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Identification, characterization and domestication of new sorghum (*Sorghum bicolor* L.) genotypes to saline environments of the Aral sea regions

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Abstract

Assessment of crop genetic resources is an efficient tool to generate new stress-tolerant varieties with high yield characteristics for harsh environments such as in the Aral Sea regions. Sorghum is a C_4 grass capable of both high biomass and grain yields in semiarid and drier parts of the world. In this study, sixteen sorghum genotypes were assessed in terms of grain and biomass production under the saline aquifer of the Aral Sea region during the 2019-2021 growing seasons. The tested sorghum genotypes were planted as a split-plot design with three replicates in the experimental field. The highest plant height was found in SSV-84 (288 cm) and Kulzha (272 cm), indicating good adaptation features under the saline environment (moderately saline serosems soil; EC 8-10 dS m^{-1}). A considerable difference was observed in the grain and biomass yield of the tested sorghum genotypes. The highest grain yield was produced by Kazakhstanskoe-16 (6970 kg ha^{-1}) while the highest biomass yield was achieved by Orange-160 (57770 kg ha^{-1}). The correlation analysis showed a weak interaction (r=0.524) between the grain yield and vegetation period parameters, implying a genetic specificity has an advantage of the agronomic performance. Lab experiments also confirmed the superiority of the selected genotypes over the local genotype in regards of seed germination and seedling growth. Based on the field and lab experiments, Kazakhstanskoe-16 and Orange-160 were found to be salt tolerant sorghum genotypes with high yield traits and recommended for further assessment to the State Varietal Commission of Agricultural Crops for large-scale use in salt-affected arid areas.

Keywords

Adaptation, Aral sea region, harsh environment, genetics, grain yield, marginal land, selection, sorghum genotypes, soil salinity

Introduction

The sustainability of irrigated agriculture in the Aral Sea regions is being threatened by rising soil salinity. According to current estimates, nearly 95 % of the region's total 508 thousand hectares of irrigated fields were salt-affected, lowering the potential yield of conventional crops like cotton and wheat harvests by up to 50 % (1). Furthermore, drought and desertification are further exacerbating this challenge, while increasing heat caused by climate change is deteriorating agricultural output. All these factors are causing significant problems to ecosystem functioning by harming agricultural sustainability, which eventually led to lower farm incomes and increased poverty and food insecurity (2).

Despite limited access to agricultural system resources, farmers continue to cultivate certain crops using a variety of strategies. Salt leaching from the root zone in the winter season is the common method used by most farmers. However, this approach needs around 10 km^3 of freshwater each year to meet the leaching requirements of these lands while maintaining soil salinity in the root zone within acceptable limits at the start of the vegetative season. Due to limited surface water sources, salt leaching was not carried out adequately in the last years (3).

Rehabilitation of salinity-affected soils in the Aral Sea regions needs substantial investment and innovations (4). Agricultural production is deteriorating further because of conventional agronomic practices, unsustainable natural resource usage, poor land and water quality, climate change, poor investments in land and water resource rehabilitation (5, 6). In this regard, the introduction of salt and drought-tolerant climate-smart crop species can rejuvenate agronomic production, while rehabilitating salt-affected irrigated fields and sustaining crop diversification systems (7). This goal is contingent upon the selection of appropriate sorghum genotypes which might endure the harsh soil and climatic circumstances.

Sorghum (*Sorghum bicolor* L.) is grown in hotter climates than other cereals. Drought and salinity resistance, heat tolerance, high production potential and minimal input use have all been shown in this crop. The culture's morphological traits permit maximal grain production for human and animal consumption in a wide range of environments. Therefore, this crop is regarded as one of the most promising commodities in dry areas, ranking fourth in global crop output behind maize, rice, wheat and barley. Sorghum grain contains starch, which is metabolized more slowly than other cereal grains. It also contains a good quantity of protein, unsaturated fat and a variety of vitamins and minerals. Sorghum grains are also high in phenolic and bioactive chemicals, including 3-deoxyanthocyanidins, tannins and polycosanols (8).

Sorghum is consumed by more than 500 million people in more than 30 nations, according to current estimates (9). The United States leads the world in sorghum production (almost 17 % of total output) with much greater yields, followed by Nigeria, Mexico, India, China, Sudan and Argentina (10). Despite its drought and salt resistance, as well as its capacity to adapt to adverse circumstances, sorghum barely covers 727 ha in the Aral Sea region (10).

Sorghum, being a member of the C4 plant family, can thrive and reproduce on nitrogen-deficient marginal soils. Furthermore, it conserves water during droughts by rolling the leaves to prevent water loss (11). Instead of dying, the crop becomes dormant under high drought conditions. A waxy cuticle on the leaves also helps to keep evapotranspiration to a minimum. Sorghum's high genetic diversity makes it possible to select genotypes that are best suited to a given environment (12). Although several studies have shown negative relationships between sorghum yield-related characteristics and salt (13-15).

However, detailed knowledge about the genetics and selection assignments of stress-tolerant sorghum genotypes under harsh environments such as in Karakalpakstan is scarce. Although the genetic diversity of sorghum facilitates maximizing production under a harsh environment, providing a range of products for multiple uses, thereby enhancing food security. In this study, the new sorghum genotypes were assessed in grain yield and biomass potential, early ripening and grain quality under the salinity and drought environment of Karakalpakstan. To date, breeding programmes have had little success in selecting, adapting and disseminating modern sorghum varieties with high yield potential in this region.

