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EVALUATION OF CLIMATE-RESILIENT AMARANTH (*AMARANTHUS* SPP.) GENOTYPES UNDER ARID AND SALT-AFFECTED SOILS

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SUMMARY

Climate change has intensified drought and soil salinity constraints in arid and semi-arid regions, necessitating the identification of stress-tolerant crop genotypes for marginal environments. This study evaluated 12 amaranth (*Amaranthus* spp.) genotypes under arid and salt-affected field conditions in Chimboy District, Karakalpakstan, Uzbekistan, during the 2023–2024 growing seasons. The experimental arrangement was in a single-factor design with three replications, and genotype assessment included biometric traits, germination, vegetation period, Fusarium wilt incidence, and yield components. According to analysis of variance, significant ($p < 0.05$) differences were evident among the amaranth genotypes for agronomic traits and yield performance. The genotype RRC-1027 (oqamarant) consistently showed superior performance, combining the highest vegetative growth (175.9 cm plant height; 190.8 leaves plant^{-1}), panicle weight (216.9 g), and improved productivity under saline conditions, with biomass yield (18.85 Mg ha^{-1}) and grain yield (4.45 Mg ha^{-1}). Genotype RRC-1027 also exhibited low Fusarium wilt incidence (6.8%) and the shortest vegetation period (113 days), indicating favorable adaptation under stress-prone environments. Overall, the results highlighted identifying RRC-1027 as a promising genotype for cultivation and further evaluation under arid and salt-affected agroecosystems.

Keywords: *Amaranthus* spp., climate resilience, salinity tolerance, yield stability, Fusarium wilt resistance, marginal agroecosystems, grain yield

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Key findings: Genotype selection relied on agronomic data, facilitating targeted breeding approaches for developing climate-resilient and nutrient-rich amaranth (*Amaranthus* spp.) genotypes suited to challenging agroecological zones of Uzbekistan. The amaranth genotype RRC-1027 (oqamarant) exhibited considerable adaptability and the highest productivity under arid and saline conditions, attaining recognition as a promising genotype for cultivation in marginal areas such as the Aral Sea basin.

INTRODUCTION

Climate change has intensified abiotic stresses, such as drought, soil salinity, and extreme temperature fluctuations, posing tough challenges to global food security. However, these climate impacts proved to be particularly severe in arid and semi-arid regions, constraining crop productivity with limited water availability, degraded soils, and increasing climatic variability (Nurbekov *et al*., 2023). In such harsh environmental conditions, conventional crops often fail to meet yield expectations, necessitating the identification and promotion of alternative crops that can thrive under marginal conditions while offering nutritional and economic benefits (Khaitov *et al*., 2022).

Amaranth (*Amaranthus* spp.), a pseudo cereal native to Latin America, has gained attention as a climate-resilient crop because of its exceptional adaptability to poor soils, high temperatures, and saline environments worldwide. Its short growing cycle, efficient C4 pathway water-use mechanisms, and resistance to biotic stress factors, such as Fusarium wilt, make it the most suitable crop for cultivation in regions vulnerable to climate stress conditions (Pandey and Singh, 2009). The agronomic versatility of amaranth bears compliments from its nutritional profile; its seeds are rich in high-quality protein, essential amino acids, dietary fibers, and micronutrients, recognizing it as a strategic crop for subsistence farming and commercial production systems (Tetyannikov *et al*., 2022).

Over the past decade, amaranth has gained domestication in various agroecological zones beyond its native origin, including some parts of Africa and South and Central Asia. In Uzbekistan and neighboring countries, soil salinization and water deficit conditions are major constraints to agricultural sustainability, and amaranth offers a viable alternative to other traditional crops, such as wheat, cotton, and rice (Ortikov *et al*., 2025). However, even with its genetic potential, systematic evaluation of amaranth genotypes remains limited in this region under stress-prone conditions. Most studies have focused on general agronomic traits, paying insufficient attention to genotypic responses to salinity, drought, and pathogen pressure (Abduvalieva and Shodiev, 2024).

