ONLINE JOURNAL OF BIOLOGICAL SCIENCES

RESEARCH ARTICLE

Evaluation of Sweet Sorghum Varieties for Bioethanol Production Under Dryland Conditions

Ildar Bogapov[1], Marden Baidalin[1], Oksana Kibalnik[2] and Saltanat Baidalina[1*]

[1]*Sh. Ualikhanov Kokshetau University, Kokshetau, Kazakhstan*
[2]*Research and Design-Technological Institute of Sorghum and Corn, Saratov, Russia*

*Corresponding Author: turlubekova_salt@mail.ru

Abstract: The objective of this study was to evaluate the productivity potential and theoretical bioethanol yield of 12 sweet sorghum genotypes under dryland conditions of Northern Kazakhstan during the 2024-2025 growing seasons using a quantitative experimental design. Significant varietal differences in agronomic traits were observed depending on meteorological conditions. In 2024, the highest theoretical bioethanol yield was achieved by Sevilya (1417 L/ha), whereas in 2025, Sauri performed best (671 L/ha), with overall ethanol yield more than twofold lower in 2025 due to contrasting hydrothermal conditions. Cluster analysis identified two main clusters, with eight varieties suitable for bioethanol production. Correlation analysis revealed positive relationships between plant height, leaf length, stem yield, and bioethanol output. The novelty of this study lies in assessing the potential of different sweet sorghum varieties for bioethanol production under short growing seasons, heat-deficient, and moisture-limited conditions.

Keywords: Sweet Sorghum, Bioethanol, Sugar, Juice, Northern Kazakhstan

Received: 14-11-2025 | **Revised:** 23-02-2026 | **Accepted:** 01-04-2026 | **DOI:** 10.3844/ojbsci.2026.26.02.051

Introduction

Sweet sorghum (Sorghum bicolor (L.) Moench) is distinguished by its high drought tolerance and ability to produce substantial yields on soils of relatively low fertility [1]. This trait reflects its origin in the arid and semi-arid regions of Central and Southeastern Africa, with ancient cultivation centers also in dryland areas of India and China [2-4].

Sweet sorghum is mainly cultivated for silage, partly for hay production, and as fresh green forage [5]. In addition, sweet sorghum is of great interest as a feedstock for bioethanol production [6]. Juice pressed from the stalks contains 7-23% water-soluble sugars [7-9], giving sweet sorghum strong potential for ethanol production comparable to corn-grain-based ethanol [10].

The cultivation of sweet sorghum is common in regions with insufficient and unevenly distributed precipitation throughout the year. In such regions, climatic conditions are often unfavorable for maize, which generally produces lower yields than sorghum [11]. This tendency is also observed in relatively cool temperate climates [12].

Kazakhstan has approximately 62 million ha of agricultural land, of which nearly 26 million ha are degraded. Large areas are affected by erosion and salinization, limiting agricultural productivity [13]. Addressing land degradation and desertification is therefore a priority for sustainable development [14]. In this context, drought-tolerant crops suitable for marginal lands are particularly important, and sweet sorghum is considered a promising bioenergy option on marginal lands [15].

Advances in genetic and agronomic approaches enable the targeted selection of genotypes with high soluble-sugar concentrations and enhanced bioethanol potential. Dual-purpose hybrids, mutation breeding, genetic modification, and optimized agronomic practices (irrigation, nutrient supply, sowing and harvest timing, fertilizer application) can significantly improve bioethanol yield [16-18].

Under the conditions of Kazakhstan, sweet sorghum is capable of producing high biomass and accumulating considerable amounts of soluble sugars in the southeastern region [19]. However, Northern Kazakhstan is characterized by more limited thermal resources (the sum of active temperatures is approximately 2200°C; [20] and a shorter growing season, which necessitates the use of early-maturing varieties for seed production. One of the main constraints to introducing sorghum into northern regions is the shortage of adapted varieties and hybrids capable of successful development under these specific climatic conditions.

Sweet sorghum research in Kazakhstan has been concentrated mainly in the southern regions [21, 22]. The novelty of this study lies in assessing the potential of different sweet sorghum varieties for bioethanol production under the conditions of a short growing season, heat deficit, and limited moisture in Northern Kazakhstan. The results may be applied in regions with similar agro-climatic conditions. The main objective was to assess the productivity potential and theoretical bioethanol yield of sweet sorghum genotypes under the dryland conditions of Northern Kazakhstan.

Materials and Methods

Field Experiments (2024-2025)

Field experiments were conducted in the Akmola region of Northern Kazakhstan during the 2024-2025 growing seasons. The experimental site was located at 53°05′50″ N latitude and 69°11′24″ E longitude, at an elevation of 307 m above sea level. The experimental design followed a randomized complete block design with three replications. Sowing was performed on 5 June 2024 and 20 May 2025. Each plot had an area of 28 m². The sowing rate was 20 seeds per m² with a row spacing of 0.7 m and a seeding depth of 4-5 cm. Three inter-row cultivations were carried out during the growing season.

Plant Materials

The following sweet sorghum genotypes were evaluated: Kapital, Sevilya, Chayka, Volonter, Volzhskoye 51, Kalibr, Sakhara, Flagman, Izolda, Shakherizada (Russian Research and Design-Technological Institute of Sorghum and Corn, Russia), Slavyanskoye Priusadebnoye (SP) (All-Russian Scientific Research Institute of Sorghum and Soybeans, Russia), and Sauri (Alfaseed Kft, Hungary). The evaluated accessions had a vegetation period of up to 120 days in their regions of origin.

Observations and Analyses

Soil pH was measured in a KCl extract (1:2.5 ratio) using a pH meter. The contents of available phosphorus and exchangeable potassium were determined by the Machigin method, which involves extraction with 1% ammonium carbonate solution followed by colorimetric determination of phosphorus and photometric measurement of potassium. Organic matter content was determined using the Tyurin method (modified by Nikitina), based on oxidation of organic carbon with potassium dichromate in sulfuric acid, followed by photometric measurement of the reduced chromium. The amount of easily hydrolyzable nitrogen was determined by the Tyurin-Kononova method, which includes alkaline hydrolysis and photometric determination of released ammonium.

The onset of phenological stages (emergence, stem elongation, heading, flowering, milk stage, and wax stage) was recorded when 75% of plants reached each phase [23, 24]. Yield was determined by harvesting the entire plot and weighing the biomass. Dry matter yield was obtained by drying the biomass to constant weight at 65°C.

For bioethanol estimation, leaves and panicles were manually removed, and stalks were weighed to determine their proportion in total biomass. The soluble sugar content (%) in the stalk juice was measured using a hand refractometer prior to harvest by applying 1 mL of juice to a glass slide [25]. The Fresh Stalk Yield (FSY), Juice Yield (JY), Sugar concentration (S), Sugar Yield (SY), and theoretical Ethanol Yield (JEY) were calculated using the following formulas [26].

FSY (t/ha) = Stem proportion (%) × Fresh biomass yield (t/ha); JY (t/ha) = FSY (t/ha) × (stem moisture, %) / 100 (converted to kg/ha for subsequent calculations); S (%) = Brix (%) × 0.75 (conversion coefficient); SY (kg/ha) = S (%) × JY (kg/ha); JEY (L/ha) = SY (kg/ha) × conversion factor (0.581 L ethanol per kg sugar).