The objectives of the present study were to identify, evaluate and domesticate new sorghum genotypes in the Aral Sea regions. With this view, a hypothesis was the selection of stress-tolerant sorghum genotypes originated from the international collection, which can be effectively integrated into the land management and rehabilitation strategies of salt-affected lands.

Materials and Methods

The study was conducted in Chimboy district of Karakalpakstan, (42.45°N 59.61°E), the north-west of Uzbekistan, during 2019-2021 growing seasons. Winter is severe in this area with absolute minimum air temperatures ranging from -10.3 up to 0.0 °C intervals in December and January. In contrast, summer is very hot. Summer temperatures varied between 26.3 and 32.0 °C, with an absolute maximum of 41.0-45.3 °C. The climate in this area was hardly hit by the drying of the Aral Sea which maintained the stability of the air temperature.

During the vegetation period, the sum of efficient temperature was 2454.2 °C in 2019, 2472.8 °C in 2020 and 2738.1 °C in 2021 (Table 1). The average daily temperature rose from 14.3 to 29.3 °C in spring, which caused additional problems during the sowing season due to intensive drying of the arable soil on a wide scale.

The numbers of maximum air temperatures above 35 °C during the growing season in the years of study are as follows: 61 days in 2019, 55 days in 2020 and 85 days in 2021, (of which the numbers of days above 40.0 °C were 15, 19, 25 days respectively). The accumulated effective temperature for this period was 1692.8, an increase of 86.6-98.5 °C in previous years. Accumulated effective temperature for the vegetation period 2021 was the highest, summing up 2738, 1 ^{0}C which was observed for the first time in 50 years.

Autumn air temperatures decrease in September, which coincides with the transition to a temperature of 10 ° C and usually accompanies by light rain (0.3 mm). In the 2021-year season, the temperature transition through 10 ° C came earlier relative to 2019 and 2020 by 18 and 22 days.

Air humidity was 12-17% lower in the second half of spring. Summer relative humidity values were 6-11% lower in 2021 than 2020 (i.e., 11-16% lower than normal). Autumn

Table 1. Air temperature, rainfall and relative humidity of the study area, Chimboy district, Karakalpakstan (2019-2021).

Year	Month of the year											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (^{0}C)												
2019	0.4	0.9	8.8	13.4	23.1	27.6	30.3	24.5	18.6	11.9	-0.4	0.2
2020	0.9	3.1	8.5	14.5	23.7	27.6	29.3	25.2	17.7	10.4	0.6	-8.2
2021	-3.4	3.4	3.9	17.2	25.3	29.1	30.3	27.8	19.2	8.7	1.5	0
Long term average												
	-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												
2019	4.9	9.3	29.5	12.8	10.9	2.0	3.6	0	0	0.4	0.8	2.4
2020	0.9	7.0	3.7	42.3	13.9	0	3.8	0	0	0	1.9	1.1
2021	1.4	7.4	15.3	41.6	2.2	8.6	0	0	2.6	2.6	1.3	0
Long term average												
	10.1	8.7	16.4	19.4	12.2	3.9	3.5	2.1	3.0	8.7	9.4	13.6
Relative humidity, %												
2019	81	72	63	53	40	35	40	42	48	48	54	73
2020	78	68	45	52	50	41	45	46	47	46	55	64
2021	65	63	60	45	36	33	35	39	46	48	56	67
Long term average												
	81	74	65	45	44	36	33	28	36	51	75	80

air humidity ranged from 45% to 47%. Precipitation was mainly the first half and at the end of vegetation and amounted to 57.0 mm (i.e., 1.7 times more than the normal). It should be noted that 2021 was very low precipitation and measures on irrigation rationing were taken. Summarizing the data obtained for the growing season 2019-2021 we can conclude that 2021 was unfavorable both in terms of temperature and precipitation.

Soil and water characteristics

Land in this area is considered as moderately saline (EC 8-10 dS m^{-1}) serosems (Table 2). Representative soil samples were collected from the study area at the following depths: 0-0.15 m, 0.15-0.30 m, 0.30-0.60 m and 0.60-1.00 m. The soil sampling was undertaken before implementing cultivation treatments (initial soil condition) and after the harvest of the crops. The collected samples were air-dried and processed for analysis. Soil bulk density ranged 1.45-1.54 g cm^3 at the 0-15 and 15-30 cm soil depth respectively. The pH level ranged from 7.75 to 8.60 and was moderate alkaline in a reaction.

Irrigation and groundwater samples were collected on a monthly basis. In addition, the groundwater level was monitored each month. The water samples were analyzed for the following parameters: pH, EC, cations such as Ca^{2+} and Mg^{2+} by titration procedure and Na^{+} and K^{+} by difference. These samples were also analyzed for anions such as

Table 2. Soil nutrients at the beginning and end of the vegetation period.

