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Sorghum genotypes response to dryland conditions of northern Kazakhstan

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ABSTRACT

Sorghum genotypes are characterised by drought resistance and high biomass production, which makes them suitable for animal feeding under conditions of fodder scarcity in dry steppe zones. Under the harsh continental conditions in northern Kazakhstan, the selection of suitable sorghum genotypes is crucial for maintaining yield stability and product quality. In 2020–2022, studies were conducted in northern Kazakhstan on 9 varieties of sweet sorghum and 7 hybrids of sweet sorghum–sudangrass to determine the relationship between qualitative and productive traits for modelling optimal material. Hybrids were inferior to sweet sorghum in terms of total yield and stem biomass, but had a higher leaf mass, making them more suitable for use as animal feed. The results contribute to a better understanding of plant resilience and support the promotion of sorghum and sorghum–sudangrass hybrids in cold regions with short summers for sustainable forage production under uncertain climatic conditions. The results show that the 2 sweet sorghum genotypes (Kapital and Volonter) are characterised by stable productivity and good adaptability under different environmental conditions, as they can reach full maturity over the three years. Volzhskoye 51 and Calibr genotypes are best suited for green mass production under higher rainfall conditions, while the SP 15 genotype is best among sorghum-sudangrass hybrids. The sweet sorghum varieties Sevilia, Kapital and Sahara stood out for their higher sugar content in stem juice and can be recommended for bioethanol production.

Keywords: Northern Kazakhstan, sweet sorghum, sweet sorghum x sudangrass hybrid, production, quality

INTRODUCTION

Sorghum (*Sorghum bicolor* (L) Moench) is the fifth most important cereal in the world after rice, wheat, maize and barley. It is grown for grain, animal feed, sugar and biofuel. In addition, sorghum extracts certain heavy metals from the soil (Osman et al., 2023), contributes to phytoremediation of leached chernozem contaminated with diesel fuel (Muratova et al., 2012), improves water infiltration, reduces soil compaction, increases the stability of soil aggregates and organic matter in the soil and suppresses weed establishment (Boga, 2020). Sorghum grains are the staple food for more than 750 million people in the semi-arid tropics of Africa, Asia and Latin America. Around the world, sorghum is grown on marginal soils under difficult conditions such as water deficit, salinity and alkalinity and is used as food, feed and biofuel (Hariprasanna and Patil, 2015). It is a C4 short-day crop with high adaptability to hot and dry agroecological conditions, which makes it a climate-tolerant crop. As such, sorghum can maintain productivity and contribute to food security, even under extreme conditions when other crops fail (Ciampitti and Prasad, 2019).

Due to these properties, sorghum is considered one of the most important crops for sustainable agriculture in the face of climate change (Mohammed and Misganaw, 2022). Sorghum has a greater tolerance to high temperatures and water stress compared to most other cereals and achieves stable grain yields even at temperatures of up to 33 °C (Tack et al., 2017) and with limited water availability (Taylor, 2019). According to Druille et al. (2020), the base and optimum temperatures for forage sorghum are 10 °C and 27.5 °C, respectively, while for grain sorghum they are 8 °C and 30 °C, which emphasises its adaptability to high temperatures. In addition, sowing at a soil temperature above 18 °C is recommended, as early sowing at a soil temperature below 15 °C can lead to sparse seedlings and poor growth performance (Chiluwal et al., 2018). Therefore, identifying sorghum genotypes that are resistant to cold temperatures in the early stages of development is crucial for extending the growing season and creating opportunities to expand sorghum cultivation in the northern regions of Kazakhstan and regions with similar climatic conditions.

The discovery of cytoplasmic male sterility in sorghum has greatly improved the utilisation of heterosis for yield and yield components and has enabled the development of commercial hybrids for forage sorghum. These hybrids are produced by crossing sorghum as the female parent with sudangrass as the male parent (Pataki et al., 2010). The sorghum-sudangrass hybrid is an annual forage crop that combines the high biomass and high leaf yield, improved tillage ability, rapid regrowth and high nutritional value of both parents, while exhibiting considerable heterosis (Lu et al., 2022). In general, newly developed sorghum and sorghum × sudangrass genotypes have high biomass yield potential, improved water and nitrogen use efficiency, better abiotic stress tolerance and the ability to grow on a wide range of soil types without specific requirements (Bollam et al., 2021; Tu et al., 2023). However, sorghum and sorghum × sudangrass genotypes respond differently to local environmental conditions at different stages of development. Recent research in Southeast Europe on sorghum genotypes (Dolapčev et al., 2025) indicates that forage sorghum hybrids are a promising alternative for both fodder and bioenergy production due to their high level of drought tolerance. Through the evaluation of genotypic variation and environmental adaptability in 60 forage sorghum genotypes — including 13 parental lines, their 40 crosses, and seven commercial hybrids — it was determined that plant height, stem diameter, and leaf-related traits contributed most significantly to genotypic differentiation. On the other hand, no single parameter proved reliable for prediction, suggesting a complex interaction among traits. Zheng et al. (2024) also emphasize that sorghum is highly stress-resistant and capable of growing under adverse environmental conditions. Identifying the mechanisms behind this resistance would enable its cultivation in regions of the world previously considered marginal.