Soil and Climatic Conditions

The experimental field was characterized by medium-humus chernozem soil with a humus horizon depth of 25-27 cm. Agrochemical properties were determined for two horizons (0-20 cm and 20-40 cm), taking into account the deep root system of sorghum crops. Table (1) The content of nitrate nitrogen and phosphorus within the 0-40 cm layer was classified as low, while the potassium content was very high. The soil reaction was neutral, with pH values ranging from 7.7 to 7.9.

Table 1: Agrochemical characteristics of the experimental field

Year	Horizon (cm)	NO_3^--N (mg/kg)	P_2O_5 (mg/kg)	K_2O (mg/kg)	Organic matter (%)	pH
2024	0-20	20.6	13.8	526.3	5.7	7.7
	20-40	17.7	13.7	444.0	5.2	7.8
2025	0-20	5.3	16.8	533.6	10.3	7.7
	20-40	5.0	16.8	410.0	8.6	7.9

To assess the meteorological conditions during 2024-2025, the Selyaninov hydrothermal coefficient (HTC) was calculated using the formula HTC = SumP05 / (SumT05 / 10), where SumP05 represents the total precipitation (mm) during the period with mean daily air temperatures above +5°C, and SumT05 is the sum of daily mean temperatures (°C) for the same period [27].

Figure (1) In 2024, the HTC values remained stable throughout the entire growing season, indicating more favorable moisture conditions for plant growth. In 2025, a sharp monthly contrast was observed: the coefficient was low in May (0.3), increased sharply in June (1.3), and then decreased again from July onward. The year 2024 was more favorable, with stable and sufficient moisture availability, whereas in 2025, the early season and the active period of biomass accumulation occurred under dry conditions. This adversely affected plant development during critical growth phases and, consequently, overall productivity.

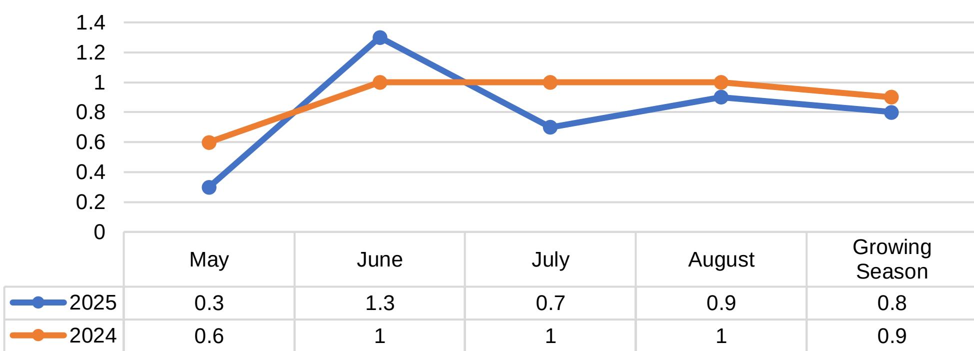


Fig. 1: Selyaninov's hydrothermal coefficient in the growing season

Statistical Analysis

Statistical analysis of the experimental data was performed using Analysis of Variance (ANOVA), hierarchical cluster analysis, and correlation analysis in STATISTICA version 10 (StatSoft, USA). A one-way ANOVA was used to evaluate differences among treatments based on the Fisher F-test, and the Least Significant Difference (LSD_{05}) was calculated at the 5% significance level ($p \leq 0.05$). Hierarchical cluster analysis was conducted using Euclidean distance and the single linkage method based on standardized trait values. Pearson's correlation coefficients were calculated to assess relationships among the studied traits.

Results

Figure (2) in 2024, the period from sowing to emergence lasted 6-7 days and showed no significant differences among the sorghum varieties. The phase “emergence-stem elongation” lasted from 49 days (Kapital) to 58 days (Chayka); “stem elongation-heading” from 9 days (Kapital and Chayka) to 12 days (Volonter); “heading-flowering” from 10 days (Flagman) to 23 days (Chayka and Volzhskoye 51); and “flowering-milk stage” from 19 days (Volonter) to 25 days (Kapital). The varieties Volonter, Kapital, and Sevilya reached the milk stage, while the remaining genotypes interrupted vegetation at the flowering-early milk stage due to a short-term frost observed on 17 September.

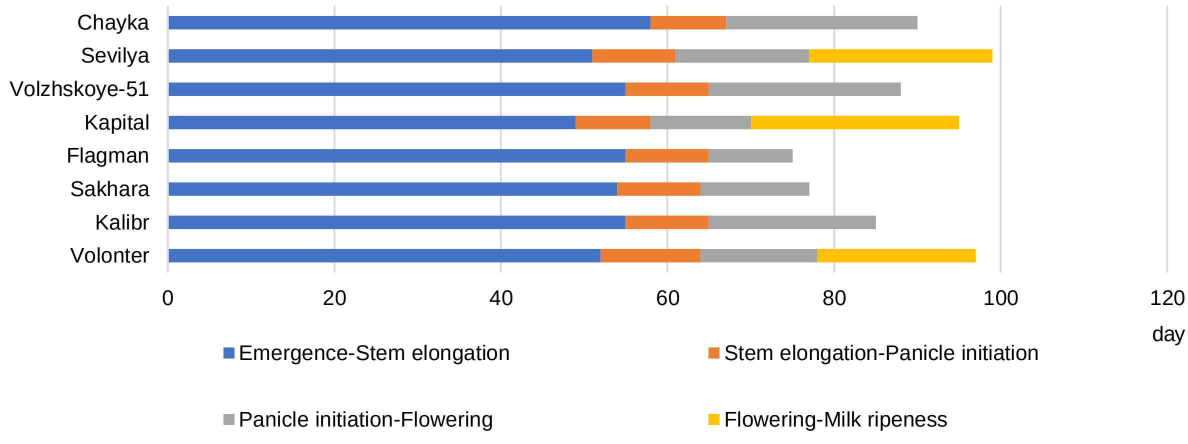


Fig. 2: Duration of interphase periods (2024)

Figure (3) in 2025, sorghum seedlings emerged within 11-12 days, which was longer than in the previous year. Evidently, the prevailing climatic conditions contributed to a slower emergence rate. The phase “emergence-stem elongation” lasted from 48 days (Volonter and Kapital) to 78 days (SP); “stem elongation-heading” from 11 days (Sahara and Flagman) to 15 days (SP); “heading-flowering” from 7 days (Volonter, Kalibr, and Izolda) to 17 days (Sahara, Flagman, and Sauri); “flowering-milk stage” from 14 days (Flagman) to 31 days (Kalibr); and “milk-wax stage” from 13 days (Volonter and Shakherizada) to 15 days (Chayka).