Soil horizons, cm	Humus, %		Total N, mg kg^{-1}		Total P, mg kg^{-1}		K, mg kg^{-1}	
	before	end	before	end	before	end	before	end
0-15	0.72	0.45	4.7	3.2	11.8	10.5	11.3	8.2
15-30	0.53	0.33	6.7	5.5	13.8	11.9	13.3	11.1
30-45	0.39	0.28	5.7	4.7	12.2	10.2	11.0	10.2
45-60	0.32	0.25	4.2	3.8	6.8	5.7	10.0	9.0
60-90	0.25	0.23	3.2	3.1	7.0	5.2	8.0	7.1
90-120	0.24	0.24	3.2	3.0	5.0	4.8	7.7	6.9
120-150	0.21	0.21	3.2	3.0	3.6	3.5	5.0	5.0

CO_3^{2-}, HCO_3^- and Cl^- by titration procedure and SO_4^{2-} by precipitation as barium sulfate.

Drainage water applied for irrigation with a salinity rate around 4000 mg L^{-1}. From April to September 2019, the salt concentration in canal water ranged from 945 to 1331 mg L^{-1} (1.33-2.07 dSm^{-1}). The levels of SAR were in the range of 4.54 and 13.49 during April - September 2020 which means using such groundwaters for irrigation without appropriate management practices may cause a gradual increase in Na^+ levels in the irrigated lands (Table 3). Sulfate ions were dominating anion with chloride ion to sulfate ratios varied from 0.56 to 0.58, revealing sulfate-chloride salinity type.

Table 3. Soil salt regime.

Soil horizons, cm	Before salt leaching		After salt leaching		At the end of the vegetation	
	Cl	Dense residue	Cl	Dense residue	Cl	Dense residue
0-15	0.032	0.482	0.023	0.278	0.024	0.238
15-30	0.035	0.474	0.028	0.334	0.023	0.227
30-45	0.036	0.484	0.026	0.371	0.022	0.297
45-60	0.032	0.415	0.023	0.351	0.018	0.281
60-90	0.028	0.384	0.022	0.332	0.019	0.229
90-120	0.036	0.374	0.022	0.334	0.020	0.285
120-150	0.038	0.364	0.026	0.332	0.021	0.282

The groundwater has high salinity ranging from 1352 to 9416 mg L^{-1} (2.06-14.60 dS m^{-1}) during the growing seasons. The pH with a value of 7.85 to 8.50 was moderate alkaline in reaction. The dominant cations were Na^+ and Mg^{2+} with wide differences in their concentrations. The levels of SAR were in the range from 4.38 to 11.43, suggesting that groundwater is marginal in its characteristics. The high salinity levels in the groundwater indicated the need to apply basin irrigation (flooding) in the initial stages of the plant establishment to suppress an upward flow from the saline groundwater.

Experiment design and cultural practices

Crop management practices such as planting, irrigation, fertilization, cultivation, pest management, harvesting were kept the same for all plots to exhibit the agronomic performance of the tested sorghum genotypes. Row length was 10 m, the interrow distance was 0.6 m (4 rows per plot) and spacing between hills was 0.2 m with one plant per hill. Seeds were sowed at the beginning of April each year. Experimental plots were irrigated three times with the same amount of water (550-600 m^3 ha^{-1}). The total amount of irrigation water applied during the crop growing season was estimated at 1750 m^3 ha^{-1}. Experimental plots were fertilized with 100 kg ha^{-1} ammonium nitrate (33% N) and 100 kg P ha^{-1} as triple superphosphate (19.8% P). These fertilizers were split into 2 portions and applied as a band placement before furrow irrigation. Agronomic indices such as plant height, number of leaves per plant, seed weight, grain yield and total biomass was observed on randomly selected ten plants in each plot.

Plant materials

16 sorghum genotypes were received from the ICBA gene bank. In order to identify the most salt-tolerant and highly productive varieties for fodder and green manure production, ICBA genotypes were evaluated using the following agro-biological characters: time of planting, seed germination under field and laboratory conditions, seedling emergence, survival rate, plant density, flowering rate, fresh and dry biomass and seed yield. The sorghum local variety (Uzbekistan-5) was tested as a control.

Grain yield and yield components

At the maturity stage, grain yield and its components were determined on plants grown in 2 middle rows of each experimental plot, an area of 6 m^2. Vegetative parameters e.g. shoot height, panicle length, leaf and node numbers were determined in tagged plants. Grains were dried before yield estimation during 72 hrs at 65 °C.

Harvest index was calculated as: $HI = \frac{GY}{BY} \times 100$ where HI, GY and BY are the harvest index (%), the grain yield (kg ha^{-1}) and the biological yield (kg ha^{-1}) respectively.

Lab experiment

The seed germination rate was observed in Petri dishes at constant temperature 25-26 °C on filter paper for 5 days. Each genotype in three replications with 30 seeds were exposed at 100, 200, 300, 400 and 500 mM concentrations of NaCl. Viability percent and energy of germinated seeds were observed along with root and shoot length of seedlings for 5 days. The lab experiment was conducted under artificially arranged 12 hrs of daylight and 12 hrs of darkness.

Statistical analysis

The entire collection was tested during the growing season 2019-2021 under the same soil-climatic and agro technique conditions. The tested sorghum genotypes were planted as a split-plot design with three replicates in the experimental field. All plots were laid out in strips (16). Statistical analyses were performed by using the ANOVA (CropStat) statistical software program (17).

Results and Discussion

Germination, growth and vegetation period of sorghum genotypes

As the field experiment shows, low seed germination and poor seedling establishment were the main challenges for sorghum production in the saline aquifers (Table 4). However, some sorghum genotypes were superior to germinate early with the highest records. The highest field germination was observed in Kazakhstan-16, Chayka, Kazakhstan-3, SSV-84 and Uzbekistan-5 genotypes with values of 48.3, 44.6, 44.5, 45.2 and 41.7% respectively, showing vigorous growth compared to the other sorghum genotypes. Whereas the lowest germination was observed in KCV-275 and Zersta-90 with rates of 26.7% and 27.9% respectively.

