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QUINOA (*CHENOPODIUM QUINOA* WILLD.) CLIMATE RESILIENCE EVALUATION UNDER ARID AND SALINE ENVIRONMENTS

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SUMMARY

This study aimed to evaluate six quinoa (*Chenopodium quinoa* Willd.) genotypes under two contrasting agro-ecological conditions in Uzbekistan: Tashkent (favorable for crop production) and Chimbay (a saline agroecosystem). Assessments of the agronomic performance of quinoa genotypes ensued during the 2024–2025 growing seasons through vegetative growth and seed traits and grain yield to determine genotypes' adaptability and environmental response. Genotypes significantly varied in grain yield across the locations, and genotypes New22 and New21 showed the highest productivity in Tashkent and Chimbay, respectively. The Check-1 genotype maintained a moderate yield and stable seed weight across both sites, confirming its reliability as a control. Seed yield per plant and 1000-seed weight revealed genotype-specific reproductive potential, with New42 and New21 outperforming the rest. Notably, New21 produced a higher grain yield in Chimbay than in Tashkent, with 2836.3 kg/ha and 2316.7 kg/ha, respectively, exhibiting salt-tolerant characteristics typical of a halophyte. However, New42 had the maximum yields in Tashkent (3488.9 kg/ha) and in Chimbay (2941.2 kg/ha). Check1 consistently exhibited the tallest stature and highest biomass, whereas New21 demonstrated considerable panicle development and adaptability. Genotype-by-environment interactions identified the genotypes New21 and New42 as promising candidates for cultivation under saline-prone and marginal environments. This study contributes to the potential of quinoa as a climate-resilient crop for sustainable agriculture in Central Asia.

Keywords: Quinoa (*C. quinoa* Willd.), genotypes, arid condition, soil salinity, marginal environment, grain yield

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Key findings: The study highlighted the valuable agronomic and compositional data through genotype-by-environment interactions, supporting targeted breeding strategies for climate-resilient quinoa (*C. quinoa* Willd.) cultivars in harsh environments of Uzbekistan. Genotypes New21 and New42 demonstrated considerable adaptability and high yield under arid and saline conditions, recognizing them to be promising candidates for cultivation in marginal environments like the Aral Sea basin.

INTRODUCTION

With mounting global challenges, such as climate change, soil degradation, and food insecurity, the search for resilient and nutritionally rich crops has intensified. Among these crops, quinoa (*Chenopodium quinoa* Willd.) has emerged as a strategic crop with exceptional agronomic and nutritional values (Toderich *et al*., 2020). Quinoa is native to the Andean region of South America, which has reached cultivation for more than 5000 years, being renowned for its adaptability to diverse agroecological conditions, including saline soils, drought-prone areas, and high altitudes (Adetunji *et al*., 2022). Its exceptional protein quality, gluten-free nature, and rich micronutrient profile have brought recognition to quinoa as a superfood in both traditional and modern food systems (Graziano *et al*., 2022).

Quinoa production beyond its native range has gained attention over the past two decades, being administered and driven by international research collaboration, policy incentives, and growing consumer demand. In particular, regions vulnerable to climate stress, such as Central Asia, have shown an increasing interest in quinoa production as a climate-resilient crop that can diversify local farming systems with improved nutritional values. The physiological traits of quinoa are particularly suitable for marginal environments (Shitikova *et al*., 2022). Its deep root system and efficient water-use mechanisms allow it to perform well under water-deficit conditions, proving it an attractive crop for arid and semi-arid regions (Oustani *et al*., 2023). Moreover, quinoa's unique genetic diversity, encompassing thousands of landraces and breeding lines, offers greater opportunities for selecting cultivars tailored to specific agroclimatic zones (Afzal *et al*., 2022). Recent advances in genomics and breeding have accelerated the development of high-yielding, disease-resistant, and regionally adapted quinoa cultivars.