According to Zhapayev et al. (2023), genotypes were responsible for 22.4% of the variation in green biomass of sweet sorghum, while environmental conditions accounted for 52.4% and genotype-environment interaction for 21.3% in Kazakhstan. According to Silva et al. (2013), the identification of varieties adapted to each region is necessary due to the large differences in weather conditions. Therefore, the choice of genotypes is a crucial factor that determines the final biomass yield and quality. Zhapayev et al. (2015) and Bulekov et al. (2023) investigated the performance of sorghum and sorghum × sudangrass genotypes and concluded that only some of them achieve yields above 100 t/ha under local conditions in Kazakhstan. Liubych et al. (2021) tested 21 varieties and hybrids of sweet sorghum from Ukraine, Russia, Brazil, the USA, Hungary, Germany and France from 2018 to 2020. The authors identified valuable germplasm with high dry matter yield (11.1–12.2 t/ha), grain yield (8.00–8.15 t/ha), and protein content (9.8–11.3%).

The main objective of this study was to evaluate the performance of sorghum and sorghum × sudangrass genotypes under dryland conditions over three years. The evaluation focused on phenological development to determine the adaptability and growth dynamics of each genotype under water-limited conditions, while aboveground biomass was quantified as a key indicator of productivity under stress conditions. In addition, stem sugar content was assessed to identify genotypes with potential for utilisation in bioenergy and forage systems, integrating biomass yield and quality traits relevant to dryland agriculture. This study also aims to evaluate the adaptability of sorghum germplasm to changing climate conditions, emphasizing its relevance for sustainable crop production and land use management in arid and semi-arid regions.

MATERIALS AND METHODS

Field experiments (2020 - 2022)

A field trial was conducted in the Northern Kazakhstan region at the research station of Sh. Ualikhanov Kokshetau University (53°28'01"N, 69°23'16"E; 222 m above sea level) using a randomised complete block design with three replicates. Sowing took place on 24 and 25 May 2020, 26 May 2021 and 24 May 2022. The experimental plots were each 28 m^2 in size and were sown with a seed rate of 20 seeds m^{-2} and a row spacing of 0.7 m.

Plant materials

In this study, 14 new genotypes were evaluated. Eight varieties of sweet sorghum (SS) originating from Russia with a growing season of up to 120 days (Kapital, Sevilia, Chaika, Volzhskoye 51, Volonter, Calibr, Sahara and Flagman) and the standard variety SP, were included. In addition, six sorghum × sudangrass hybrids (SSH), also originating from Russia (Anion, Agat, SP 15, SP 18, Sosed, and Ershovskiy 5), and the standard hybrid Solaris were used.

Observations

The onset of each growth stage was recorded when 75% of the plants had reached that stage. The following stages were monitored: emergence (BBCH 09), tillering stage (BBCH 20-29), budding stage (BBCH 39), panicle emergence (BBCH 50-59), anthesis (BBCH 60-69), milk ripeness (BBCH 71-77), wax ripeness (BBCH 85-87) and full ripeness (BBCH 89), according to the methods of Rao et al. (2008), Roozeboom and Prasad (2019) and Meier (2018).

The biometric measurements were performed on 10 labelled plants per plot. The following traits were recorded: number of internodes on the main shoot, total tillering (number of tillers per plant), plant height (cm) from the ground to the top of the panicle, stem diameter (mm) using a digital calliper and panicle length (cm). All SS varieties were harvested at the milk maturity stage, with the exception of the genotypes that did not reach physiological maturity under the climatic conditions of the region and were therefore harvested at the anthesis or panicle emergence stage, depending on their stage of development. The harvest of the green mass was recorded by cutting the plant material from a 5 m^2 area within each plot. In addition, potential for bioethanol production was included as a subplot (5 m^2) in each treatment, allowing the simultaneous evaluation of biomass characteristics and bioethanol yield across genotypes and years. The structure of the harvested biomass was assessed by dividing it into leaves, stems, and panicles, which were weighed in the fresh state, and their proportions expressed as a percentage of the total biomass. All genotypes were harvested in September.

Leaf area was calculated during panicle formation and flowering according to the formula described by Stickler et al. (1961), and Handiso and Mamo (2022):

$$S = 0.747 \times L \times W,$$

where S is the leaf area, L is the leaf length, W is the maximum width of the leaf, and 0.747 is a correction factor for sorghum.

The sugar content (%) of the stem juice was measured using a refractometer (model IRF454B2M). In each replicate, three samples were taken before harvest. Stem juice was extracted from 4 to 5 internodes of the core stem. The purified juice was measured by adding 1 ml to the refractometer slide (Kasegn et al., 2024).

Statistical analysis of experimental data

The statistical analysis of the experimental data was performed with STATISTICA version 10 (StatSoft, Tulsa, OK, USA). A field experiment was arranged in a completely randomised design with three replicates. A one-way analysis of variance (ANOVA) was used to determine significant differences between treatments, and comparisons of means were performed using Tukeys test at the 5% level of significance (LSD). The relationships between the analysed parameters were evaluated with Pearson correlation coefficients ($P≤0.05$ and $P≤0.01$).

Description of the soil and climate conditions

Field experiments (2020–2022) were conducted in the Akmola region, northern Kazakhstan, on medium-humic, medium-loamy chernozem soil, typical for the agricultural zone. The soil was characterized by low phosphorus (16.7 mg/kg), high potassium (666 mg/kg), moderate nitrogen (153 mg/kg), organic matter content of 4.6%, and slightly alkaline pH (7.5–7.6). Nutrient analyses followed standard methods: Machigin (P and K), Tyurin–Nikitin (organic matter), and Tyurin–Kononova (hydrolysable N). pH was measured in a 1:5 water extract using a pH meter.

Climatic data were obtained from the Kokshetau observatory (https://kazhydromet.kz/en/). Long-term (2000–2019) and experimental period (2020–2022) data were used to calculate the hydrothermal index (K) based on Selyaninov index (K):

$$K = (M_o \times 10) / (D_t \times days),$$

where K is the hydrothermal coefficient for a month of the growing season, M_o is the sum of monthly precipitation and D_t is the average daily temperature in a given month.