Table 4. Growth variables of sorghum genotypes at maturity (averaged across 2019 and 2021 growing seasons).

	Sorghum genotypes	Germination, %	Vegetation period, day	Shoot height, cm	Length of panicle, cm
1	Chayka	44.6b	127c	228.0ab	21.0c
2	AOS 4250	38.9c	129c	94.4d	22.0c
3	FS Harmatta	30.8e	140ab	142.0c	22.0c
4	KCV-275	26.7f	139ab	204.0b	10.8f
5	Zersta-90	27.9f	128c	163.0c	21.0c
6	Stavropolsky	31.3e	117e	83.0d	10.0f
7	Kazakhstanskoe-16	48.3a	129c	217.0b	15.0e
8	Galiya	30.7e	125d	206.0b	21.0c
9	Uzbekistan-5	41.7c	128c	215.0b	29.0a
10	Chaigo	38.8c	138b	120.0c	20.0cd
11	Kazakhstanskoe-3	44.5b	137b	151.0c	18.0d
12	SSV-84	45.2b	147a	288.0a	19.0d
13	Orange-160	38.9c	146a	243.0ab	13.0ef
14	Kulja	33.7d	135b	272.0a	23.0b
15	ISCV-112	35.8d	136b	126.0c	21.0c
16	Line-1	32.8d	138b	206.8b	24.6b

Means marked with different letters represent significant differences ($p<0.05$).

The plant density was kept at a normal rate for all the tested sorghum genotypes, not more than 7-8 plants per meter in a row. This plant removing practice was done at the seedling stage to provide the plants to grow well and form heavyweight panicles.

The height of the main stem of the tested sorghum genotypes varied considerably and were conditionally divided into 3 groups. The first group - growth below 100 cm AOS 4250 (94.0 cm), Stavropolsky (83.0 cm); second group - stem height 100 cm and above: FS Harmatta (142.0 cm), Zersta-90 (163.0 cm), Chaigo (120.0 cm), Kazakhstanskoe-3 (151.0 cm), ISCV-112 (126.0 cm); the third group - the highest height of the main stem (above 200 cm): Chaika (228 cm), KCV-275 (204 cm), Kazakhstanskoe-16 (217 cm), Galiya (206 cm), Uzbekistan-5 (215 cm), SSV-84 (288 cm), Orange-160 (243 cm), Kulja (272 cm) and Line-1 (206.8 cm).

In terms of the panicle length, the shortest panicles between 10.0-15.0 cm length were observed in the following genotypes: KCV-275 (10.8 cm), Stavropol (10.0 cm), Kazakhstanskoe-16 (15.0 cm), and Orange-160 (13.0 cm). Whereas, the longest panicles (20-22 cm) were detected in Chayka, AOS 4250, FS Harmatta, Zersta-90, Chaigo, ISCV-112.

Almost half of the sorghum varieties were late ripe, i.e. FS Harmatta, KCV-275, Chaigo, Kazakstanskoe-3, SSV-84, Orange-160, ISCV-112 and Line-1, summing the vegetation period of 136-147 days. The most extended growing season was observed in Orange-160 and SSV-84 with 146-147 days' period. Among the tested genotypes of sorghum, the Stavropolsky genotype surpassed the others with the shortest growing season (117 days) and accordingly all stages of ripeness (lactic, waxy and full) occurred early. The wax maturity stage in all sorghum samples taken the entire month of August and full maturity occurred in the second and third decades of August, growing season 127-140 days.

The field experiment detected the superior growth performance of new sorghum genotypes in the new environment. These sorghum genotypes might become an integral component of farm production systems as the best land management practices, considering unfavourable environments of the region. The selection and evaluation of new salt-tolerant crop genotypes require a comprehensive understanding of alternative mechanisms of cultivation and seed multiplication processes (18).

Total biomass, vegetative mass and grain yield

The result indicated that the yield indices of the tested sorghum genotypes differed significantly (Table 5). The highest weight of seeds per panicle was found in Kazakhstanskoe-16 (84.2 g) followed by ISCV-112 (80.5 g) and Kazakhstanskoe-3 (70.8 g). AOS 4250 and FS Harmatta generated the same weight of seeds per panicle (68.0 g), whereas, the lowest indicators were determined in Orange-160 and KCV-275, producing 39.1 and 37.3 g respectively. By weight of 1000 seeds, higher indices were obtained in Chayka

(30,8 g), KCS-275 (31,2 g), Uzbekistan-5 (30.9 g). Whereas, the lowest weight of 1000 seeds were observed in Sta ropolsky (17.5 g), Kazakstanskoe-16 (16.8 g), Kazakstanskoe-3 (16.1 g).