Understanding the biometric traits, disease resistance, and yield of diverse amaranth genotypes is crucial for selecting genotypes with climate resilience and higher productivity. Genotype-by-environment interactions also play a vital role in the identification of crop cultivars with better performance under marginal conditions, and such targeted evaluation can manage the breeding strategies and agronomic recommendations according to local needs. In particular, resistance to Fusarium wilts, a soil-borne fungal disease that considerably reduces amaranth yield in drought-prone environments (Oustani *et al*., 2023).

By generating genotype-specific data and identifying climate-resilient cultivars, this research contributes to the broader efforts of enhancing crop sustainability, food security, and climate adaptation in vulnerable agroecosystems of Central Asia (Kulmatov *et al*., 2020). Thus, the subsequent amaranth selection strategy will be more effective for this region, particularly in enhancing crop production under harsh agroecosystem conditions. This study provides significant scientific insights while also offering practical contributions, particularly for advancing breeding strategies suitable for marginal lands.

The following research aimed to investigate amaranth (*Amaranthus* spp.) genotypes under arid and saline field conditions and identify climate-resilient cultivars suitable for marginal environments in Karakalpakstan, Uzbekistan. This study focused on evaluating 12 amaranth genotypes for their agronomic and physiological performance, including biometric parameters (plant height, leaf number, panicle traits, and seed weight), Fusarium wilt incidence, and yield components (biomass and grain yield).

MATERIALS AND METHODS

Experimental site and climatic conditions

Field trials on *Amaranthus* spp. commenced during the 2023 and 2024 growing seasons in the Chimboy District, Republic of Karakalpakstan, Uzbekistan (42.45°N, 59.61°E). The site basically has arid climatic conditions with moderate to high soil salinity. Weather data, including monthly temperature and rainfall during the experimental years and long-term averages, appear in Table 1.

The experimental site also has characteristics of a sharply continental climate, with hot and dry summers and cool and moisture-limited winters. The mean annual temperature was approximately 14.1 °C, with summer peaks reaching 35.6 °C and winter lows dropping to −1.5 °C (Table 1). Annual precipitation typically ranges between 50 and 200 mm, concentrated in winter and spring, while summer months remain predominantly dry.

During the experimental study years, precipitation occurred markedly below average, recorded at 54.2 mm in 2023 and 23.3 mm in 2024. In July and August, the peak temperature ranged from +40 °C to +45 °C, whereas winter extremes fell between −25 °C and −28 °C, indicating severe thermal stress conditions for crop growth.

Soil characteristics

The experimental field has a meadow-alluvial silty loam soil classification, according to FAO standards. Soil salinity ranged from 5.6 to 8.6 dS m^{-1} across soil depths (0–90 cm). Soil chemical properties, including pH, exchangeable sodium percentage (ESP), humus, total nitrogen, and available nutrients (NO_3, P_2O_5, K_2O), are available in Table 2.

Organic matter content was relatively low, with the humus levels ranging from 0.85% (topsoil) to 0.47% (deeper layers). Total nitrogen was severely deficient, ranging from 0.01% to 0.0011%, while nitrate concentrations were the highest in the surface layer (12.2 mg/kg) and declined sharply with depth. These soil conditions reflect a challenging environment for crop establishment and productivity, necessitating the use of stress-tolerant genotypes.

Table 1. Weather data comprising air temperature, rainfall, and relative humidity of the study areas at Chimbay, Karakalpakstan.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (°C)												
2023	-2.6	-0.3	6.3	17.8	20.2	28.9	28.2	26.8	18.1	13.6	6.8	3.5
2024	-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)												
2023	3.8	0.7	15.7	0.5	23.2	1.3	7.8	0.3	0.9	0	13.1	19.9
2024	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

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

Table 2. Soil chemical analysis.