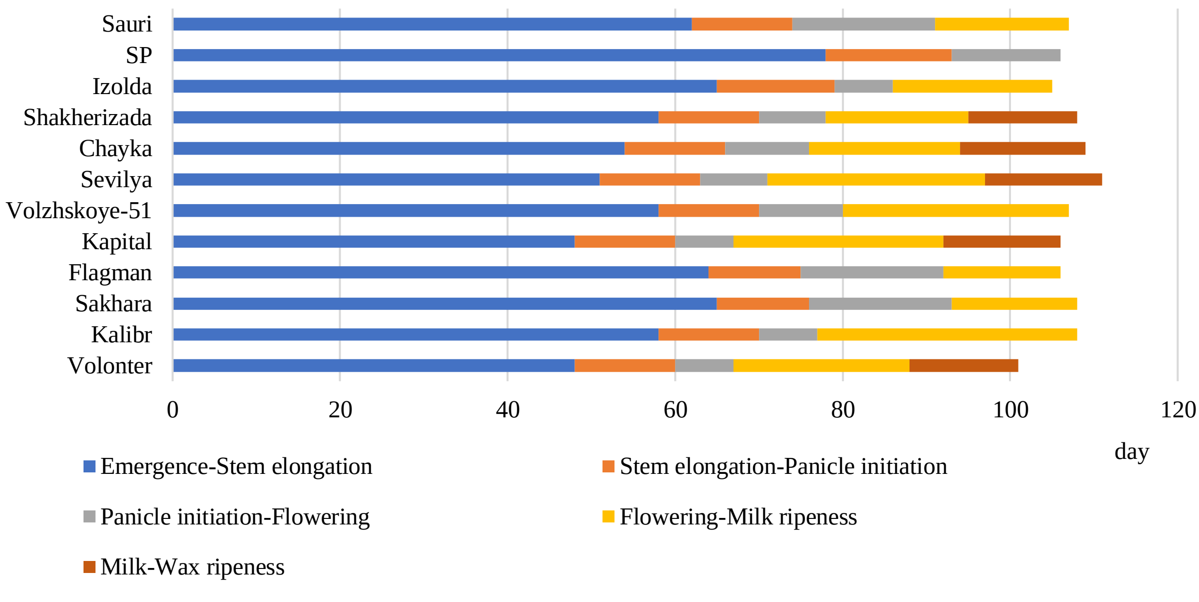


Fig. 3: Duration of interphase periods (2025)

Tables (2-3) present the yield and breeding characteristics of sweet sorghum plants during the vegetation periods. The results of the analysis of variance (ANOVA) indicated statistically significant differences (at the 5% level) among the studied varieties over the two years for all evaluated traits.

In 2024, plant height ranged from 189.2 to 231.6 cm, depending on genotypic characteristics. The tallest plants were recorded for the varieties Sevilya (231.6 cm), Flagman (221.4 cm), and Kapital (214.9 cm). The length of the largest leaf varied from 53.3 cm (Sevilya) to 72.0 cm (Flagman). The width of the largest leaf ranged from 6.1 cm (Flagman) to 7.4 cm (Volonter). Leafiness (% of total plant) ranged from 8.4% to 16.4%, with the highest values in Flagman (16.4%), followed by Sahara (13.0%) and Kapital (11.3%). Very low leafiness (<10%) was observed in Volonter, Volzhskoye 51, and Chayka. These differences in leafiness reflect varietal differences in leaf distribution and density, which may influence biomass accumulation.

The green biomass yield among the varieties varied from 30.1 t/ha (Chayka) to 36.8 t/ha (Volzhskoye 51). Higher yields were also recorded for Flagman (35.3 t/ha) and Sevilya (34.0 t/ha). The stem yield ranged from 25.3 t/ha (Volonter) to 31.5 t/ha (Volzhskoye 51). Under the growing conditions of the season, Kapital and Sevilya produced 26.9 t/ha and 28.1 t/ha, respectively (Table 2). Overall, these patterns indicate varietal-specific productivity and potential for bioethanol-oriented selection.

The concentration of soluble sugars in the stem juice ranged from 9.6% to 15.6%. The highest sugar content was recorded in Kapital (15.6%), Volonter (15.3%), and Sevilya (15.2%), while the lowest value was found in Chayka (9.6%). Genotypes combining high stem yield and sugar content may be prioritized for bioethanol production.

Table 2: Yield and selected breeding traits of sweet sorghum varieties (2024)

No.	Variety	Plant height (cm)	Largest leaf parameters		Yield		Leafiness (%)	Sugar (Brix)
			Length (cm)	Width (cm)	Biomass (t/ha)	Stems (t/ha)		
1	Volonter	205.5	58.6	7.4	32.1	25.3	9.5	15.3
2	Kalibr	200.4	70.0	6.6	32.6	26.7	10.8	12.0
3	Sakhara	189.3	56.7	7.2	32.2	26.4	13.0	13.6
4	Flagman	221.4	72.0	6.1	35.3	26.7	16.4	12.0
5	Kapital	214.9	66.0	6.7	32.2	26.9	11.3	15.6
6	Volzhskoye-51	197.7	62.0	6.4	36.8	31.5	8.4	10.1
7	Sevilya	231.6	53.3	6.1	34.0	28.1	10.0	15.2
8	Chayka	189.2	62.2	7.3	30.1	25.5	9.3	9.6
	F_{05}	90.52	23.40	3.70	6.88	8.86	1437.20	18.82
	LSD_{05}	4.53	4.34	0.80	2.38	1.96	0.20	1.61

Table (3) In 2025, plant height ranged from 101.9 cm (SP) to 195.8 cm (Sauri). The length of the largest leaf varied from 38.7 cm (Volonter) to 56.7 cm (Sauri). The width of the largest leaf ranged from 3.6 cm (Shakherizada) to 7.6 cm (SP). Leafiness ranged from 4.0% (Shakherizada) to 12.0% (SP). These differences in leafiness among varieties may affect biomass production.

Biomass and stem yields were much lower in 2025 compared to 2024. The green biomass yield varied from 13.0 t/ha (Volonter) to 19.1 t/ha (Chayka), reflecting a significant influence of both genotypic and environmental factors. Higher biomass yields were also recorded for Sauri (18.1 t/ha), Sahara (17.7 t/ha), and Flagman (17.1 t/ha). Stem yield ranged from 9.8 t/ha (Volonter) to 14.7 t/ha (Chayka), showing a trend similar to that of total biomass yield. The sugar content in stem juice ranged from 9.4% (SP) to 18.3% (Izolda). Higher values were also found in Sevilya (17.9%), Kapital (17.1%), and Sauri (16.0%). Varieties combining high stem yield and sugar content may be prioritized for bioethanol production.

Figure (4a) an important trait in the breeding of sweet sorghum is stem moisture content, which in 2024 varied from 73.7% (Kapital) to 80.7% (Chayka). Most varieties were characterized by high stem moisture, ranging between 76.0% and 78.2%. Juice yield varied from 19.7 t/ha (Kapital) to 25.2 t/ha (Volzhskoye 51). Figure (4b) in 2025, the stem moisture content of sorghum ranged from 68.6% (Sevilya) to 82.7% (SP). The remaining varieties showed similar values, ranging between 70.4% and 76.8%. Juice yield ranged from 7.49 t/ha (Volzhskoye 51) to 11.26 t/ha (Chayka).