Sorghum genotypes had grain yields ranging from 3240 to 6970 kg ha^{-1}. Kazakhstanskoe-16 produced the greatest grain output (6970 kg ha^{-1}), followed by Uzbekistan-5 (6720 kg ha^{-1}) and ISCV-112 (6640 kg ha^{-1}). Numerous sorghum genotypes demonstrated an average grain production, e.g. Chayka (5310 kg ha^{-1}), AOS 4250 (5640 kg ha^{-1}), Zersta-90 (4270 kg ha^{-1}), Stavropolsky (5810 kg ha^{-1}), Chaigo (4400 kg ha^{-1}), Kazakhstanskoe-3 (5820 kg ha^{-1}) and SSV-84 (4980 kg ha^{-1}). Orange-160 (3240 kg ha^{-1}) and KCV-275 (3070 kg ha^{-1}) showed the lowest grain yields, despite their extended growth cycles of 146 and 139 days respectively. The correlation analysis also showed a weak interaction (r=0.524) between the grain yield and vegetation period parameters, implying a genetic specificity has an advantage on the agronomic performance of the tested sorghum genotypes (Fig. 1). This discovery is consistent with earlier research demonstrating the adaptive specificity and varied physiological response of sorghum genotypes to salt (19). The selection of salt-tolerant genotypes is a sensitive task due to the complexity of biochemical, morphological and genetic traits (20, 21).

Table 5. Total biomass, vegetative mass and grain yield (averaged across 2019 and 2021 growing seasons).

	Sorghum genotypes	Total yield, kg ha^{-1}	Biomass, kg ha^{1}	Grain yield, kg ha^{-1}	Harvest index	Weight of 1000 seeds, g	Weight of seeds in 1 panicle, g
1	Chayka	54450b	49140c	5310c	0.10de	30.8a	64.0bc
2	AOS 4250	33530e	27890f	5640b	0.17b	26.9b	68.0b
3	FS Harmatta	28380f	24400g	3980de	0.14c	24.5b	68.0b
4	KCV-275	33200e	30130ef	3070f	0.09de	31.2a	37.3ef
5	Zersta-90	23100g	18830h	4270d	0.18b	22.6c	51.0d
6	Stavropolsky	24070g	18260h	5810b	0.24a	17.5e	43.0e
7	Kazakhstanskoe-16	60340a	53370b	6970a	0.12d	16.8e	84.2a
8	Galiya	-	-	-	-	-	-
9	Uzbekistan-5	30380ef	23660g	6720ab	0.22ab	30.9a	52.0d
10	Chaigo	32790e	28390f	4400d	0.13cd	24.9b	53.0d
11	Kazakhstanskoe-3	39100d	33280e	5820b	0.15c	16.1e	70.8b
12	SSV-84	43820c	38840d	4980cd	0.11d	23.0c	60.0c
13	Orange-160	61010a	57770a	3240f	0.05f	18.8d	39.1f
14	Kulja	-	-	-	-	-	-
15	ISCV-112	37100d	30460ef	6640ab	0.18b	25.6b	80.5ab
16	Line-1	-	-	-	-	-	-

Means marked with different letters represent significant differences ($p<0.05$).

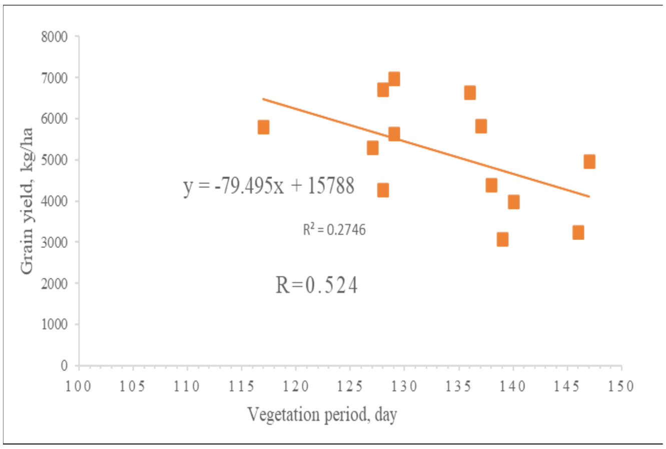

Fig. 1. Correlation analysis between sorghum grain yield and vegetation period (averaged across 2019 and 2021 growing seasons).

Straw production of the sorghum genotypes is usually high compared to other crops. This parameter considerably differentiated among the tested sorghum genotypes. The sorghum genotype Orange-160 produced a higher biomass yield (57770 kg ha^{-1}), followed by Kazakhstanskoe-16 (53370 kg ha^{-1}) and Chayka (49140 kg ha^{-1}). The following sorghum genotypes SSV-84, Kazakhstanskoe-3, KCV-275 and ISCV-112 showed average biomass yield with values of 38840, 33280, 30130 and 30460 kg ha^{-1} respectively. In contrast, Zersta -90 and Stavropolsky exhibited the lowest biomass yield with values of 18830 and 18260 kg ha^{-1} respectively.

The total yield based on biomass and grain yields was higher in Orange-160 and Kazakhstanskoe-16 followed by Chayka genotypes with values of 61010, 60340 and 54450 kg ha^{-1} respectively.

The ratio of grain yield to total biomass, i.e., harvest index (HI) of the tested sorghum genotypes was greatly differentiated. HI was higher in Stavropolsky (0.24) and Uzbekistan-5 (0.22), while lower in Orange-160 (0.05). Kazakhstanskoe-16 is the genotype with the greatest grain production, also had an average HI value (0.12).