Results (Table 1) indicated predominantly arid to semi-arid conditions during most of the growing season, with relatively favourable moisture availability typically occurring in July.

The study area is characterized by a continental climate with arid to semi-arid conditions, typical of the Central Asian steppes. According to the Köppen climate classification, this region falls under the BSk (Cold Semi-Arid Climate) zone. The climate is marked by long, cold winters and hot, dry summers, with an average annual precipitation of 250–300 mm.

The seasonal precipitation total of 218.8 mm for 2022 was 60% above the 2020 average (89.6 mm), 50.1% above the 2021 average (109.7 mm) and 7% above the long-term average of 203.8 mm (Table 2). The average temperatures during the study period were similar across years and corresponded to the long-term average values. The growing season in 2020 was dry, which is confirmed by the low precipitation values (Figure 1) and the low values of the hydrothermal Selianinov index for precipitation. Approximately 58% of the precipitation fell in July (51.8 mm). The reserves of productive moisture in the period before sowing were sufficient to ensure uniform seedling emergence and good rooting of the plants.

The year 2021 was also characterised by drought and relatively cooler temperatures compared to 2020. The relatively late warming of the soil and the onset of stable active temperatures in May meant that the total quantity during the sweet sorghum growing season remained at the same level as the previous year, as a warm front with active temperatures arrived in September and the autumn frosts set in relatively late, with the first being recorded on 21 September.

Table 1. Hydrothermal Selianinov index (K) in the growing season (May to September)

	May	June	July	August	September
2000-2019	0.7	0.8	1.1	0.8	0.6
2020	0.4	0.1	0.8	0.5	0.5
2021	0.3	0.4	0.7	0.6	0.6
2022	0.3	1.2	1.9	0.4	0.1

Selianinov Index (K): <0.5–drought, 0.5–1.0–semi-drought, 1.0–1.5–border of optimal moisture, >1.5–excessive moisture.

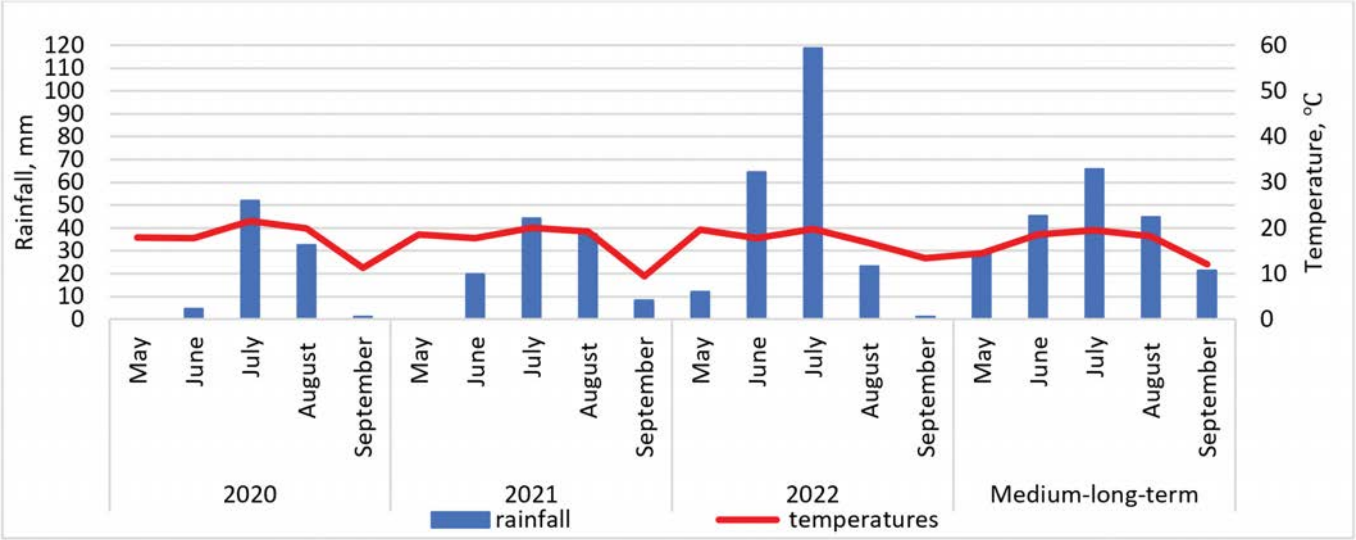


Figure 1. Meteorological conditions

Table 2. General indicators of meteorological conditions during growing period

	2020	2021	2022	Medium-long-term
Precipitation, mm	89.6	109.7	218.8	203.8
Sum of active temperatures >10 °C	2064	2065	2125	2343
Accounting dates	24.05-9.09	26.05-20.09	24.05-23.09	May-September

The 2022 growing season had more consistent and abundant precipitation (218.8 mm), especially in July, when more than half the precipitation of the summer period (118.6 mm) fell. The first short-term frost occurred on 23 September, which significantly extended the growing season.

RESULTS

The most important morphological traits, yield and quality parameters are listed in Table 3 for SS and in Table 4 for SSH. Among the SS varieties analysed in three years, the lowest number of internodes was observed in the variety Volonter (5.3–7.0), similar characteristics were observed in Sevilia (5.8–7.3), Kapital (6.7–8.0), Chaika (6.4–7.6), Sahara (7.2–7.4) and Volzhskoye 51 (7.1–7.4). The highest number of internodes was observed in the variety SP (10.4–10.7), which can be characterised as late-maturing, which is confirmed by the longest growth period. The variety SP did not reach maturity under regional conditions (Figures 4-6). In SSH, the number of internodes on the main stem was, on average, 6.3% higher than in SS. The lowest values were observed in the hybrids Anion (7.4–7.8) and Agat (7.4–8.0), while the highest values were recorded in the hybrids Ershovskiy 5 (9.0–10.5) and SP 15 (9.4–10.6).