In Central Asia, particularly in Uzbekistan and neighboring countries, quinoa has attracted greater attention as part of broader efforts to enhance agricultural sustainability and climate adaptation (Karimov *et al*., 2025). The region is facing considerable challenges related to soil salinization, water scarcity, and declining productivity of traditional crops such as fiber and cereal crops (Nurbekov *et al*., 2025). Pilot studies have demonstrated the potential of quinoa to grow under saline and low-input conditions, with promising yields and acceptable grain quality under the environmental conditions of Uzbekistan (Khaitov *et al*., 2020). Previous research findings have spurred interest in scaling up quinoa production through targeted research, farmers' training, and institutional support (Taaime *et al*., 2024).

Despite its climate resilience, quinoa cultivation faces several challenges in new regions, including limited access to well-adapted and promising germplasms, lack of farmer awareness and technical knowledge, inadequate postharvest infrastructure, and market uncertainties (HlásnáCepková *et al*., 2022). Agronomic practices, such as sowing time, irrigation regimes, fertilization, and pest management, first require optimization for these existing conditions (Anuradha *et al*., 2023). Furthermore, quinoa's sensitivity to water scarcity and saline agroecosystems necessitates careful selection of cultivars and production technologies (Sultanova *et al*., 2021). Addressing these constraints requires a multidisciplinary approach involving agronomists, breeders, extension agents, and policymakers.

This study aimed to present a comprehensive framework for managing quinoa production in similar agroecological zones in Uzbekistan. This study focused on local trials and agronomic innovations to identify best practices and strategic entry points. The objectives of this study were to a) assess the suitability of quinoa under varying climatic and soil conditions and b) evaluate the performance of selected quinoa genotypes for grain yield, grain quality, and stress tolerance under two different agroecosystems.

MATERIALS AND METHODS

Study site and climatic conditions

Field trials on quinoa (*C. quinoa* Willd.) took place during the growing seasons of 2024–2025 at two distinct locations, i.e., the experimental site of Tashkent State Agrarian University (41°22′N, 60°54′E; 572.2 m above sea level) and b) the Chimbay District in the Republic of Karakalpakstan (42.45°N, 59.61°E). The experimental site in the Tashkent Region has characteristics of hot, dry summers and cool and wet winters. The average annual temperature was approximately 14.1 °C, with a summer high reaching up to 35.6 °C and a winter low around -1.5 °C. The annual precipitation averages 250–300 mm, predominantly occurring in winter and spring, while summers remain largely arid. During the experimental seasons, the annual average precipitation was 213.2 and 223 mm in 2024 and 2025, respectively.

The Chimbay District lies downstream along the geochemical flow of the Amudarya River, resulting in significant salt accumulation in both soil and groundwater. The region experiences a sharp continental pattern, marked by hot summers and cold winters, with pronounced daily and seasonal temperature variations. Precipitation was low during experimental seasons, recording 54.2 mm in 2024 and 23.3 mm in 2025. Peak summer temperatures in July and August averaged between +40 °C and +45 °C, while winter temperatures ranged between –2.5 °C and –13 °C.

Soil characteristics

In the Tashkent Region, the typical sierozem soils exhibited low salinity levels, with ECe (electrical conductivity) values ranging from 1.8 dS/m at the surface to 0.9 dS/m at deeper layers (FAO methods). The soil pH remained slightly acidic to neutral (6.6–6.8), and ESP (exchangeable sodium percentage) was consistently low (0.1%), indicating minimal sodicity risk. Humus content ranged from 1.31% (topsoil) to 0.79% (60–90 cm depth), whereas total nitrogen content decreased from 0.2% to 0.11% with depth. Nitrate levels declined, from 15.6 to 9.7 mg/kg, whereas phosphorus and potassium showed moderate variability, with K_2O peaking at 216.7 mg/kg in the top layer.

The soils in the Chimbay experimental area had a meadow-alluvial silty loam classification, with a heavy loam texture in the upper 0–30 cm layer. These soils were moderately to highly saline, particularly in the upper layer. The surface ECe reached 8.6 dS/m, decreasing to 5.6 dS/m at 60–90 cm. Soil pH ranged from 6.1 to 7.0, and ESP was high (0.4%–0.5%), indicating potential sodium-induced constraints on plant growth (Table 1). Humus content ranges from 0.85% to 0.47%. Total nitrogen was notably deficient, with values between 0.01% and 0.0011%. Nitrate concentrations were highest in the surface layer (12.2 mg/kg) but declined sharply with depth.