Crop testing under high salinity enabled the collection to be classified into two distinct categories based on their end-use purpose: grain production or forage production. Firstly, Kazakhstanskoe-16 generated high values of grain yield (6970 kg ha^{-1}), even though it accumulated a good biomass yield (53370 kg ha^{-1}), implying this genotype may serve for dual-purpose end-use. The second selected genotype - Orange-160 accumulated a high biomass yield (57770 kg ha^{-1}) than grain yield (3240 kg ha^{-1}). This genotype can be used to single-purpose end-use (forage). Most of the tested genotypes were identified to have high ability to grain purpose end-use rather than forage purpose end-use. These values are essential for developing a national sorghum breeding programme and establishing a seed production and dissemination system among farmers under saline environments in the region. In addition, some researchers suggested modifying the infrastructure towards creating and scaling up sugar-bearing varieties/improved lines of sorghum, hence generating revenue from ethanol extraction (22). Alternatively, fodder provided by sorghum cultivation can solve the animal feeding problem and sustain the agricultural productivity of salt-affected areas, thereby increasing the profits of farmers (23).

This study elucidated the selection process of the best performing sorghum genotypes by the conventional breeding technique, using a range of selection criteria for widespread production to the specific agricultural habitat. High grain yield is considered the most important selection criteria in this study, followed by high biomass productivity and earliness. These findings corroborate numerous prior studies indicating that stress-tolerant crop genotypes may have an advantage in input efficiency without sacrificing yields under adverse circumstances (24). However, it is important to undergo genetic improvement for newly adapted crop genotypes, especially with respect to grain yield-related traits (25, 26). Also, it is worthy to notify that according to the results of the field experiments, three samples (Galia, Kulzha and Line-1) were rejected for further testing because of poor performance of agronomically valuable signs.

Salt tolerance indications of the selected sorghum genotypes

Experiments in Petri dishes indicated developed tolerance mechanism of the tested sorghum genotypes towards salinity (Fig. 2). Observations after 5 days of the seed germination process showed that Kazakhstanskoe-16 and Orange-160 had higher viability with 92 and 89.2% values compared to the local genotypes Uzbekistan-5 (68%) under non-saline condition. However, the seed germination rate values of the tested sorghum genotypes gradually decreased with increasing salinity concentrations. At 100 mM NaCl, the highest germination rate was observed in Kazakhstanskoe-16 (57.2%), followed by Orange-160 (41.2%) and Uzbekistan-5 (26.8%). Germination rates further decreased at 200 mM NaCl concentration, exhibiting 41.2; 22.4 and 9.2% for Kazakhstanskoe-16; Orange-160 and Uzbekistan-5 respectively. The local Uzbekistan-5 genotype did not show any germination at 300 mM NaCl and higher concentrations, while Kazakhstanskoe-16 and Orange-160 genotypes showed 22.4 and 11.2% germination at 300 mM NaCl and 6 and 4.4% at 400 mM NaCl concentration. But the germination rate was equal to zero in the tested sorghum genotypes at 500 mM NaCl salt concentration.

Exposure to various concentrations of NaCl (100-500 mM) significantly depressed seedling development.

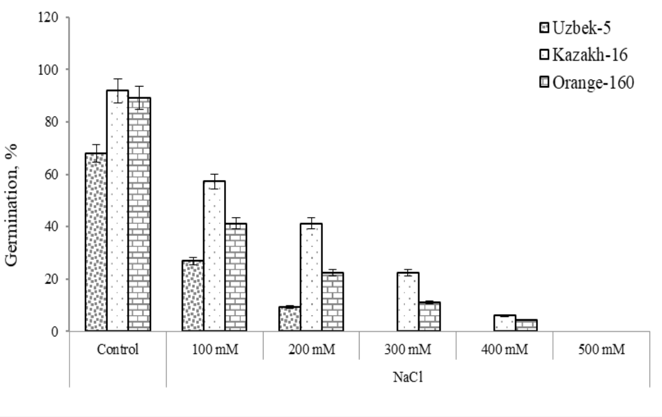

Fig. 2. Germination level of the selected sorghum genotypes under different concentrations of NaCl in Petri dishes (%).

A similar trend was also observed in root and shoot development experiments (Fig. 3, 4), exhibiting higher salt-tolerant abilities of new sorghum genotypes Kazakhstanskoe-16 and Orange-160 than that of the local Uzbekistan-5 genotype at different salt concentrations. As exhibited in the Fig. 2-4, higher seedling development indices were revealed in Kazakhstanskoe-16 followed by Orange-160, showing superiority in terms of salt tolerance.

This lab experiment confirmed the highest viability and germination values of the new sorghum genotypes, although these effects are dependent upon plant genetic characteristics. Indeed, salinity causes a decrease in biological and grain yield in various genetic materials, testifying the need of unique adaption features in stressful conditions (27, 28). For a long period of time, a few sorghum cultivars have been developed that are well suited to the severe climate of the Aral Sea region. However, many of them did not extend to large areas due to their inability to grow well in the tough environment.

Furthermore, these introduced sorghum genotypes demonstrated their potential for salinity tolerance as they surpassed in terms of seed germination, vegetative and reproductive development, dynamics of plant growth during the vegetative period and yield traits, which allow positively characterizing of their biological potential.