Table 3: Yield and selected breeding traits of sweet sorghum varieties (2025)

No.	Variety	Plant height (cm)	Largest leaf parameters		Yield		Leafiness (%)	Sugar (Brix)
			Length (cm)	Width (cm)	Biomass (t/ha)	Stems (t/ha)		
1	Volonter	185.9	38.7	5.1	13.0	9.8	8.2	13.9
2	Kalibr	176.5	49.6	5.0	15.1	11.1	7.9	11.1
3	Sakhara	176.9	54.2	7.3	17.7	13.6	7.9	12.6
4	Flagman	185.3	49.1	5.1	17.1	13.4	5.2	15.1
5	Kapital	188.2	49.8	5.1	13.7	11.0	6.8	17.1
6	Volzhskoye-51	138.6	44.2	5.3	13.9	10.6	11.6	13.6
7	Sevilya	194.7	41.3	4.4	14.9	11.3	6.4	17.9
8	Chayka	181.6	52.8	5.8	19.1	14.7	6.3	12.7
9	Shakherizada	182.6	47.6	3.6	15.0	11.7	4.0	14.6
10	Izolda	170.8	45.0	6.2	13.7	10.4	9.3	18.3
11	SP	101.9	52.5	7.6	13.6	10.0	12.0	9.4
12	Sauri	195.8	56.7	5.9	18.1	13.7	9.6	16.0
	F_{05}	92.56	2.40	10.90	5.79	7.04	3.79	9.45
	LSD_{05}	7.89	10.26	1.01	2.54	1.84	3.67	2.61

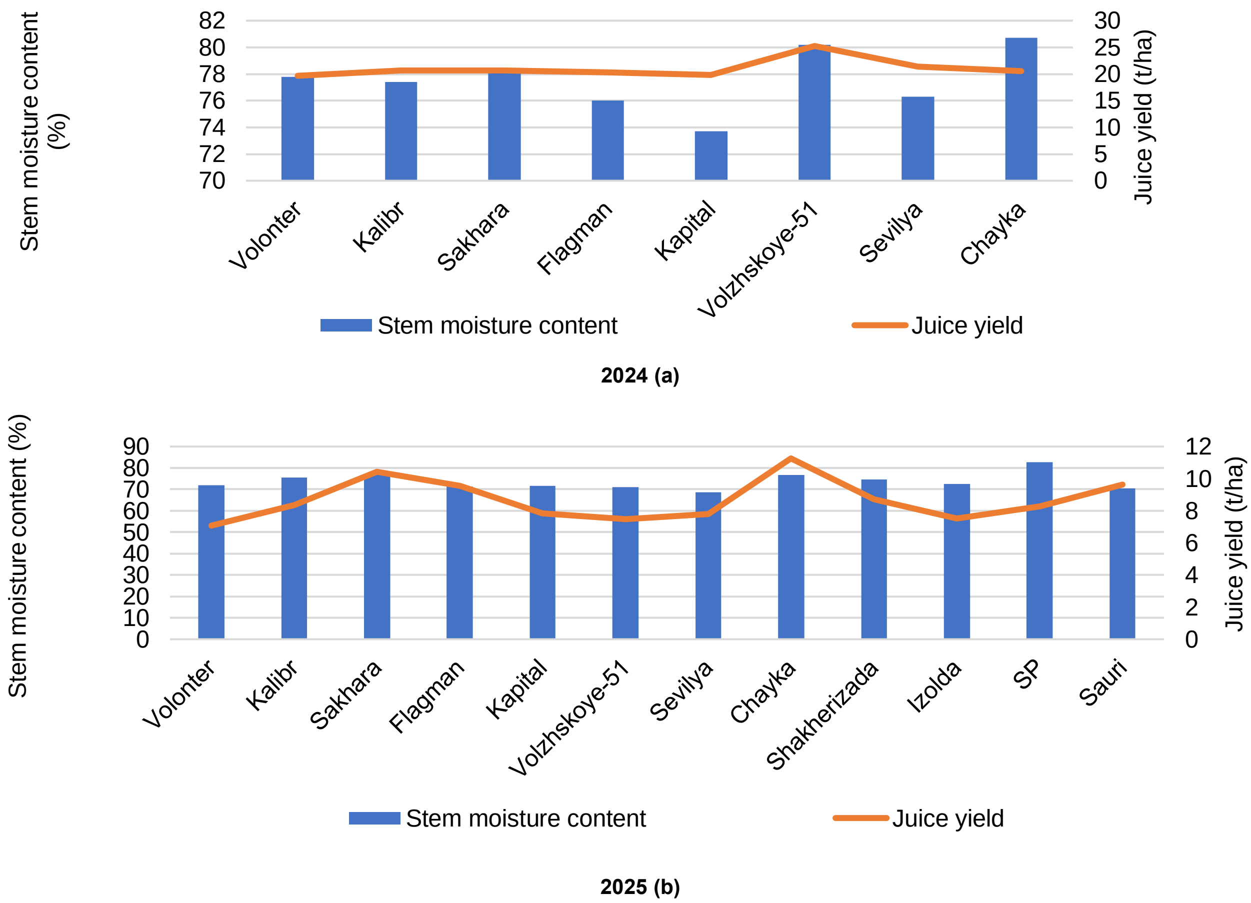


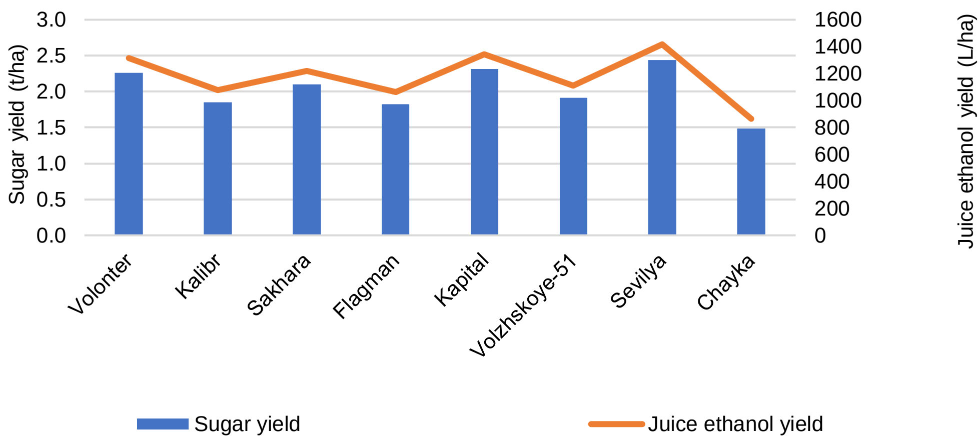
Fig. 4: Stem moisture content and juice yield of sweet sorghum accessions from the working collection (2024-2025)