Soil depth (cm)	Soil ECe (dS/m)	Soil pH	Exchangeable Na percentage (ESP)	Total forms (%)		Available form (mg/kg)		
				Humus	N	NO_3	P_2O_5	K_2O
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

Source: Soil samples for analysis taken from the experimental field of the Karakalpak Agriculture Research Institute.

Plant material

Twelve amaranth (*Amaranthus* spp.) genotypes obtained from the International Center for Biosaline Agriculture (ICBA) attained evaluation. The genotypes included New 65, New 21, Check 2, New 41, New 13, New 30, Check 7, Check 5, New 45, Check 3, RRC-1027, and Marhamat (control). These genotypes' selection relied on prior screening for salinity and drought tolerance and yield potential.

Experimental design and crop management

The experiment layout was in a randomized complete block design (RCBD) with three replications in each year. Each plot measured 24 m² with 1 m spacing between plots. Row spacing was 60 cm, and plant spacing within rows was 15 cm. Seed sowing took place in early April in both years. The amaranth growing season in this region extends from April to October. Applying organic manure was at 5 t ha^{-1} before sowing. Fertilization treatment equivalent to $N_{150}P_{90}K_{90}$ kg ha^{-1} was according to regional recommendations. Irrigation and crop management practices proceeded uniformly across treatments.

Phenological observations entailed recording throughout the growing season, focusing on key traits. These are germination rate, days to maturity, plant height, panicle length, Fusarium wilt incidence (%), aboveground biomass (Mg ha^{-1}), grain yield (Mg ha^{-1}), and 1000-seed weight (g).

Statistical analysis

All the recorded experimental data underwent statistical analysis using CropStat software. Analysis of variance (ANOVA), as performed, determined the significance of genotype effects across measured traits. The conduct of mean separation used LSD at the 5% probability level ($p \leq 0.05$). The analysis enabled considerable evaluation of amaranth genotypes' performance under variable environmental conditions.

RESULTS

Biometric traits evaluation

The 12 amaranth (*Amaranthus* spp.) genotypes revealed significant genotypic variability across key morphological parameters, including plant height, leaf number, panicle length and weight, and 1000-seed weight (Table 3). These traits could serve as critical indicators of vegetative vigor, reproductive capacity, and potential yield performance under arid and saline conditions.

The amaranth genotype New 65 exhibited the tallest plants (195.1 cm), followed by two other genotypes, RRC-1027 (175.9 cm) and New 30 (178.6 cm), indicating robust vegetative growth. In contrast, the genotype Check 2 recorded the shortest plants (90.1 cm), suggesting limited biomass accumulation. Leaf number considerably varied, and the genotype RRC-1027 showed the highest count (190.8 leaves/plant),

Table 3. Biometric parameters of amaranth genotypes.

Amaranth genotypes	Plant height	Leaf number	Panicle length	Panicle weight	1000-seed weight
New 65	195.1	148.2	47.4	162.8	2.23
New 21	148.8	92.8	56.6	133.0	2.32
Check 2	90.1	117.5	32.4	158.6	2.28
New 41	168.5	150.8	45.4	210.0	2.48
New 13	151.1	93.2	44.1	163.1	2.42
New 30	178.6	100.2	43.6	166.9	2.38
Check 7	148.5	96.6	35.7	165.2	2.50
Check 5	114.9	95.2	40.2	126.8	2.41
New 45	138.3	107.8	44.4	198.4	2.68
Check 3	138.4	174.8	36.4	212.9	2.45
RRC-1027 (oqamarant)	175.9	190.8	52.6	216.9	2.48
Marhamat (control)	142.1	122.6	35.2	149.0	2.25
$LSD_{0.05}$				12.76	0.12

reflecting vigorous foliage development. Genotypes New 21 and New 13 had the lowest leaf number (92.8 and 93.2, respectively), which may also influence photosynthetic capacity and eventually overall productivity.