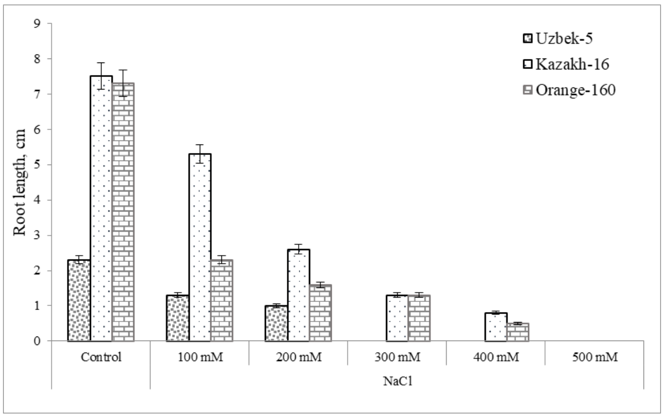

Fig. 3. Root development of the selected sorghum genotypes under different concentrations of NaCl in Petri dishes.

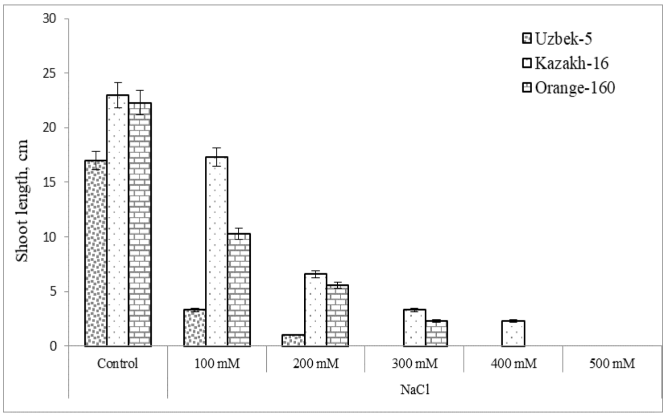

Fig. 4. Shoot development of the selected sorghum genotypes under different concentrations of NaCl in Petri dishes.

Conclusion

Selection and domestication of salt-tolerant, highly productive sorghum genotypes were found to be an innovative remediation strategy to enhance agricultural output under extreme saline edaphic of the Aral Sea regions. The top-performing Kazakhstanskoe-16 showed the highest grain yield of 6970 kg ha^{-1}, whereas Orange-160 yielded higher biomass (57770 kg ha^{-1}) than the other sorghum genotypes. Due to these positive features under the saline aquifer, these sorghum genotypes were recommended for further assessment to the State Varietal Commission of Agricultural Crops for large-scale use in this region.

It would be a great asset to study the genes controlling salt tolerance in sorghum, which may contribute to generating new stress-tolerant genotypes with high yield traits.

To summarize, a particular focus should be made to expanding sorghum production as a nutritious food and feed crop in salt-affected marginal regions of the Aral Sea regions, as it possesses significant potential and great adaption characteristics.

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Authors contributions

BK conceptualized, supervised and drafted the manuscript. AK and RY carried out the field researches and participated in the lab analysis. AK participated in the design of the study and performed the statistical analysis. YCK conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

References

1. Khaitov B, Karimov AA, Toderich K, Sultanova Z, Mamadrahimov A, Allanov K, Islamov S. Adaptation, grain yield and nutritional characteristics of quinoa (*Chenopodium quinoa*) genotypes in marginal environments of the Aral sea basin. J Plant Nutr. 2020;44(9):1365-79. https://doi.org/10.1080/01904167.2020.1862200
2. Khabibullaev BSh, Shomurodov KhF, Adilov BA. Impact of long-term climate change on *Moluccella bucharica* (B. Fedtsch.) Ryding. Population decline in Uzbekistan. Plant Sci Today. 2022; 9(2): 357-63. https://doi.org/10.14719/pst.1464
3. Allanov K, Sheraliev K, Ulugov C, Ahmurzayev S, Sottorov O, Khaitov B, Park KW. Integrated effects of mulching treatment and nitrogen fertilization on cotton performance under dryland agriculture. Commun Soil Sci Plant Anal. 2019;50(15): 1907-18. https://doi:org/10.1080/00103624.2019.164849
4. Vom Brocke K, Trouche G, Weltzien E, Barro-Kondombo CP, Gozé E, Chantereau J. Participatory variety development for sorghum in Burkina Faso: Farmers' selection and farmers' criteria. Field Crops Res. 2010; 119(1): 183-94. https://doi:org/10.1016/j.fcr.2010.07.005
5. Alirzayeva E, Ali-zade V, Shirvani T, Toderich K. Evaluation of wild halophytes of Aralo-Caspian flora towards soil restoration and food security improvement. In: Plants, Pollutants and Remediation. Dordrecht: Springer. 2015; p. 63-98. https://doi.org/10.1007/978-94-017-7194-8_4
6. Zewdu E, Hadgu G, Nigatu L. Impacts of climate change on sorghum production in North-Eastern Ethiopia. Afr J Environ Sci Tech. 2020; 14(2): 49-63. https://doi:org/10.5897/AJEST2019.2803
7. Mehmet OTEN. The effects of different sowing time and harvesting height on hydrocyanic acid content in some silage sorghum (*Sorghum bicolor* L.) varieties. Turk J of Field Crops. 2017;22(2):211-17. https://doi.org/10.17557/tjfc.356224
8. Ramatoulaye F, Mady C, Fallou S. Production and use sorghum: a literature review. J Nutr Health Food Sci. 2016;4(1):1-4. http://dx.doi.org/10.15226/jnhfs.2016.00157
9. USAID; Sector Environmental Guideline: Crop Production. 2020; Available at: www.usaid.gov/environmental-procedures/sectoral-environmental-social-best-practices/seg-crop-production/pdf
10. FAOSTAT Online Database. 2021; Available at: www.faostat.org (accessed December 2021).