DOI: 10.3844/ojbsci.2026.26.02.051

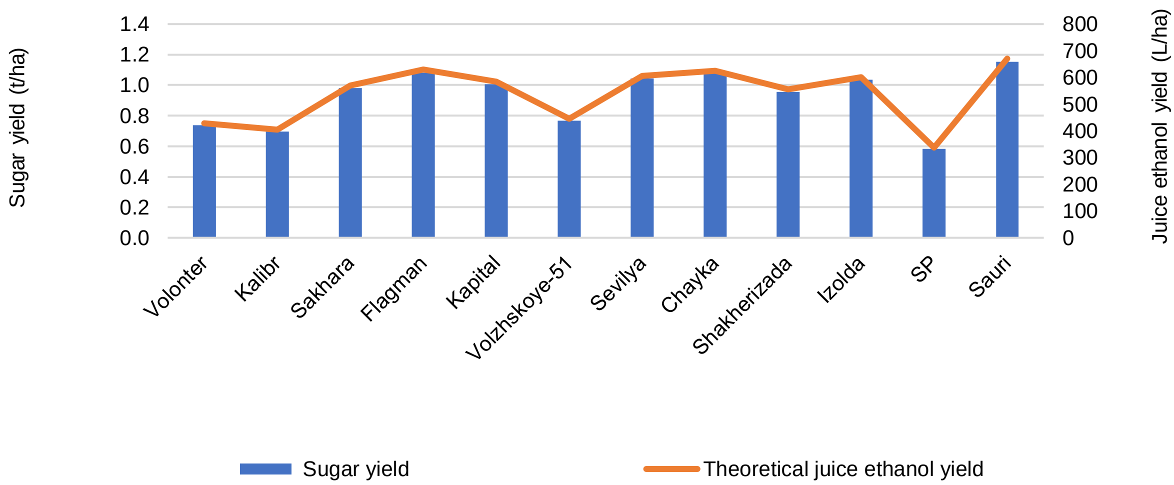
Figure (5a) In 2024, the sugar yield among the studied sweet sorghum varieties ranged from 1.5 t/ha (Chayka) to 2.4 t/ha (Sevilya). High sugar yields were also recorded for Sakhara, Volonter, and Kapital (2.1-2.3 t/ha). The theoretical ethanol yield from juice ranged from 864 L/ha (Chayka) to 1417 L/ha (Sevilya). High ethanol potential was also observed in Kapital (1344 L/ha) and Volonter (1314 L/ha). For Kalibr, Sakhara, and Volzhskoye 51, the theoretical ethanol yield ranged between 1076 and 1219 L/ha.

Figure (5b) In 2025, the sugar yield varied from 0.58 t/ha (SP) to 1.15 t/ha (Sauri). Yields exceeding 1.0 t/ha were recorded for Chayka, Flagman, Sevilya, Izolda, and Kapital (1.00-1.08 t/ha). The theoretical ethanol yield per hectare ranged from 337 L/ha (SP) to 671 L/ha (Sauri). The data presented in the diagrams indicate that, in 2025, both sugar and ethanol yields decreased more than twofold compared to the previous year.

Figure (6) Cluster analysis is one of the multivariate statistical methods that allows processing a large set of object characteristics and grouping them into clusters based on their similarity. To assess the degree of similarity among the working collection accessions (a total of 12), a hierarchical cluster analysis was performed using Euclidean distance and the single linkage method. The analysis included the following traits: sugar content (%), stem moisture content (%), juice yield (t/ha), biomass yield (t/ha), stem yield (t/ha), leafiness (%), duration of the “emergence-flowering” period (days), plant height (cm), length and width of the largest leaf (cm), theoretical sugar yield (t/ha), and theoretical ethanol yield from stem juice (L/ha). Based on the resulting dendrogram, two main clusters were identified.



2024 (a)



2025 (b)

Fig. 5: Sugar yield and theoretical ethanol yield per hectare of sweet sorghum accessions (2024-2025)

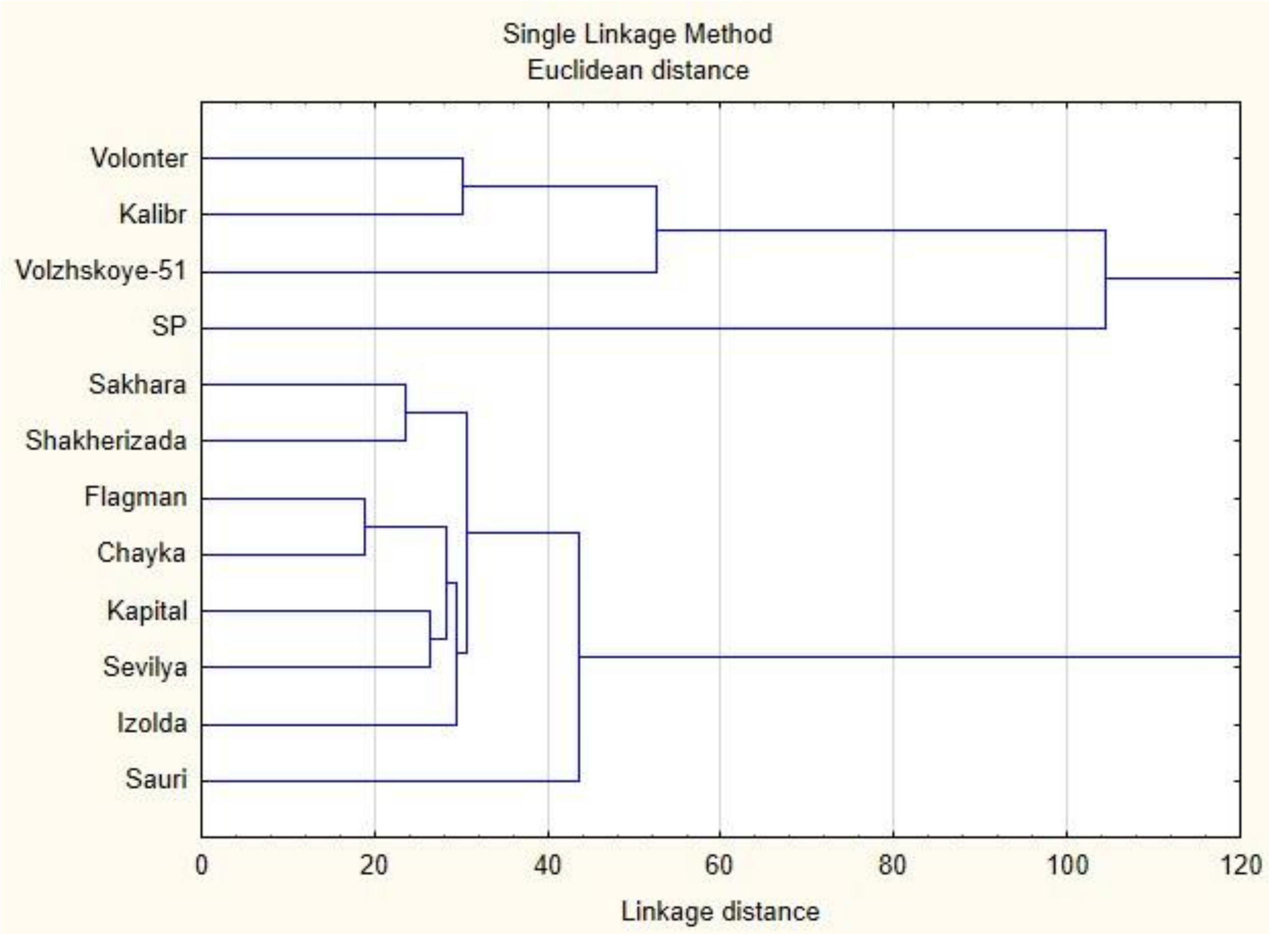


Fig. 6: Dendrogram of cluster analysis of sweet sorghum accessions from the working collection (2025)

Table (4) The first cluster included four accessions - Volonter, Kalibr, Volzhskoye 51, and SP - which showed the greatest distance from the other groups. Analysis of variance (ANOVA) confirmed significant differences between the clusters. The first cluster consisted of short-statured plants (average height 150.7 cm) with higher leafiness (9.93%) and lower stem yield (10.38 t/ha). These accessions were also characterized by moderate sugar accumulation in stem juice (12.08%), sugar yield of 0.69 t/ha, and a theoretical ethanol yield of 403.5 L/ha per hectare. The second cluster included eight accessions - Sakhara, Shakherizada, Flagman, Chayka, Kapital, Sevilya, Izolda, and Sauri. The breeding value of this group of accessions allows it to be recommended for the development of new varieties intended for industrial (technical) use. This cluster comprised tall plants (average height 184.5 cm) with low leafiness (6.94%) that produced 12.47 t/ha of stem yield. The synthesis of 15.54% sugars in stem juice resulted in a sugar yield of 1.04 t/ha and a theoretical ethanol yield of 605.38 L/ha per hectare.