The number of tillers per plant also influenced ontogeny and yield. During the study period, the SS plants produced between 1.00 and 3.67 tillers. The fewest tillers were observed in the variety Sahara (1.00–1.44), while the most tillers were produced by Volzhskoye 51 (1.78–3.67). SSH produced more tillers (on average 2.7) than SS plants (on average 1.7). Among the SSH, Solaris had the highest total tillering (3.80–5.00).

Table 3. Sweet sorghum varieties characteristics, yield and quality parameters

Variety	Plant parameters						HOGM	Quality parameters		
	NOI	TT	PH	LA	SD	PL		F	S	SC
2020										
Kapital	7.2^{d}	2.37^{ab}	166^{bc}	1109^{c}	0.99^{c}	27.1^{a}	12.3^{c}	9.2^{b}	76.6^{b}	16.1
Volonter	7.0^{d}	1.33^{b}	182^{a}	776^{f}	1.00^{c}	28.8^{a}	15.5^{abc}	5.8^{d}	66.9^{c}	12.5
Chaika	7.1^{d}	2.10^{ab}	157^{d}	1214^{b}	1.11^{bc}	28.8^{a}	15.0^{bc}	7.2^{cd}	65.8^{c}	12.4
Sahara	7.2^{d}	1.00^{b}	168^{bc}	908^{e}	1.25^{b}	26.3^{a}	14.3^{bc}	10.9^{a}	71.4^{bc}	14.2
Flagman	9.4^{b}	2.23^{ab}	162^{c}	1005^{d}	1.21^{b}	27.6^{a}	14.3^{bc}	7.6^{cd}	66.4^{c}	13.1
Sevilia	7.0^{d}	1.33^{b}	170^{b}	603^{g}	0.97^{c}	22.3^{b}	13.1^{c}	4.9^{d}	66.9^{c}	13.6
Volzhskoye 51	7.1^{d}	3.23^{a}	163^{c}	781^{f}	1.21^{b}	27.9^{a}	18.9^{a}	5.1^{d}	72.8^{bc}	14.3
SP	10.7^{a}	1.23^{b}	143^{d}	1697^{a}	1.73^{a}	25.0^{ab}	17.4^{ab}	6.0^{d}	84.9^{a}	12.4
Calibr	8.1^{c}	2.10^{ab}	163^{c}	1022^{cde}	1.12^{bc}	26.4^{a}	18.7^{a}	7.9^{c}	66.7^{c}	15.1
F test	**	**	**	**	**	**	**	**	**	NS
$LSD_{0.05}$	0.35	1.08	4.2	82	0.120	2.85	2.60	1.16	4.64	3.51
$LSD_{0.01}$	0.48	1.48	5.8	114	0.165	3.93	3.58	1.59	6.40	4.83
2021										
Kapital	8.0^{bc}	1.56^{bc}	157^{a}	1214^{b}	1.23^{bc}	24.0	10.7^{cd}	14.9^{bcd}	69.1^{b}	15.7^{ab}
Volonter	7.4^{c}	1.11^{c}	154^{ab}	701^{d}	1.06^{d}	22.7	10.7^{cd}	11.0^{d}	61.9^{e}	12.5^{c}
Chaika	7.6^{bc}	1.89^{bc}	143^{b}	1168^{bc}	1.31^{bc}	26.3	12.2^{bc}	11.8^{cd}	62.5^{de}	13.9^{bc}
Sahara	7.4^{c}	1.00^{c}	144^{b}	913^{bcd}	1.23^{bc}	24.5	12.2^{bc}	14.6^{bcd}	63.5^{cde}	16.7^{a}
Flagman	9.7^{a}	2.00^{bc}	158^{a}	1200^{b}	1.32^{b}	22.8	12.4^{bc}	16.0^{b}	68.3^{bc}	14.8^{abc}
Sevilia	7.3^{c}	1.22^{c}	152^{ab}	519^{d}	1.04^{d}	22.6	9.6^{d}	11.8^{cd}	63.7^{cde}	17.1^{a}
Volzhskoye 51	7.3^{c}	3.67^{a}	147^{ab}	817^{cd}	1.20^{c}	26.1	17.4^{a}	15.6^{bc}	64.5^{bcde}	15.0^{abc}
SP	10.6^{a}	1.11^{c}	130^{c}	1582^{a}	1.63^{a}	22.1	11.0^{cd}	20.8^{a}	74.8^{a}	12.8^{c}
Calibr	8.4^{b}	2.67^{ab}	155^{ab}	966^{bcd}	1.24^{bc}	25.2	14.1^{b}	15.6^{bc}	67.1^{bcd}	15.0^{abc}
F test	**	**	**	**	**	NS	**	**	**	**
$LSD_{0.05}$	0.66	0.94	9.2	265	0.083	3.03	1.42	3.0	3.6	1.77
$LSD_{0.01}$	0.92	1.30	12.6	365	0.117	4.17	1.95	4.1	5.0	2.44
2022										
Kapital	6.7^{cd}	1.22	186^{a}	1139	1.14^{c}	24.2^{ab}	13.6^{ab}	7.7	76.9^{ab}	14.6^{ab}
Volonter	5.3^{f}	1.33	162^{b}	668	0.91^{d}	25.4^{a}	11.2^{bc}	9.6	62.3^{d}	12.7^{b}
Chaika	6.4^{de}	2.00	163^{b}	1055	1.25^{bc}	24.5^{ab}	14.1^{ab}	8.0	67.9^{cd}	10.1^{d}