11. Özyazici MA, Açıkbaş S. Effects of different salt concentrations on germination and seedling growth of some sweet sorghum [*Sorghum bicolor* var. *saccharatum* (L.) Mohlenbr.] Cultivars. Türkiye Tarim Araşt Derg. 2021; 8(2): 133-43. https://doi.org/10.19159/tutad.769463
12. Rajabi Dehnavi A, Zahedi M, Ludwiczak A, Cardenas Perez S, Piernik A. Effect of salinity on seed germination and seedling development of sorghum (*Sorghum bicolor* (L.) Moench) genotypes. Agron. 2020;10(6):859. https://doi.org/10.3390/agronomy10060859
13. Geressu K, Gezaghegne M. Response of some lowland growing sorghum (*Sorghum bicolor (*L.) Moench) accessions to salt stress during germination and seedling growth. Afr J Agric Res. 2008;3:44-48. https://doi.org/10.5897/AJAR12.045
14. El Naim AM, Mohammed KE, Ibrahim EA, Suleiman NN. Impact of salinity on seed germination and early seedling growth of three sorghum (*Sorghum biolor* (L.) Moench) cultivars. Sci Technol. 2012;2:16-20. https://doi.org/10.5923/j.scit.20120202.03
15. Mbinda W, Kimtai M. Evaluation of morphological and biochemical characteristics of sorghum (*Sorghum bicolor* (L.) Moench) varieties in response salinity stress. Annu Res Rev Biol. 2019;15:1-9. https://doi.org/10.3390/agronomy10060859
16. NIAST. Methods of soil and plant analysis. National Institute of Agricultural Science and Technology. Suwon, Korea: Academic Press; 2000.
17. CropStat 2.7. Statistical Software Program. 2015. International Rice Research Institute, Philippines. www.bbi.irri.org/products (Accessed December 21, 2021).
18. Hefny MM, Metwali EMR, Mohamed AI. Assessment of genetic diversity of sorghum (*Sorghum bicolor* (L.) Moench) genotypes under saline irrigation water based on some selection indices. Aust J Crop Sci. 2013; 7(12): 1935-45. https://doi.org/10.1016/j.sjbs.2014.05.005
19. Punia H, Tokas J, Malik A, Singh S, Phogat DS, Bhuker A et al. Discerning morpho-physiological and quality traits contributing to salinity tolerance acquisition in sorghum (*Sorghum bicolor* (L.) Moench). S Afr J Bot. 2021;140: 409-18. https://doi.org/10.1016/j.sajb.2020.09.036
20. Ogbaga CC, Stepien P, Dyson BC, Rattray NJW, Ellis DI, Goodacre R, Johnson GN. Biochemical analyses of sorghum varieties reveal differential responses to drought. PLoS One 2016;11:1-20. https://doi.org/10.1371/journal.pone.0154423
21. Singh D, Singh CK, Kumari S, Tomar RSS, Karwa S, Singh R et al. Discerning morpho-anatomical, physiological and molecular multiformity in cultivated and wild genotypes of lentil with reconciliation to salinity stress. PLoS ONE 2017; 12(5): p.e0177465. https://doi.org/10.1371/journal.pone.0177465
22. Erickson JE, Woodard KR, Sollenberger LE. Optimizing sweet sorghum production for biofuel in the southeastern USA through nitrogen fertilization and top removal. Bioenergy Res. 2012; 5(1):86-94. https://doi.org/10.15159/AR.20.072
23. Mumtaz A, Hussain D, Saeed M, Arshad M, Yousaf MI. Stability and adaptability of sorghum hybrids elucidated with genotype-environment interaction biplots. Turk J Field Crops. 2019;24(2):155-63. https://doi.org/10.17557/tjfc.631130
24. Pancaldi F, Trindade LM. Marginal lands to grow novel biobased crops: A plant breeding perspective. Front Plant Sci. 2020; 11:227. https://doi.org/10.3389/fpls.2020.00227
25. Jones MB, Finnan J, Hodkinson TR. Morphological and physiological traits for higher biomass production in perennial rhizomatous grasses grown on marginal land. GCB Bioenergy. 2015;7:375-85. https://doi.org/10.1111/gcbb.12203
26. Zhu XG, Chang TG, Song QF, Finnan J, Barth S, Mårtensson LM. A Systems approach guiding future biomass crop development on marginal land. In: Barth S, Murphy-Bokern D, Kalinina O, Taylor G, Jones M (Editors). Perennial Biomass Crops for a Resource-Constrained World. Berlin: Springer. 2016; p. 209-24. https://doi.org/10.1007/978-3-319-44530-4_18
27. Shakeri E, Emam Y, Tabatabaei SA, Sepaskhah AR. Evaluation of grain sorghum (*Sorghum bicolor* L.) lines/cultivars under salinity stress using tolerance indices. Int J Plant Product. 2017;11(1):101-15. https://doi.org/10.1080/11263504.2019.1569568
28. Khatun M, Shuvo MAR, Salam MTB, Rahman SH. Effect of organic amendments on soil salinity and the growth of maize (*Zea mays* L.). Plant Sci Today. 2019;6(2):106-11. https://doi.org/10.14719/pst.2019.6.2.491

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