Table (5) Simple correlation coefficients calculated for the studied sorghum varieties showed moderate positive correlations between stem yield (HS) and plant height (H) (r = 0.45), as well as with the Length of the Largest Leaf (LLL) (r = 0.65). A moderate negative correlation was found between green biomass yield (HOGM) and both stem yield (HS) and leafiness (L) (r = -0.31 and -0.41, respectively). Plant height (H) was strongly correlated (r = 0.72) with Sugar Yield (SY) and theoretical ethanol yield (JEY). Strong and moderate associations of theoretical ethanol yield (JEY) with green biomass and stem yield confirm the logical relationship between biomass productivity and ethanol potential.

DOI: 10.3844/ojbsci.2026.26.02.051

Table 4: Mean trait values of sweet sorghum accessions grouped into clusters (2025)

Trait	Cluster		F_{05}	LSD_{05}
	1	2		
Period “emergence-flowering” (days)	82.50	81.75	0.01	ns
Plant height (cm)	150.73 a	184.49 b	6.16*	30.31
Length of the largest leaf (cm)	46.25	49.56	1.0	ns
Width of the largest leaf (cm)	5.75	5.43	0.206	ns
Leafiness (%)	9.93 b	6.94 a	5.93*	2.73
Biomass yield (t/ha)	13.98	16.16	4.13	ns
Stem yield (t/ha)	10.38 a	12.47 b	6.50*	1.84
Sugar content in stem juice (%)	12.08 a	15.54 b	6.61*	3.00
Sugar yield (t/ha)	0.69 a	1.04 b	66.26*	0.09
Stem moisture content (%)	75.25	72.78	1.12	ns
Juice yield (t/ha)	7.79	9.09	3.23	ns
Theoretical ethanol yield (L/ha)	403.5 a	605.38 b	67.24*	54.85

$p \le 0.05$. Values marked with different letters differ significantly according to Duncan’s multiple range test at $p \le 0.05$. ns — not significant

Table 5: Correlation between agronomic and bioenergy-related traits of sweet sorghum accessions (2025)

Trait	S	SM	JE	HOGM	HS	L	H	EF	SY	JEY	LLL	WLL
S	1,00	-0,81	-0,27	-0,09	0,00	-0,33	0,62	-0,42	0,71	0,71	-0,34	-0,43
SM		1,00	0,31	0,05	-0,02	0,26	-0,67	0,55	-0,53	-0,53	0,46	0,62
JE			1,00	0,95	0,94	-0,32	0,21	0,34	0,48	0,48	0,75	0,30
HOGM				1,00	0,99	-0,31	0,38	0,25	0,61	0,61	0,68	0,17
HS					1,00	-0,41	0,45	0,19	0,70	0,70	0,65	0,11
L						1,00	-0,72	0,44	-0,52	-0,52	0,08	0,64
H							1,00	-0,58	0,72	0,72	-0,09	-0,54
EF								1,00	-0,12	-0,12	0,59	0,71
SY									1,00	1,00	0,25	-0,20
JEY										1,00	0,25	-0,20
LLL											1,00	0,52
WLL												1,00

Legend: S - Sugar content in stem juice; SM - Stem moisture content; JE - Juice yield; HOGM - Harvest of green mass; HS - Harvested stems (stem yield); L - Leafiness; H - Plant height; EF - Emergence-flowering period; SY - Sugar yield; JEY - Theoretical ethanol yield from juice; LLL - Length of the largest leaf; WLL - Width of the largest leaf. r>= -1 -0,80 -0,60 -0,40 -0,20 0 0,20 0,40 0,60 0,80 1

Discussion

A number of studies have confirmed that an important factor in the use of sweet sorghum is the selection of varieties for specific purposes, while the initial material must possess high adaptive capacity.

In a previous study by [28], the average green biomass yield of sweet sorghum was comparable to the values obtained in 2025. In 2024, however, plant productivity was significantly higher (30.1-36.8 t/ha), reflecting more favorable weather conditions and the influence of environmental factors on genotypic potential. Annual variations in sweet sorghum yield were also reported by [29], where noticeable differences in productivity were observed among varieties across different years.

Earlier studies established that genotypic features have the greatest influence on reducing sugar yield, while the parameters of acid and enzymatic hydrolysis for ethanol production have a much smaller effect under dryland conditions in various regions of the world [30]. At the same time, cultivation of sweet sorghum in northeastern Mexico resulted in 1051 L/ha of ethanol, and up to 1901 L/ha in Turkey [31, 32]. In the present study, the theoretical ethanol yield was strongly dependent on both genotypic and environmental factors, reaching 1417 L/ha under favorable conditions. These results highlight how genotype × environment interactions determine ethanol potential in Northern Kazakhstan.

The use of multivariate statistical methods, particularly cluster analysis, is widely applied and practically valuable for optimizing breeding programs. In sweet sorghum, the effectiveness of hierarchical structuring has been demonstrated for selecting accessions with the highest ethanol yield [33], sugar yield per hectare [34], and similar genetic background or origin [35, 36]. The results of this study are consistent with previous findings on genotypic diversity in sweet sorghum. Cluster analysis revealed clear distinctions between the groups and enabled the clustering of accessions with similar agronomic and biochemical traits. Among them, eight accessions of the second cluster were identified as the most promising for bioethanol production. The high values of key traits reflect not only genotypic characteristics but also adaptive potential for cultivation under the climatic conditions of the studied region.

The correlation analysis of the studied traits in sweet sorghum revealed positive associations between plant height and leaf length, as well as yield parameters. Similar results were reported in other studies [37]. Furthermore, ethanol yield was significantly influenced by sugar content in stem juice, stem yield, plant height, and sugar yield per hectare ($r = 0.70$-1.00). Moderate positive correlations were also found with green biomass yield and stem moisture ($r = 0.61$-0.62). These findings confirm the importance of these agronomic and biochemical traits as indicators of productivity and theoretical ethanol yield for breeding purposes.