Quinoa germplasm selection

The first quinoa experiment commenced in 2020 with an initial set of 186 quinoa genotypes obtained from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India. After two consecutive seasons of mass selection, the study proceeded with 16 quinoa genotypes during the 2022–2023 growing seasons. Finally, six promising genotypes, namely, Check1, New14, New21, New42, New170, and New141, were the options for further evaluation in crop seasons 2024–2025. These accessions

Table 1. Soil chemical analysis in Tashkent and Chimbay, Uzbekistan.

Soil depth (cm)	Soil ECe (dS/m)	Soil pH	Exchangeable Na percentage (ESP)	Total forms (%)		Exchangeable form (mg/kg)		
				Humus	N	NO_3	P_2O_5	K_2O
Tashkent								
0-15	1.8	6.8	0.1	1.31	0.2	15.6	18.1	216.7
15-30	1.2	6.7	0.1	1.25	0.12	14.4	12.5	220.6
30-60	0.9	6.7	0.1	0.84	0.11	12.1	8.5	190.8
60-90	0.9	6.6	0.1	0.79	0.11	9.7	8.2	152.8
Chimbay								
0-15	8.6b	6.1	0.4	0.85	0.01	12.2	25.16	322
15-30	7.2a	6.5	0.4	0.67	0.015	10.3	17.02	300
30-60	7.8a	7.0	0.5	0.58	0.0011	7.12	9.18	284
60-90	5.6	6.8	0.5	0.47	0.0011	5.5	14.94	256

Table 2. Weather data comprising air temperature, rainfall, and relative humidity of the study areas inTashkent and Chimbay, Uzbekistan.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (°C)												
2024 T	3.1	5.6	7.9	18.3	23.4	26	30.7	26.4	24.5	16.5	6.3	5.4
2025 T	1.5	2.5	11.1	18.5	22.3	30.5	32.6	30.7	24.2	15.8	6.5	1.6
L.T.A.	1.1	6.5	9.8	14.4	21.3	26.9	29.3	27.7	24.1	13.4	7.7	7.3
2024 Ch	-2.6	-0.3	6.3	17.8	20.2	28.9	28.2	26.8	18.1	13.6	6.8	3.5
2025 Ch	-4.7	-1.8	7.6	19.5	24.6	26.8	29.9	26.7	19.9	14.1	-	-
L.T.A.	-2.3	0.2	4.5	13.9	21.3	26.4	28.0	26.0	19.4	10.7	4.0	-1.7
Rainfall (mm)												
2024 T	26	11.2	51.3	36.7	33.6	2.1	1.2	-	-	5.5	21.9	23.7
2025 T	43.1	29.9	53.7	12.9	67.4	10.9	0.6	4.5	-	13.9	14.6	30.3
L.T.A.	28.9	39.5	39.2	28.9	19.9	8.7	2.1	2.5	2.1	15.2	23.8	21.5
2024 Ch	3.8	0.7	15.7	0.5	23.2	1.3	7.8	0.3	0.9	0	13.1	19.9
2025 Ch	1.3	6.8	3.8	2.0	1.6	6.0	0	0	0	1.5	-	-
L.T.A.	10.1	8.7	16.4	19.4	12.2	3.9	3.5	2.1	3.0	8.7	9.4	13.6

Chimbay and Tashkent (2024 to 2025 growing years and long-term data).
Source: Meteorological Station of Chimbay and Tashkent. T- Tashkent; Ch – Chimbay. L.T.A.-Long-term average.

obtained selection based on their demonstrated tolerance to salinity and drought, as well as their early maturity and high yield-related traits.