Continued. Table 3

Variety	Plant parameters						HOGM	Quality parameters		
	NOI	TT	PH	LA	SD	PL		F	S	SC
Sahara	7.3^{bc}	1.44	184^{a}	1525	1.29^{b}	21.1^{bc}	15.4^{a}	10.0	74.9^{ab}	13.9^{abc}
Flagman	7.8^{b}	1.33	158^{bc}	1267	1.20^{bc}	20.9^{bc}	14.3^{ab}	11.8	73.8^{ab}	11.6^{cde}
Sevilia	5.8^{ef}	2.22	180^{a}	605	0.89^{d}	23.4^{abc}	8.7^{c}	13.7	65.6^{d}	15.7^{a}
Volzhskoye 51	7.4^{bc}	1.78	154^{c}	898	1.04^{cd}	25.6^{a}	16.3^{a}	11.2	66.8^{cd}	12.8^{bc}
SP	10.4^{a}	1.78	164^{b}	1829	1.73^{a}	20.2^{c}	14.3^{ab}	14.6	78.9^{a}	9.3^{e}
Calibr	7.8^{b}	1.22	159^{bc}	1138	1.16^{bc}	23.2^{abc}	15.6^{a}	12.8	71.8^{bc}	12.5^{bcd}
F test	**	NS	**	**	**	**	**	NS	**	**
LSD$_{0.05}$	0.56	0.74	4.7	151	0.11	2.70	2.6	4.5	4.1	1.86
LSD$_{0.01}$	0.78	1.02	6.5	208	0.15	3.71	3.6	6.2	5.7	2.57

Legend: NOI - number of internodes; TT - total tillering; PH (cm) - plant height; LA (cm^2) - leaf area; SD (mm) - Stem diameter (lower part); PL (cm) - Panicle length (inflorescence); HOGM - Harvest of green mass; F (%) - Foliage (%); S (%) - Stems (%); SC - Sugar content.

[1] Significant at *P*<0.05 (*) and *P*<0.01 (*); not significant (ns). Figures in the same column followed by the same letter are not statistically different according to the LSD test (P<0.05).

Table 4. Sorghum × sudangrass hybrids characteristics, yield and quality parameters

Variety	Plant parameters						HOGM	Quality parameters		
	NOI	TT	PH	LA	SD	PL		F	S	SC
2020										
Agat	8.0^{de}	2.33	200^{a}	973^{bc}	1.13^{b}	42.0^{ab}	10.5^{b}	6.99^{bc}	74.2^{abc}	11.3
Anion	7.4^{e}	2.80	212^{a}	901^{c}	1.07^{c}	45.7^{a}	10.9^{b}	6.84^{bc}	69.9^{bc}	9.96
SP 15	9.7^{ab}	2.23	212^{a}	1250^{a}	1.39^{a}	36.9^{abc}	11.8^{ab}	4.67^{c}	78.^{9a}	11.8
SP 18	8.6^{cd}	3.00	131^{b}	1230^{ab}	1.33^{ab}	34.7^{b}	12.2^{ab}	7.52^{abc}	67.4^{c}	11.9
Ershovskiy 5	10.5^{a}	2.43	140^{b}	1256^{a}	1.29^{abc}	26.3^{d}	12.8^{ab}	9.79^{ab}	79.5^{a}	13.5
Sosed	9.4^{bc}	2.37	127^{b}	1397^{a}	1.35^{ab}	25.3^{d}	11.5^{ab}	11.9^{a}	77.3^{ab}	12.4
Solaris	8.2^{de}	3.80	129^{b}	1195^{ab}	1.18^{abc}	32.0^{cd}	14.1^{a}	8.00^{abc}	82.2^{a}	11.6
F test	**	NS	**	**	*	**	**	**	**	NS
LSD$_{0.05}$	0.65	1.18	13.2	198	0.17	6.98	2.16	2.99	5.86	3.59
LSD$_{0.01}$	0.91	1.66	18.5	277	0.24	9.79	3.02	4.19	8.21	5.03
2021										
Agat	7.4^{d}	2.67^{b}	197^{a}	1045^{bc}	1.20^{c}	36.6^{a}	11.1^{b}	20.7^{b}	66.4^{a}	11.7^{b}
Anion	7.6^{cd}	2.56^{b}	191^{a}	981^{c}	1.14^{c}	38.1^{a}	10.8^{b}	20.9^{b}	64.3^{ab}	14.4^{a}