Conclusion

Genotypic characteristics of the varieties exerted the strongest influence on reducing sugar yield. The highest theoretical ethanol yield was obtained for Sevilya (1417 L/ha) in 2024 and for Sauri (671 L/ha) in 2025, demonstrating a wide range of variability among genotypes and growing seasons. The use of multivariate statistical methods enabled the grouping of accessions with similar agronomic and biochemical characteristics and identified eight promising accessions (Sakhara, Shakherizada, Flagman, Chayka, Kapital, Sevilya, Izolda, and Sauri) for bioethanol production. Correlation analysis revealed positive relationships between plant height, leaf length, and yield, as well as strong correlations between theoretical ethanol yield and sugar content in stem juice, stem yield, plant height, and sugar yield per hectare. These parameters can be effectively used as selection indicators for improving productivity and developing varieties for energy and industrial purposes. The results highlight the potential of sweet sorghum for bioethanol production and the need for targeted breeding and introduction of adapted varieties under the dryland conditions of Northern Kazakhstan.

Acknowledgment

The authors express their gratitude to the Russian Research and Design-Technological Institute of Sorghum and Corn (Russia) and to Alfaseed Kft (Hungary) for providing the seed materials used in this study.

Funding Information

The research was funded by the Scientific Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under the “Zhas Galym” grant program for young researchers (2024-2026, 36 months) as part of the project entitled “Biochemical and energy evaluation of sweet sorghum genotypes and improvement of biomass production methods for processing into bioethanol” (Project IRN: AP22683056).

Author’s Contributions

Ildar Bogapov: Conceptualization, field experiments, statistical processing, drafting, and final revision of the manuscript.

Marden Baidalin: Field data collection, data tabulation, manuscript drafting.

Oksana Kibalnik: Methodological supervision, interpretation of results, manuscript revision.

Saltanat Baidalina: Laboratory analysis, data verification, and contribution to manuscript editing.

Ethics

This study was conducted in accordance with research ethics guidelines and national regulations. Field experiments on sweet sorghum were performed on agricultural research plots. The research did not involve experiments on humans or animals.

References

1. Getachew, G., Putnam, D. H., De Ben, C. M., & De Peters, E. J. (2016). Potential of Sorghum as an Alternative to Corn Forage. American Journal of Plant Sciences, 7(7), 1106-1121. https://doi.org/10.4236/ajps.2016.77106
2. Venkateswaran, K., Elangovan, M., & Sivaraj, N. (2019). Origin, Domestication and Diffusion of Sorghum bicolor. Breeding Sorghum for Diverse End Uses, 15-31. https://doi.org/10.1016/b978-0-08-101879-8.00002-4
3. Wet, J. M. J., & Huckabay, J. P. (1967). The Origin of Sorghum Bicolor. Ii. Distribution and Domestication. Evolution, 21(4), 787-802. https://doi.org/10.1111/j.1558-5646.1967.tb03434.x
4. Kimber, C. T. (2000). Origins of domesticated sorghum and its early diffusion to China and India. Sorghum: Origin, History, Technology, and Production, 3-97.
5. Zhapayev, R., Toderich, K., Kunypiyaeva, G., Kurmanbayeva, M., Mustafayev, M., Ospanbayev, Z., Omarova, A., & Kusmangazinov, A. (2023). Screening of Sweet and Grain Sorghum Genotypes for Green Biomass Production in Different Regions of Kazakhstan. In Journal of Water and Land Development (Vol. 56, Issues 1-3, pp. 118-126). https://doi.org/10.24425/jwld.2023.143752
6. Mathur, S., Umakanth, A. V., Tonapi, V. A., Sharma, R., & Sharma, M. K. (2017). Sweet sorghum as biofuel feedstock: recent advances and available resources. Biotechnology for Biofuels, 10(1), 146. https://doi.org/10.1186/s13068-017-0834-9
7. Almodares, A., & Hadi, M. R. (2009). Production of bioethanol from sweet sorghum: A review. African Journal of Agricultural Research, 4(9), 772-780.
8. Regassa, T. H., & Wortmann, C. S. (2014). Sweet sorghum as a bioenergy crop: Literature review. Biomass and Bioenergy, 64, 348-355. https://doi.org/10.1016/j.biombioe.2014.03.052
9. Habtegiorgis, T., Getahun, T., Guadie, D., Enyew, M., & Feyissa, T. (2025). Biochemical evaluations of Ethiopian sweet sorghum [Sorghum bicolor (L.) Moench] accessions for sugar production. Scientific Reports, 15(1), 37514. https://doi.org/10.1038/s41598-025-21488-3
10. Hunter, E. L., Anderson, I. C., & Janick, J. (1997). Sweet sorghum. Horticultural Reviews, 21, 73-104. https://doi.org/10.1002/9780470650660.ch3
11. Maw, M. J. W., Houx, J. H., & Fritschi, F. B. (2017). Maize, sweet sorghum, and high biomass sorghum ethanol yield comparison on marginal soils in Midwest USA. Biomass and Bioenergy, 107, 164-171. https://doi.org/10.1016/j.biombioe.2017.09.021
12. Alix, H., Tremblay, G. F., Chantigny, M. H., Bélanger, G., Seguin, P., Fuller, K. D., Bittman, S., Hunt, D., Larney, F. J., Acharya, S. N., & Vanasse, A. (2019). Forage yield, nutritive value, and ensilability of sweet pearl millet and sweet sorghum in five Canadian ecozones. Canadian Journal of Plant Science, 99(5), 701-714. https://doi.org/10.1139/cjps-2019-0031
13. Yessenbayeva, G., Ilyas, A., Kenenbayev, S., Zhanbyrbayev, Y., Kulanbay, K., Dutbayev, Y., & Kultassov, B. (2025). Impact of Agritechnologies on the Biomass and Nutritional Parameters of Crops: A Study of Corn, Soybean, and Pea in Southeast Kazakhstan. OnLine Journal of Biological Sciences, 25(4), 1063-1069. https://doi.org/10.3844/ojbsci.2025.1063.1069
14. Apshikur, B., Alimkulov, M., Kapasov, A., & Toleubekyzy, I. (2024). Innovative technology for assessing the degradation of the Earth by sand desertification of soils with specialized processing of space materials. InterCarto. InterGIS, 30(2), 223-235. https://doi.org/10.35595/2414-9179-2024-2-30-223-235
15. Fu, H. M., Meng, F. Y., Molatudi, R. L., & Zhang, B. G. (2016). Sorghum and Switchgrass as Biofuel Feedstocks on Marginal Lands in Northern China. BioEnergy Research, 9(2), 633-642. https://doi.org/10.1007/s12155-015-9704-0
16. Kanbar, A., Flubacher, N., Hermuth, J., Kosová, K., Horn, T., & Nick, P. (2021). Mining Sorghum Biodiversity—Potential of Dual-Purpose Hybrids for Bio-Economy. Diversity, 13(5), 192. https://doi.org/10.3390/d13050192
17. Xu, Y., Li, J., Xin, Z., Bean, S. R., Tilley, M., & Wang, D. (2020). Water-Soluble Sugars of Pedigreed Sorghum Mutant Stalks and Their Recovery after Pretreatment. Applied Sciences, 10(16), 5472. https://doi.org/10.3390/app10165472
18. Alsanad, M. A., & Emara, E. I. R. (2024). Optimizing Bioethanol (C2H5OH) Yield of Sweet Sorghum Varieties in a Semi-Arid Environment: The Impact of Deheading and Deficit Irrigation. Water, 16(10), 1456. https://doi.org/10.3390/w16101456
19. Baiseitova, G., Moraru, G., Sarsenbayev, B., Kirshibayev, E., & Kenenbayev, S. (2021). Biological Characteristics and Productivity of Sweet Sorghum Varieties in the Arid Conditions of Southeastern Kazakhstan. OnLine Journal of Biological Sciences, 21(2), 245-252. https://doi.org/10.3844/ojbsci.2021.245.252
20. Baisholanov, S., Akshalov, K., Mukanov, Y., Zhumabek, B., & Karakulov, E. (2024). Agro-Climatic Zoning of the Territory of Northern Kazakhstan for Zoning of Agricultural Crops Under Conditions of Climate Change. Climate, 13(1), 3. https://doi.org/10.3390/cli13010003
21. Sarsenbayev, B., Kirshibayev, Y., Kamunur, M., Baiseitova, G., Sarybayeva, E., & Nokerbekova, N. (2013). A biotechnology for production of bioethanol from stems sweet sorghum (Sorghum saccharatum (L.) Pers.). Eurasian Journal of Applied Biotechnology, 3, 61-64. https://doi.org/https://biotechlink.org/index.php/journal/article/view/282
22. Mambetov, K., Bozhbanov, A., Dzhakupova, I., Abildaeva, R., & Mamykova, R. (2024). Influence of Fertilizers and Bioactive Substances on Sugar Sorghum Yield in Southern Kazakhstan. International Journal of Design & Nature and Ecodynamics, 19(2), 591-603. https://doi.org/10.18280/ijdne.190225
23. Rao, S. S., Elangovan, M., Umakanth, A. V., & Seetharama, N. (2008). Characterizing phenology and growth stages of sorghum hybrids. Sorghum Improvement in the New Millennium, 16-22.
24. Roozeboom, K. L., & Prasad, P. V. (2019). Sorghum growth and development. 58. https://doi.org/10.2134/agronmonogr58.c8