Experimental design and agronomic practices

The establishment of a quinoa field experiment was successful using a strip plot design with three replicates. Each experimental plot measured 24 m², with 1-m spacing maintained between plots in both directions to minimize the border effects. The row spacing was 60 cm apart, with the seeds sown at the depth of 1.5–2 cm. Within-row plant spacing was set to 15 cm. Sowing began in early April during both years of the study to coincide with the optimal soil and environmental conditions. At the time of planting, soil temperatures ranged from 11 °C to 13 °C, air temperatures ranged from 16 °C to 20 °C, and soil moisture was approximately 75% of the field capacity (Table 2).

Before quinoa sowing, incorporating organic manure into the soil had a rate of 5 t/ha during primary tillage operations. Estimates of the nutrient contribution of this amendment would be equivalent to $N_{110}P_{90}K_{90}$ kg/ha. All other agronomic practices, including irrigation, weeding, and pest control, proceeded in accordance with regional recommendations for quinoa crop cultivation. Phenological observations entailed recording throughout the growing season, focusing on key traits, such as seed germination rate, days to maturity, plant height (cm), panicle length (cm), total aboveground biomass, grain yield (kg/ha), and 1000-seed weight (g).

Seed biochemical analysis

The analysis of quinoa seed's protein content employed neutron activation analysis (NAA) for elemental quantification, following several steps of required preparations. For the determination of extractable compounds and crude saponin content, an exhaustive extraction took place with ethanol using a Soxhlet apparatus, with each quinoa genotype processed separately.

Statistical analysis

All collected data underwent analysis using the CropStat software, applying the analysis of variance (ANOVA) framework. Using the least significant difference (LSD) test helped assess the significance of differences among treatment means**.** Statistical significance determination was at the 5% probability level ($P \leq 0.05$), unless specified otherwise.

RESULTS

Genotypes' seed traits across sites

Six quinoa (*C. quinoa* Willd.) genotypes (Check1, New14, New21, New42, New170, and New141) succeeded in their evaluation under agroecological conditions of Tashkent and Chimbay, Uzbekistan. The traits of genotypes assessed comprised grain yield, 1000-seed weight, and seed yield per plant, providing insights into their adaptability and agronomic potential. The genotypes varied significantly with grain yield across the locations. In Tashkent, the genotype New42 exhibited the highest grain yield (3488.9 kg/ha), followed by the genotypes New21 (3267.6 kg/ha) and Check1 (3194.4 kg/ha). In contrast, the genotype New21 was the leading performer at Chimbay (2836.3 kg/ha), indicating considerable adaptability across the locations and exhibiting salt-tolerant traits typical of a halophyte. However, the lowest grain yield resulted in the genotype New14 in Tashkent (1053.7 kg/ha), suggesting poor environmental compatibility.

For 1000-seed weight, the quinoa genotypes showed moderate variation. In Tashkent, New42 had the highest 1000-seed weight (1.73 g), slightly exceeded by Check1 (1.75 g). In Chimbay, Check1 maintained a high seed weight (1.93 g), highlighting its genetic stability. The lowest seed weight was evident in the genotype New141 (1.11 and 1.52 g) in Chimbay and Tashkent, respectively, possibly reflecting environmental stress and genotype-specific limitations. Seed yield per plant was the highest for genotypes New42 (14.4 g seeds/plant) and New21 (14.2 g seeds/plant) in Tashkent, indicating robust reproductive capacity. In Chimbay, the genotypes New21 and New42 showed relatively lower values (6.37 and 6.36 g seeds/plant, respectively), which may be due to reduced fertility and unfavorable growing conditions (Table 3).

Among the evaluated quinoa genotypes, New21 and New42 demonstrated consistent performance across both locations, with the highest grain yield and seed traits. These results suggested the suitability of these genotypes across various agroecosystems. Notably, the genotype New21 produced a higher grain yield in Chimbay than in Tashkent, with 2836.3 and 2316.7 kg/ha, respectively, exhibiting enhanced salinity tolerance typical of a halophyte. The genotype Check1 maintained a stable seed weight and moderate yield, reinforcing its role as a reliable control.

Genotypes' growth traits across sites

Vegetative evaluation of the quinoa plants focused on three key morphological traits, i.e., plant height (cm), panicle length (cm), and plant dry weight (g), which are critical indicators of vegetative vigor and biomass

Table 3. Yield components of quinoa genotypes in Tashkent and Chimbay, Uzbekistan.