Continued. Table 4

Variety	Plant parameters						HOGM	Quality parameters		
	NOI	TT	PH	LA	SD	PL		F	S	SC
SP 15	10.6^{a}	1.56^{b}	196^{a}	1562^{ab}	1.34^{bc}	27.9^{b}	15.4^{a}	22.9^{b}	67.0^{a}	13.4^{ab}
SP 18	8.8^{b}	1.67^{b}	141^{b}	1224^{abc}	1.57^{ab}	29.2^{b}	11.3^{b}	21.2^{b}	59.5^{b}	15.3^{a}
Ershovskiy 5	10.4^{a}	2.89^{b}	113^{c}	1055^{bc}	1.29^{bc}	16.8^{d}	10.2^{b}	29.8^{ab}	62.9^{ab}	14.9^{a}
Sosed	10.1^{a}	2.00^{b}	113^{c}	1612^{a}	1.72^{a}	22.6^{c}	12.0^{a}	26.0^{b}	64.0^{ab}	15.0^{a}
Solaris	8.6^{bc}	5.00^{a}	131^{bc}	1417^{abc}	1.40^{abc}	21.2^{c}	10.6^{b}	31.6^{a}	62.5^{ab}	11.7^{ab}
F test	**	**	**	*	**	**	*	**	*	**
$LSD_{0.05}$	0.75	1.28	13.7	368	0.25	3.28	2.69	4.03	4.44	1.73
$LSD_{0.01}$	1.05	1.80	19.2	515	0.35	4.60	3.77	5.64	6.23	2.43
							2022			
Agat	7.8^{b}	3.89^{ab}	195^{a}	1142^{b}	1.08	36.5^{a}	11.7	15.4^{b}	73.3^{ab}	8.0^{ab}
Anion	7.8^{b}	2.44^{ab}	190^{a}	796^{c}	1.17	37.1^{a}	10.6	18.7^{ab}	67.5^{b}	8.5^{ab}
SP 15	9.4^{a}	2.00^{b}	190^{a}	1212^{b}	1.24	30.2^{b}	12.3	18.3^{ab}	70.4^{ab}	8.3^{ab}
SP 18	7.8^{b}	2.56^{ab}	127^{b}	1100^{b}	1.21	27.4^{b}	10.4	12.8^{c}	70.3^{ab}	10.9^{a}
Ershovskiy 5	9.0^{a}	3.78^{ab}	134^{b}	1139^{b}	1.23	24.5^{cd}	12.0	23.4^{ab}	68.4^{b}	9.3^{ab}
Sosed	9.1^{a}	2.78^{ab}	117^{c}	1473^{a}	1.26	23.7^{cd}	12.2	25.8^{a}	63.8^{b}	10.9^{a}
Solaris	8.2^{b}	4.22^{a}	110^{c}	1154^{b}	1.30	22.9^{d}	10.0	14.6^{b}	80.3^{a}	5.7^{b}
F test	**	*	**	**	NS	**	NS	**	*	*
$LSD_{0.05}$	0.53	1.36	6.9	126	0.16	2.70	3.40	6.49	7.77	2.57
$LSD_{0.01}$	0.74	1.91	9.7	176	0.23	3.78	4.76	9.09	10.9	3.60

Legend: NOI - number of internodes; TT - total tillering; PH (cm) - plant height; LA (cm^2) - leaf area; SD (mm) - Stem diameter (lower part); PL (cm) - Panicle length (inflorescence); HOGM - Harvest of green mass; F (%) – Foliage (%); S (%) - Stems (%); SC - Sugar content.

[1] Significant at $P<0.05$ (*) and $P<0.01$ (**); not significant (ns). Figures in the same column followed by the same letter are not statistically different according to the LSD test ($P<0.05$).

Plant height and main stem diameter before harvest contribute significantly to the total biomass of the plant. In 2020, the tallest plants were recorded in the Volonter variety at 182 cm, while in 2022, the Kapital variety stood out with a height of 186 cm. The standard variety SP had the largest stem diameter (1.63–1.73 cm) throughout the study period, but also had the shortest plants (130–164 cm). The thinnest stems were found in the variety Sevilia (0.89–1.04 cm). The average height of sorghum × sudangrass hybrids (160.1 cm) was similar to that of SS (161.8 cm). The average panicle length was greater for sorghum × sudangrass hybrids (31.4 cm) than for SS (27.8 cm). Some sorghum × sudangrass hybrids reached a height of more than 200 cm (Agat, Anion, SP 15). Ershovskiy 5 and Sosed in 2021, as well as Sosed and Solaris in 2022, were short-stemmed and had a height of less than 120 cm. In general, the shorter plants had thicker stems.

A larger leaf area indicates a higher potential for photosynthetic activity. The leaf area of SS varied considerably in the different years. The largest leaf area was found in the variety SP (1582–1829 cm²), the smallest in the variety Sevilia (519–603 cm²). Sorghum × sudangrass hybrids had a larger average leaf area (1136.4 cm²). Among them, the hybrid Sosed stood out with values between 1397 and 1612 cm².

The yield indicators varied considerably between the different genotypes. The Volzhskoye 51 produced the highest dry matter yield (16.3-18.9 t/ha), followed by Calibr (14.1-18.7 t/ha), while the lowest yield was observed in the variety Sevilia (8.7-13.1 t/ha).

In the three years of the study, all sorghum genotypes analysed were harvested to determine their sugar content as a potential for bioethanol production. Sweet sorghum genotypes consistently reached the milk ripeness stage at harvest, with the exception of the standard variety SP, which remained in the flowering stage in all three years. The sorghum × sudangrass hybrid showed variability in phenological stages at harvest; in the three years, the standard genotype Solaris was once at the flowering stage and twice in the panicle emergence stage. This was similar to the Sosed and Ershovsky-5 genotypes, while Anion reached the milk ripeness stage in all three years. The remaining three genotypes (Agat, SP 15 and SP 18) fluctuated between milk ripeness and the flowering stage depending on the year. The sugar content in the stalk juice ranged from 9.3% to 17.1%, with the varieties Kapital, Sahara and Volzhskoye 51 consistently showing the highest values. The highest proportion of stems to yield was observed in SP (74.8-84.9%), as was the proportion of leaves (F, 6.0-20.8%), although it should be noted that this genotype did not form seeds under these conditions. The variety Kapital also showed a higher proportion of stems in the yield (69.1-76.9%) and also formed seeds. Among the sorghum × sudangrass hybrids, SP 15 achieved the highest yield in some years (11.8-15.4 t/ha). The sorghum × sudangrass hybrids were inferior to sweet sorghum in terms of total yield and stem biomass, but had a higher leaf mass, making them more suitable for use as animal feed. Sweet sorghum has greater potential for bioethanol production due to its higher sugar and stem content.