25. Kasegn, M. M., Simachew, A., Redda, Y. T., Gebremedhn, H. M., Berhanu, A. D., & Mossa, M. M. (2024). Evaluation of sugar content and bioethanol production of Ethiopian local varieties “Nech Tinkish” and “Hawaye. Biotechnology for the Environment, 1(1), 2. https://doi.org/https://doi.org/10.1186/s44314-024-00001-6
26. Nazli, R. I., Tansi, V., Gulnaz, O., Kafkas, E., Kusvuran, A., Ozturk, H. H., & Bostan Budak, D. (2020). Interactive Effects of Nitrogen and Humic Substances Applications on Bioethanol Production from Sweet Sorghum and Combustion Characteristics of Its Bagasse. Agronomy, 10(9), 1397. https://doi.org/10.3390/agronomy10091397
27. Devyatova, E., Kochugova, E., & Cydenzapov, M. (2022). Comparison of Selyaninov’s Hydrothermal Coefficient (Aridity Criterion) over Buryatia, Russia, in the Summer Period from 1979 to 2019 according to Meteorological Stations and ECMWF ERA5. Proceedings of the 5th International Electronic Conference on Atmospheric Sciences, 55. https://doi.org/10.3390/ecas2022-12805
28. Bogapov, I., Memeshov, S., Kibalnik, O., & Sagalbekov, U. M. (2024). Sweet Sorghum (Sorghum Bicolor l.) Genotypes Assessment for Food, Fodder, and Energy Values in Northern Kazakhstan. SABRAO Journal of Breeding and Genetics, 56(1), 156-167. https://doi.org/10.54910/sabrao2024.56.1.14
29. Porčová, L., Frantová, N., Rábek, M., Jovanović, I., Smutný, V., Řiháček, M., & Mrkvicová, E. (2025). Yield Potential of Silage Sorghum: Cultivar Differences in Biomass Production, Plant Height, and Tillering Under Contrasting Soil Conditions in Central Europe. Agronomy, 15(10), 2352. https://doi.org/10.3390/agronomy15102352
30. Mehmood, S., Gulfraz, M., Tahir, M. S., Ur Rehman, M. S., Aqil, T., & Mahmood, T. (2014). Statistical screening and selection of sweet sorghum varieties for bioethanol production. Pakistan Journal of Botany, 46(3), 1115-1120.
31. Davila-Gomez, F. J., Chuck-Hernandez, C., Perez-Carrillo, E., Rooney, W. L., & Serna-Saldivar, S. O. (2011). Evaluation of bioethanol production from five different varieties of sweet and forage sorghums (Sorghum bicolor (L) Moench). Industrial Crops and Products, 33(3), 611-616. https://doi.org/10.1016/j.indcrop.2010.12.022
32. Nazli, R. I., Aslankaciran, C., Yang, D., Liaqat, W., Polat, M., Cavdar, A. S., Tansi, V., & Baloch, F. S. (2024). Assessment of Sweet Sorghum Genotypes for Bioethanol Production Potential and Bagasse Combustion Characteristics in a Semi-Arid Mediterranean Climate. Agronomy, 14(11), 2626. https://doi.org/10.3390/agronomy14112626
33. Umakanth, A. V., Nsikhil, B. S. krisshna, & Tonapi, V. A. (2019). Genetic diversity studies in sweet sorghum [Sorghum bicolor (L.) Moench], a candidate crop for biofuel production. Forage Research, 45(1), 28-32. https://forageresearch.in/wp-content/uploads/2019/06/28-32.pdf
34. Kibalnik, O. P., & Kibalnik, S. V. (2025). Forecasting and choice of the starting material in the selection of sugar sorghum based on clustering. Bulletin of NSAU (Novosibirsk State Agrarian University), 4, 54-61. https://doi.org/10.31677/2072-6724-2024-73-4-54-61
35. Yahaya, M. A., Shimelis, H., Nebie, B., Ojiewo, C. O., Rathore, A., & Das, R. (2023). Genetic Diversity and Population Structure of African Sorghum (Sorghum bicolor L. Moench) Accessions Assessed through Single Nucleotide Polymorphisms Markers. Genes, 14(7), 1480. https://doi.org/10.3390/genes14071480
36. Sejake, T., Shargie, N., Christian, R., Amelework, A. B., & Tsilo, T. J. (2021). Genetic diversity in sorghum (Sorghum bicolor L. Moench) accessions using SNP based Kompetitive allele-specific (KASP) markers. Australian Journal of Crop Science, 15(06), 890-898. https://doi.org/10.21475/ajcs.21.15.06.p3088
37. Anija Hari Kumar, S., Chacko Thomas, U., Al-Salman, Y., Cano, F. J., Stephen, R., Pillai, P. S., & Ghannoum, O. (2025). Evaluation of Yield-Related Morphological, Physiological, Agronomic, and Nutrient Uptake Traits of Grain Sorghum Varieties in the Kerala Region (India). Agronomy, 15(10), 2320. https://doi.org/10.3390/agronomy15102320
38. Somu, G., Meena, N., & Badigannavar, A. (2025). Exploring genetic variability for morphological and yield contributing traits in sorghum (Sorghum bicolor (L.) Moench) germplasm from Southern India. Genetic Resources and Crop Evolution, 72(5), 5179-5194. https://doi.org/10.1007/s10722-024-02251-5