Quinoa genotypes	Grain yield (kg/ha)		1000-seed weight (g)		Grain weight plant^{-1} (g)	
	Tashkent	Chimbay	Tashkent	Chimbay	Tashkent	Chimbay
Check1	3194.4	2084.5	1.75	1.93	12.2	7.93
New14	1053.7	792.2	1.77	1.42	6.6	4.38
New21	2316.7	2836.3	1.71	1.46	14.2	6.37
New42	3488.9	2941.2	1.73	1.54	14.4	6.36
New170	1540.7	1354.3	1.75	1.28	9.2	3.97
New141	1300.2	348.2	1.52	1.11	5.5	2.73
$LSD_{0.05}$	165.3	236.1	0.04	0.08	2.14	1.78

Table 4. Crop growth and development traits of quinoa in Tashkent and Chimbay, Uzbekistan.

Quinoa genotypes	Plant height (cm)		Width of panicle (cm)		Plant dry weight (g)	
	Tashkent	Chimbay	Tashkent	Chimbay	Tashkent	Chimbay
Check1	140.7	86.9	15.7	12.0	31.1	29.6
New14	127.3	78.2	13.7	10.3	27.5	20.3
New21	118.0	82.8	22.0	19.0	26.0	29.5
New42	101.7	78.9	19.0	17.7	23.9	24.7
New170	81.3	62.1	12.7	10.3	20.1	20.9
New141	64.0	51.1	15.0	10.7	14.1	12.7
$LSD_{0.05}$	14.7	7.6	2.8	2.2	2.7	2.1

accumulation. The tallest plants were visible with the genotype Check1 (140.7 cm), followed by genotypes New14 (127.3 cm) and New21 (118.0 cm) in Tashkent. In Chimbay, the genotype plant height was generally lower, and the genotype Check1 was again leading (86.9 cm), whereas New141 showed the shortest plant height (51.1 cm). The results suggested quinoa genotypes respond differently to environmental conditions, and soil salinity was the main constraint in crop vegetative and generative development (Table 4).

The longest panicles prevailed for the quinoa genotype New21 at Tashkent (22.0 cm) and Chimbay (19.0 cm), indicating enhanced reproductive development. In Chimbay, the genotype New42 also generated a long panicle (17.7 cm), closely followed by Check1 (12.0 cm). New170 and New141 showed consistently shorter panicles, suggesting limited floral development at both locations. Biomass accumulation was the highest in the Check1 genotype (29.6 g), followed by genotypes New21 (29.5 g) and New42 (24.7 g) in Chimbay. In Tashkent, the genotype Check1 again led (31.1 g), whereas New141 had the lowest dry weight (12.7 g). Interestingly, the genotypes New42 and New21 revealed improved biomass in Chimbay compared with Tashkent, indicating their potential for adaptation to saline soil and harsh climatic conditions.

Overall, the quinoa genotype Check1 consistently outperformed other genotypes for all traits across both locations, confirming its prominent role as a robust control. The genotypes New21 and New42 demonstrated greater panicle development and stable biomass, identified as promising candidates for further breeding in saline agroecosystems. However, New14, New141, and New170 genotypes exhibited the weakest performance in all parameters, suggesting limited suitability in both environments.

Seed composition analysis

The biochemical composition of quinoa seeds varied considerably among the genotypes and between the growing locations, reflecting the significant influence of genotype-by-environment interactions. The seed compositional data for the six quinoa genotypes cultivated under the agroecological conditions of Tashkent and Chimbay are available in Tables 5 and 6. The seed dry

Table 5. Biochemical composition of quinoa seeds grown in Tashkent, Uzbekistan.