Panicle length ranged from 32.4 cm (Check 2) to 56.6 cm (New 21), and the longer panicles showed a general association with enhanced reproductive output. Panicle weight was the highest in amaranth genotypes RRC-1027 (216.9 g), Check 3 (212.9 g), and New 41 (210.0 g), indicating superior floral biomass and seed-bearing potential. However, the lowest panicle weight resulted in Check 5 (126.8 g), suggesting reduced reproductive efficiency.

The 1000-seed weight is a key determinant of grain quality and market value. Genotype New 45 had the highest 1000-seed weight (2.68 g), followed by two other genotypes, Check 7 (2.50 g) and RRC-1027 (2.48 g). Lower seed weight was notable in New 65 (2.23 g) and Marhamat (2.25 g) amaranth genotypes, which may affect grain density and yield efficiency.

Overall, the amaranth genotype RRC-1027 consistently ranked among the top performers across all the biometric traits, indicating robust adaptability and agronomic potential under stress-prone conditions. Genotypes New 41, New 45, and Check 3 also demonstrated favorable combinations of vegetative and reproductive traits.

Germination, vegetation period, and Fusarium wilt incidence

The germination percentage among the evaluated amaranth genotypes ranged from 31.3% to 54.4%, reflecting notable variation in seed vigor and early establishment potential (Table 4). The amaranth genotype RRC-1027 (oqamarant) demonstrated the highest germination rate (54.4%), indicating considerable viability under stress-prone conditions. Vegetation periods varied from 113 to 138 days, and the genotype RRC-1027 exhibited the shortest growth cycle (113 days), whereas the New 41 genotype required the longest (138 days). Genotypes with shorter vegetation periods, such as RRC-1027 and New 65, may offer agronomic advantages in regions with limited growing seasons and harsh climatic constraints, thereby supporting their suitability for cultivation in marginal environments.

Fusarium wilt (*Fusarium oxysporum*) is a major biotic stressor affecting amaranth overall productivity. Disease incidence evaluation was by calculating the percentage of deceased plants per genotype. The lowest infection rate (6.8%) was evident in four amaranth genotypes, New 65, New 41, New 13, and RRC-1027, suggesting relatively higher resistance to Fusarium wilt. Genotype Check 2 exhibited the highest disease incidence (9.5%), followed by four other genotypes: New

Table 4. Germination, vegetation period, and *Fusarium oxysporum* in amaranth genotypes.

Amaranth genotypes	Germination (%)	Vegetation period (days)	Infected plants (%)
New65	44.7	118	6.8
New21	43.5	124	9.3
Check 2	34.2	133	9.5
New41	41.4	138	6.8
New13	37.7	123	6.8
New30	36.3	124	9.3
New45	41.4	127	9.0
Check 7	31.3	119	9.3
Check5	44.8	124	9.0
Check3	33.7	134	7.0
RRC-1027 (oqamarant)	54.4	113	6.8
Marhamat (control)	43.9	124	9.3
$LSD_{0.05}$			1.2

Table 5. Yield components of amaranth genotypes.

Amaranth genotypes	Total yield (Mg ha^{-1})	Biomass yield (Mg ha^{-1})	Grain yield (Mg ha^{-1})
New65	12.34	10.21	2.13
New21	15.87	12.45	3.42
Check 2	14.67	12.11	2.56
New41	14.22	11.36	2.86
New13	13.34	10.87	2.47
New30	16.08	12.87	3.21
New45	15.26	12.32	2.94
Check 7	13.71	11.14	2.57
Check5	20.15	16.35	3.8
Check3	23.27	19.25	4.02
RRC-1027 (oqamarant)	23.3	18.85	4.45
Marhamat (control)	20.87	17.0	3.87
$LSD_{0.05}$	1.82	1.08	0.67

21, New 30, Check 7, and Marhamat (9.3%). However, the recorded intermediate susceptibility was in the amaranth genotypes New 45 and Check 5 (9.0%), whereas Check 3 showed moderate tolerance (7.0%).

