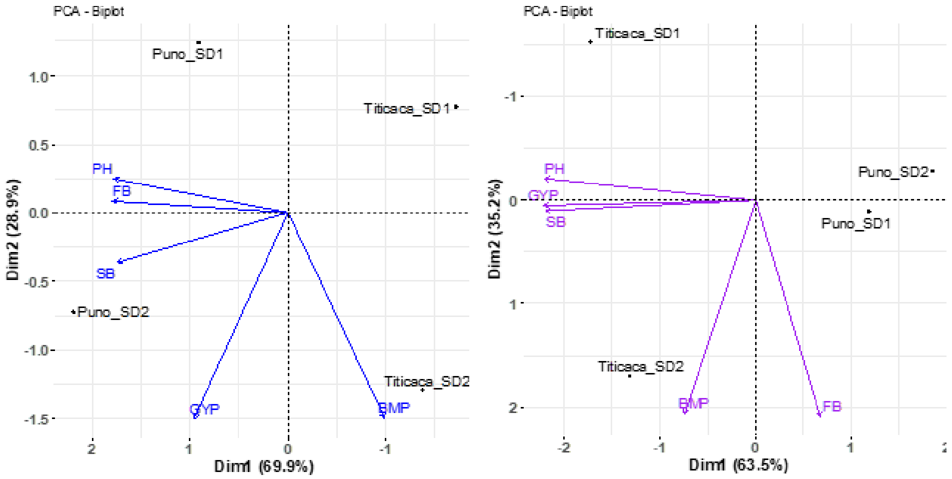
Note: Different letters (a, b, c) indicate significant differences ($p < 0.05$)

Figure 6. Analysis of the main factors and their interaction contributing to grain yield per plant variation in quinoa during the experiment: Share of the analyzed factors and their interaction in the total trait variation (a), mean values of grain yield per plant in two genotypes ('Puno' and 'Titicaca') grown at two sowing densities during three seasons (b).

Interrelationship between the agro-morphological traits

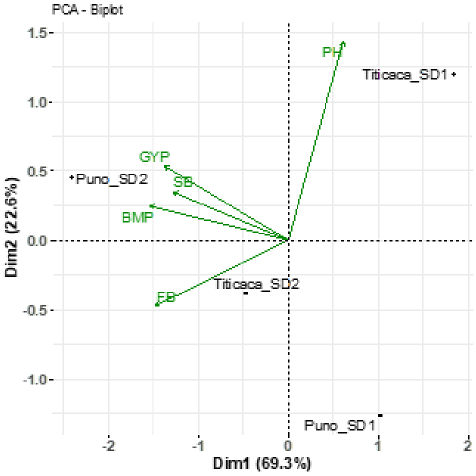
In order to analyze the interrelationship between the agro-morphological traits, a principal component analysis (PCA) was conducted (Figure 7). This approach has been utilized by numerous researchers to elucidate the interrelationships among agro-morphological parameters of quinoa (De Bock et al., 2021; Thiam et al., 2021). Due to the predominant influence of the season on the variation of the analyzed quinoa traits, separate PCA analyses were performed for each season. Within each analyzed season, two PCA components were extracted from the input data, both possessing eigenvalues greater than 1. In Season 1 (Figure 7a), the primary contributors to PCA 1 were the vectors representing plant height, number of flower branches, and number of side branches. These vectors exhibited a notable positive correlation, forming a sharp angle with each other. Also, Shah et al. (2020) established a positive correlation between grain yield and the number of side branches. Genotype 'Puno' at lower sowing density (SD2) is positioned along the vector representing the mentioned traits. The vector representing biomass per plant is segregated into a distinct quadrant of the biplot, characterized by a positive value along the PCA1 axis and a significantly negative value along the PCA2 axis. Genotype 'Titicaca', positioned close to this vector, demonstrated the highest biomass value at lower sowing density (SD2). This positioning highlights the significance of sowing density in influencing biomass production. During Season 2 (Figure 7b), positive correlations were identified among plant height, grain yield per plant, and the number of side branches. This is consistent with findings reported by Dostalíková et al. (2023) and Dumschott et al. (2022), who established a positive correlation between plant height and quinoa grain yield. In this season, 'Titicaca' at a higher sowing density (SD1) is positioned closest to the vectors representing the previously mentioned traits. Furthermore, when considering biomass per plant, 'Titicaca' at a lower sowing density (SD2) closely aligns with the corresponding vector. This indicates that 'Titicaca' performs well in both grain yield and biomass production under varying sowing densities. In contrast, 'Puno', at both sowing densities, shows low values along the PCA2 axis and high positive values along the PCA1 axis. This positioning places it far from the vectors associated with the analyzed traits, indicating a different expression of the traits compared to 'Titicaca' in season 2. In Season

3 (Figure 7c), characterized as the most unfavorable, the vectors of most of the analyzed traits overlapped at a sharp angle. This suggests that environmental conditions during this season prevented the genotypes from reaching their full genetic potential, resulting in a reduction in all traits. Vectors indicating biomass per plant, the number of side branches, and grain yield per plant are positioned in the first quadrant of the biplot, indicating positive correlations between these traits. This observed pattern aligns with the findings presented by Maliro et al. (2017), who observed that quinoa varieties exhibiting the highest grain yield also produced a high yield of biomass. Positive correlations between the number of branches, biological yield, and grain yield were also established by Asif et al. (2022). At a lower sowing density (SD2), 'Puno' is positioned in close proximity to the vector representing a majority of the traits (Figure 7c). This positioning suggests that the 'Puno' is more suitable for growing in less favorable environmental conditions, especially at a lower sowing density.



a) Season 1

b) Season 2



c) Season 3

Figure 7. Principal component analysis (PCA) of agro-morphological traits in two quinoa genotypes ('Puno' and 'Titicaca') at two sowing densities (SD1 and SD2), cultivated across three growing seasons: Season 1 (a), Season 2 (b), and Season 3 (c). PH: Plant height; SB: number of side branches; FB: number of flower branches; BMP: biomass per plant; GYP: grain yield per plant.

CONCLUSIONS

The production of quinoa in Serbian agro-climatic conditions is primarily influenced by environmental factors, particularly the amount of precipitation and seasonal variations. The study suggests that a lower sowing density (10 cm between plants) may be more favorable for achieving high values across all analyzed traits in conditions of a moderately continental climate.

The significant interaction between genotype and season in variations of plant height, number of side branches, and biomass, as well as the significance of the interaction between season and sowing density in the variation of biomass indicated that genotypes are ranked differently under different environmental conditions. The PCA analysis identifies 'Puno' as more adaptable to less favorable environmental conditions, especially at lower sowing densities. In contrast, 'Titicaca' demonstrates high biomass production, particularly in Season 2, characterized by a low amount of precipitation, but uniformly distributed across months.

Author contribution

Conceptualization: S.S. Methodology: B.C., I.R. Software: M.M.S. Validation: S.S., V.Z., Z.J. Formal analysis: B.C., M.M. Investigation: B.C., I.R. Resources: D.C. Data curation: M.M.S., M.M. Writing-original draft: B.C., M.M.S. Writing-review & editing: Z.J., V.Z., S.S. Visualization: M.M.S. Supervision: Z.J., S.S. Project administration: D.C. Funding acquisition: S.S. All co-authors reviewed the final version and approved the manuscript before submission.

Acknowledgements

This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, grant numbers: 451-03-66/2024-03/200054, 451-03-65/2024-03/200116, 451-03-66/2024-03/200216 and 451-03-66/2024-03/200010. Thanks Sven-Erik Jacobsen, PhD, for the donation of quinoa seeds.

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