Main plot (Quinoa genotypes)	Dry matter	Protein (%)	Lignin (%)	Fat (%)	Ash (%)	NFS (%)	Gross energy (kcal)
Check1	90.8	14.24	4.49	10.6	27.1	16.1	3459.5
New14	91.2	10.85	3.21	7.6	18.7	15.6	3865.8
New21	90.1	13.78	4.78	11.4	24.9	17.7	4319.8
New42	91.1	15.43	4.94	9.8	23.9	17.4	4254.2
New170	92.8	12.95	4.17	6.9	21.6	15.6	4056.7
New141	88.7	10.91	3.12	7.3	20.4	15.3	3456.4
$LSD_{0.05}$	0.71	0.66	0.47	1.2	2.3	0.68	197.6

Table 6. Biochemical composition of quinoa seeds grown in Chimbay, Uzbekistan.

Main plot (Quinoa genotypes)	Dry matter	Protein (%)	Lignin (%)	Fat (%)	Ash (%)	NFS (%)	Gross energy (kcal)
Check1	91.4	13.8	4.65	10.2	28.3	15.9	3428.7
New14	91.7	10.4	3.35	7.2	19.8	15.2	3812.3
New21	90.6	13.3	4.92	11.0	26.1	17.3	4265.1
New42	91.6	14.9	5.08	9.4	25.0	17.0	4198.6
New170	93.2	12.5	4.32	6.5	22.8	15.3	3987.9
New141	89.2	10.5	3.25	6.9	21.5	14.9	3412.1
$LSD_{0.05}$	0.87	1.22	0.97	0.78	2.13	1.33	211.4

matter values of the quinoa genotypes ranged from 88.7% to 92.8% in Tashkent and from 89.2% to 93.2% in Chimbay. The genotype New170 consistently exhibited the topmost dry matter at both locations, with a slight increase in Chimbay (93.2%) compared with Tashkent (92.8%). This elevation in seed dry matter could refer to the arid climate and higher evapotranspiration rates in Chimbay, which further promote moisture loss and the concentration of solids in seeds.

Protein levels showed notable genotype-dependent variations. The quinoa genotype New42 had the maximum protein content in both regions, with 15.43% in Tashkent and a slight decrease to 14.9% in Chimbay. Conversely, genotypes New14 and New141 maintained the lowest protein levels, with marginal reductions in Chimbay. These differences suggest that salinity stress in Chimbay may suppress nitrogen assimilation and protein biosynthesis in sensitive quinoa genotypes, whereas the resilient genotype, such as New42, sustains higher protein accumulation. Lignin concentrations were generally higher, especially in the quinoa genotypes New21 and New42 (4.92% and 5.08%, respectively) in Chimbay. This increase may reflect adaptive responses to abiotic stress, as lignin contributes to structural rigidity and stress tolerance. The elevated lignin levels in Chimbay-grown quinoa genotype seeds signify enhanced cell wall fortification under harsh environmental conditions.

Fat content was the highest in the quinoa genotype New21 across both sites, with a slight decline from 11.4% in Tashkent to 11.0% in Chimbay. Most genotypes showed reduced fat levels in Chimbay, likely due to stress-induced metabolic shifts favoring carbohydrate and protein synthesis over lipid accumulation. This trend aligns with previous findings that drought and salinity can inhibit fatty acid biosynthesis in quinoa.

Ash content, indicative of quinoa mineral accumulation, was consistently higher in Chimbay. The quinoa genotypes Check1 and New21 recorded the supreme ash content (28.3% and 26.1%, respectively). The elevated ash levels in the Chimbay-grown genotype seeds could be because of the increased uptake of soil minerals under saline conditions, particularly sodium, calcium, and magnesium. This mineral enrichment could enhance the nutritional value of quinoa but may also affect taste and processing characteristics. Nitrogen-free extract (NFS) values were highest in the New21 and New42 genotypes, exceeding 17% in both regions. These quinoa genotypes appeared to maintain considerable carbohydrate reserves regardless of location. However, a slight reduction in NFS was evident in Chimbay for most genotypes, possibly due to altered carbon partitioning within stress. The stability of NFS in quinoa genotypes New21 and New42 reinforces their potential as high-energy cultivars.