The results revealed amaranth genotypes with ≤7% disease incidence might be options for promising candidates for breeding programs targeting Fusarium resistance. Genotype RRC-1027, in particular, has low disease incidence and superior biometric performance, reinforcing its suitability for cultivation in pathogen-prone environments.

Yield performance

The assessment of yield components focused on total biomass, grain yield, and overall productivity (Table 5). The results revealed substantial genotypic variations, highlighting several promising amaranth candidate genotypes with the highest yield. Amaranth genotype RRC-1027 recorded the highest grain yield (4.45 Mg ha^{-1}), followed by Check 3 (4.02 Mg ha^{-1}), Marhamat (3.87 Mg ha^{-1}), and Check 5 (3.80 Mg ha^{-1}). Among the newly developed genotypes, New 21 (3.42 Mg ha^{-1}) and New 30 (3.21 Mg ha^{-1}) showed competitive productivity. However, the lowest grain yield emerged in the genotype New 65 (2.13 Mg ha^{-1}), indicating limited reproductive output despite its tall stature.

Genotype Check 3 produced the maximum biomass yield (19.25 Mg ha^{-1}), followed by RRC-1027 (18.85 Mg ha^{-1}) and Marhamat (17.00 Mg ha^{-1}). These genotypes also displayed robust panicle development and seed weight, reinforcing their agronomic potential. Genotypes RRC-1027 and Check 3 led to the total yield, both exceeding 23 Mg ha^{-1}, indicating the highest overall productivity. The amaranth genotypes Check 5 and Marhamat also performed well, with total yields of 20.15 and 20.87 Mg ha^{-1}, respectively. Genotypes, such as New 65, New 13, and Check 7, showed moderate total yields (12–14 Mg ha^{-1}), suggesting the potential for improvement through future breeding and agronomic optimization.

The amaranth genotype RRC-1027 (oqamarant) emerged as the top-performing cultivar across all the evaluated parameters, combining high-grain output, robust-biomass accumulation, and low-disease incidence. Genotypes Check 3, Marhamat, and Check 5 also demonstrated considerable yield potential and were recognizably suitable candidate genotypes for cultivation in yield-focused programs. Genotypes New 41 and New 13, with lower grain yield but moderate biomass, could serve for a dual purpose and further evaluation in stress conditions.

DISCUSSION

The introduction and cultivation of climate-resilient crops with broad adaptability to the harsh agroclimatic conditions of Central Asia represent a promising strategy for enhancing food security. Indigenous sensitive crops rely on similar stress-response mechanisms and often fail to thrive and yield adequately under severe environmental stress conditions (Ozeki *et al*., 2022). The presented study revealed substantial genotypic variations for morphological traits, disease resistance, and yield performance among the 12 amaranth (*Amaranthus* spp.) genotypes cultivated under arid and saline conditions in Uzbekistan. These results underscore the importance of genotype-specific evaluations for identifying climate-resilient cultivars suitable for marginal environments (Nkuna *et al*., 2025).

Biometric traits analysis demonstrated that amaranth genotypes New 65, RRC-1027, and New 30 exhibited superior vegetative growth, as evidenced by their highest plant stature and leaf counts. These traits are indicators of enhanced photosynthetic capacity and biomass accumulation, which are crucial for drought tolerance and soil coverage in stress-prone agroecosystems. However, the genotypes with the tallest height alone did not consistently correlate with reproductive efficiency, with the same observed in genotype New 65, and despite its plant height, it recorded the lowest grain yield. These results suggest vegetative vigor requires complementation with reproductive traits to ensure agronomic success and productivity (Motyleva *et al*., 2021).