The simple correlation coefficients for sorghum varieties showed that green biomass had a weak to moderate correlation with the measured parameters. Leaf area showed (Tables 5 and 6) a very strong positive correlation with stem diameter (r = 0.92), a strong positive correlation with the number of internodes (r = 0.84), and the percentage of stems (r = 0.83). The number of internodes showed a strong positive correlation with the stem diameter (r = 0.88), the percentage of foliage (r = 0.75), and the percentage of stems (r = 0.78), while the stem diameter showed a strong correlation with the percentage of stems (r = 0.80). The Pearson correlation coefficients for sorghum × sudangrass hybrids also showed that green biomass had a weak to moderate correlation with the measured parameters. Stem diameter showed a strong positive correlation with leaf area (r = 0.83), while plant height correlated strongly with panicle length (r = 0.86). Panicle length was strongly negatively correlated with the proportion of foliage (r = -0.74).

In 2020 (Figure 2), sorghum emergence lasted from 8 (Ershovskiy 5, Sosed, SP 18, SP 15) to 11 days (Flagman), emergence-to-tillering from 17 (Volzhskoye 51) to 25 days (Sevilia and Chaika), tillering-to-booting from 26 (Volonter) to 54 days (Ershovskiy and Sosed), booting-to-panicle emergence from 5 (Volzhskoye 51) to 22 days (Ershovskiy), panicle emergence-to-anthesis from 8 (Anion and Kapital) to 27 days (Solaris), anthesis-to-milk ripeness from 8 (Kapital) to 22 days (Volzhskoye 51), milk ripeness-to-wax ripeness from 7 (Volonter) to 14 days (Chaika) and from wax ripeness to full ripeness only Kapital (14 days) and Volonter (15 days).

In 2021 (Figure 3), sorghum emergence lasted from 10 to 12 days, indicating favourable conditions for uniform emergence. The emergence-to-tillering phase lasted from 16 to 18 days, also reflecting favourable conditions and uniform progression in both SS and SSH genotypes, tillering-to-booting lasted from 32 (Sevilia) to 44 days (Ershovskiy), booting-to-panicle emergence from

7 (Chaika) to 27 days (SP), panicle emergence-to-anthesis from 9 (Sakhara) to 18 days (Agat), anthesis-to-milk ripeness from 6 (Kapital) to 17 days (Chaika, SP 18 and Anion), milk ripeness-to-wax ripeness from 12 (Volonter, Sevilia and Kapital) to 17 days (Volozhskoye 51) and from wax ripeness-to-full ripeness only Kapital (11 days), Sevilia (11 days), Volonter (11 days) and Sakhara (12 days).

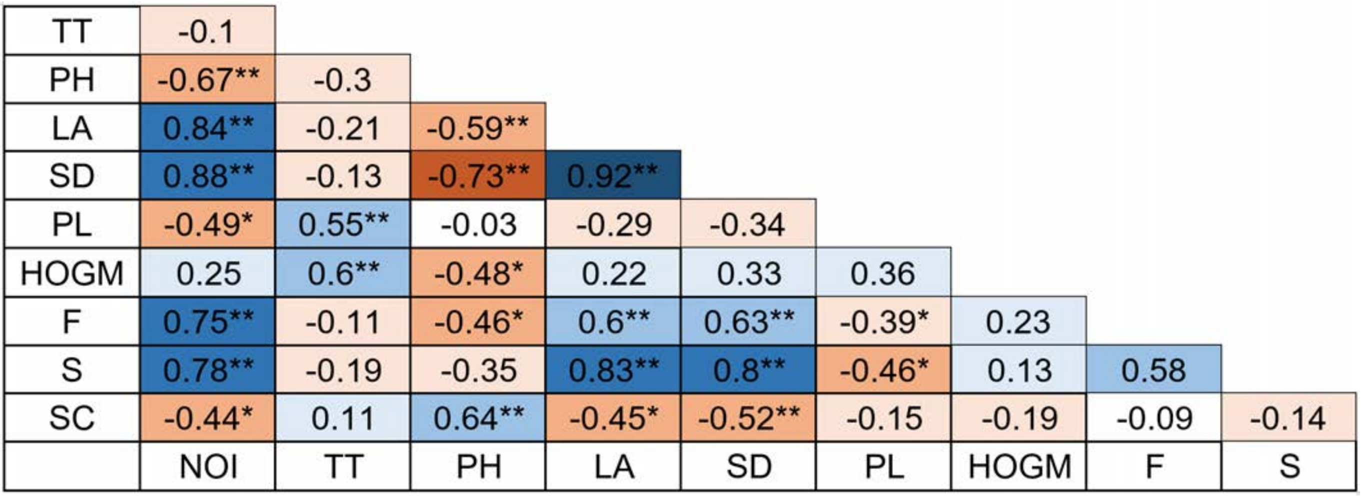
In 2022 (Figure 4), sorghum emergence lasted from 9 (Volzhskoye 51) to 15 days (Calibr), emergence-to-tillering from 15 (Kapital and Ershovskiy 5) to 24 days (Solaris), tillering-to-booting lasted from 31 (Anion) to 63 days (Ershovskiy), booting-to-panicle emergence from 7 (Volonter) to 22 days (SP), panicle emergence-to-anthesis from 9 (Kapital) to 26 days (SP 15), anthesis-milk ripeness from 8 (Kapital) to 19 days (Calibr), milk ripeness to wax ripeness from 11 (Chaika and Sakhara) to 17 days (Volozhskoye 51) and from wax ripeness to full ripeness only Kapital (11 days) and Volonter (11 days).