Gross energy values mirrored trends in fat and NFS contents. The quinoa genotypes New21 and New42 were again leading with more than 4200 kcal in both environments, confirming their superior caloric density. In contrast, the Check1 and New141 genotypes exhibited the lowest energy values, particularly in Chimbay, where a reduction of 30–50 kcal emerged. These shifts highlighted the importance of genotype selection for energy-rich seed production under marginal conditions.

DISCUSSION

The presented study highlighted the significant genotype-by-environment interactions in quinoa (*C. quinoa* Willd.) performance across the two distinct agroecological zones (Tashkent and Chimbay) of Uzbekistan. Grain yield, seed traits, and vegetative growth parameters varied markedly among the quinoa genotypes and environmental conditions, underscoring the importance of localized evaluation for crop adaptation.

New21 and New42 appeared as highly adaptable quinoa genotypes, demonstrating consistent grain yield and biomass accumulation across both experimental sites. Their increased panicle length and reproductive capacity further reinforce their potential for broader cultivation in semi-arid zones. In contrast, New14, New170, and New141 genotypes showed lower grain yield and seeds per plant at both experimental sites, suggesting location-specific suitability and possible sensitivity to salinity and climatic stressors. The genotype Check1, the standard control, maintained stable seed weight and vigorous vegetative growth across environments, reaffirming its role as a benchmark for evaluating genotypic stability.

In agreement with the concerned study, several previous studies have emphasized the importance of selecting climate-resilient quinoa genotypes well adapted to challenging soil and environmental conditions (Choukr-Allah *et al*., 2016). Such selection supports the development and expansion of infrastructure for quinoa cultivation (Al-Naggar *et al*., 2023). Moreover, the production of high-value quinoa grain offers a promising solution to nutrient deficiencies and food insecurity while enhancing agricultural productivity in salt-affected areas and boosting farmers' income (Goussi *et al*., 2024).

Morphological traits, such as plant height and panicle length, were generally lower in Chimbay, which may be ascribable to environmental constraints such as soil salinity, temperature fluctuations, and less water availability. Notably, the quinoa genotypes New42 and New21 exhibited enhanced biomass in Chimbay compared with Tashkent, indicating their potential for adaptation to marginal soils and stress-prone environments. The genotype New141 consistently recorded the lowest values for all measured traits, indicating poor environmental compatibility and limited agronomic potential. These findings align with global evidence on quinoa’s plasticity and stress tolerance while also emphasizing the need for region-specific genotype selection (Iqbal *et al*., 2025). The observed variation in seed traits and vegetative growth supports the hypothesis that quinoa genotypes respond differentially to environmental conditions. Variations in soil physicochemical properties and water quality across locations are likely to contribute to differences in genotype yield outcomes, underscoring the need for detailed site-specific analysis.

Soil characterization provides a critical context for interpreting genotype responses and supports targeted agronomic recommendations for quinoa cultivation in diverse environments (Jahantighi *et al*., 2023). The elevated quinoa grain yields observed in the challenging environment of the Aral Sea basin underscore the crop's resilience as a facultative halophyte. These results confirm quinoa's tolerance to abiotic stresses, such as salinity and water scarcity, as well as highlight its value as a nutritionally rich crop with significant potential for sustainable agriculture and food security (Iqbal *et al*., 2025).

Overall, the results supported the strategic expansion of quinoa cultivation into saline-prone regions, such as Karakalpakstan, provided the resilient genotypes become priority. These results contribute to the growing body of knowledge regarding quinoa as a versatile crop for sustainable development. Future research should focus on the physiological and molecular mechanisms underlying stress tolerance, as well as participatory breeding approaches to align genotype selection with farmer preferences and regional needs.

CONCLUSIONS

The study provides valuable insights into the agronomic performance and environmental adaptability of six quinoa (*C. quinoa* Willd.) genotypes under contrasting conditions in Uzbekistan. Genotypes New21 and New42 proved as promising candidates for wide-scale cultivation due to their consistent grain yield, reproductive vigor, and biomass accumulation. These quinoa genotypes showed potential for targeted use in specific regions, while Check1 remained a reliable control for comparative evaluation. These quinoa genotypes performed well under saline and marginal conditions while offering strategic values for climate-resilient agriculture in Central Asia.

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