Significant genotypic variation in plant height, leaf number, panicle weight, and 1000-seed weight confirms the presence of exploitable genetic diversity within the tested germplasm. Reports of similar variability in morphological and yield-related traits of *Amaranthus* species have come from Jamalluddin *et al*. (2022) and Sarker *et al*. (2020), who highlighted the importance of trait-based selection in improving stress adaptation and yield potential. However, in this study, vegetative vigor alone did not guarantee higher grain productivity. For example, genotype New 65 exhibited the greatest plant height but comparatively lower grain yield, indicating that selection should prioritize reproductive efficiency alongside biomass accumulation.

Panicle weight and 1000-seed weight showed significant genotype effects and a positive association with higher grain yield. Genotypes RRC-1027 and Check 3 combined superior panicle development with high grain output, suggesting that reproductive biomass allocation plays a critical role under saline and arid conditions. Previous breeding studies in amaranth have also identified panicle traits as reliable selection indices for yield improvement under environmental stress (Ajayi, 2024; Sagar *et al*., 2018).

The remarkable variation in Fusarium wilt incidence among genotypes further supports the presence of genetic differences in disease resistance. Genotypes exhibiting ≤6.8% infection, including RRC-1027, displayed a relatively stable resistance across years, despite substantial effects from the environment. Integration of disease resistance with high-yield potential is a critical breeding objective, particularly in marginal agroecosystems where abiotic and biotic stresses frequently co-occur. Similar observations on stress-resilient genotypes combining yield and disease tolerance have been a result reported by Anuradha *et al*. (2023).

Yield analysis confirmed the amaranth genotype RRC-1027 as the top performer, with the highest grain yield (4.45 Mg ha^{-1}), biomass yield (18.85 Mg ha^{-1}), and total productivity (23.3 Mg ha^{-1}). Genotypes Check 3, Marhamat, and Check 5 also demonstrated robust yield potential, suggesting that both local checks and newly selected lines could contribute to diversified cropping systems. Among the new genotypes selected, New 21 and New 30 showed competitive grain yields (>3.2 Mg ha^{-1}), indicating their adaptability and productivity under marginal and stressed conditions. Under harsh agroecological conditions, these amaranth genotypes with superior yield can maintain productivity, food security, and income generation for smallholder farmers, emphasizing crop genetic diversity and its adaptability to marginal environments (Sarker *et al*., 2020).

Yield performance analysis indicated that RRC-1027 consistently ranked among the highest-yielding genotypes across both seasons. Although year effects were not significant, the relatively stable ranking of RRC-1027 and Check 3 across environments suggests broader adaptability. The presence of significant G×Y interaction implies that some genotypes responded differently under variable climatic conditions, reinforcing the necessity of multi-environment testing for accurate genotype recommendation. Reports of comparable findings in stress-adapted amaranth lines have emerged under drought and salinity conditions in semi-arid regions (Motyleva *et al*., 2021; Tetyannikov *et al*., 2022).

The observed trade-off between vegetative growth and reproductive output in certain genotypes highlights the need for balanced selection strategies. Genotypes, such as New 41 and New 13, which exhibited moderate biomass but relatively lower grain yield, may serve as potential dual-purpose types for forage and grain systems, depending on breeding objectives (Oduwaye *et al*., 2019).

Overall, the significant genetic variability detected for yield components, disease resistance, and phenological traits under saline and arid conditions indicates promising opportunities for selection and breeding. The superior and relatively stable performance of RRC-1027 across traits suggests its suitability as a candidate genotype for further evaluation and potential varietal advancement under marginal agroecological conditions.

CONCLUSIONS

Significant genetic variability was evident among the 12 amaranth (*Amaranthus* spp.) genotypes based on morphological traits, disease incidence, and yield components under arid and saline conditions. The relevant genotypes and genotype-by-environment effects highlighted the importance of multi-season evaluation in stress-prone agroecosystems. Among the tested materials, genotype RRC-1027 demonstrated superior agronomic performance, combining high grain yield, favorable reproductive traits, and relatively stable resistance to Fusarium wilt. These findings indicate the potential of RRC-1027 as a promising candidate for further breeding and adaptation studies in salt-affected and arid environments.

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