Based on the statistical analysis, all monitored parameters presented in Table 3 showed significant differences for SS (*P*<0.01) across all three years, except for SC in 2020, PL in 2021, and TT and F in 2022, which were not significant (NS). In Table 4, for SSH, the differences in parameters varied in significance between years (p < 0.01 and *P*<0.05), with four parameters, TT and SC in 2020, and SD and HOGM in 2022, showing no significant differences across years (NS).

When analysing the developmental stages by year and the genotypic responses to the growing conditions, the first two stages (emergence and emergence to tillering) show only slight differences in the different years and in the number of days required for sorghum to progress through them. Especially in 2021, a high degree of uniformity was observed between the genotypes — they emerged and went through the tillering phase in the same way.

There were significant differences between genotypes in the duration of the tillering phase, ranging from a minimum of 26 days in 2020 to 63 days in 2022. The subsequent phase, ranging from tillering to panicle initiation, was terminal in some genotypes and lasted between 5 days in 2020 and a maximum of 27 days in 2021. Each subsequent development phase was reached by fewer and fewer genotypes. The sweet sorghum varieties Kapital and Volonter consistently reached the full ripeness stage in all three years of the study.

Table 5. Correlation between plant and quality parameters of SS (2020-2022)



	NOI	TT	PH	LA	SD	PL	HOGM	F	S
TT	-0.1								
PH	-0.67**	-0.3							
LA	0.84**	-0.21	-0.59**						
SD	0.88**	-0.13	-0.73**	0.92**					
PL	-0.49*	0.55**	-0.03	-0.29	-0.34				
HOGM	0.25	0.6**	-0.48*	0.22	0.33	0.36			
F	0.75**	-0.11	-0.46*	0.6**	0.63**	-0.39*	0.23		
S	0.78**	-0.19	-0.35	0.83**	0.8**	-0.46*	0.13	0.58	
SC	-0.44*	0.11	0.64**	-0.45*	-0.52**	-0.15	-0.19	-0.09	-0.14

Legend: NOI - number of internodes; TT - total tillering; PH (cm) - plant height; LA (cm^2) - leaf area; SD (mm) - Stem diameter (lower part); PL (cm) - Panicle length (inflorescence); HOGM - Harvest of green mass; F (%) - Foliage (%); S (%) - Stems (%); SC - Sugar content.
Significance levels: * *P* < 0.05; ** *P* < 0.01.

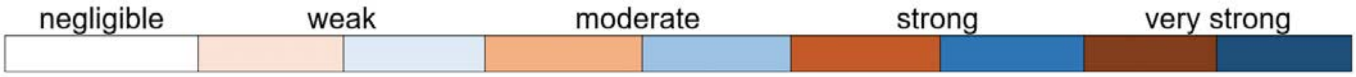
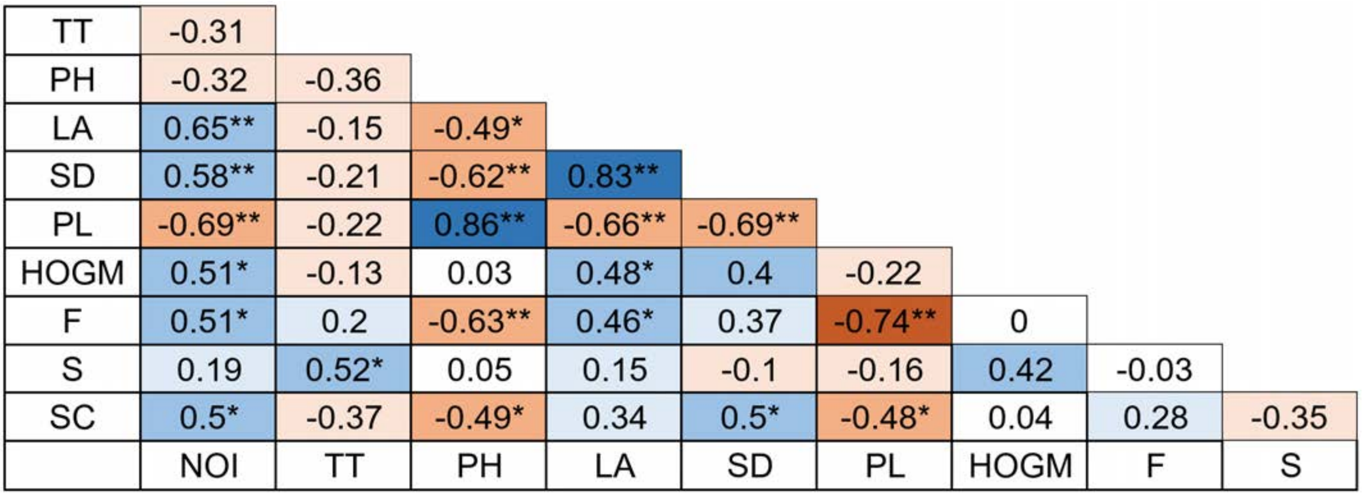


Table 6. Correlation between plant and quality parameters of SSH (2020-2022)



	NOI	TT	PH	LA	SD	PL	HOGM	F	S
TT	-0.31								
PH	-0.32	-0.36							
LA	0.65**	-0.15	-0.49*						
SD	0.58**	-0.21	-0.62**	0.83**					
PL	-0.69**	-0.22	0.86**	-0.66**	-0.69**				
HOGM	0.51*	-0.13	0.03	0.48*	0.4	-0.22			
F	0.51*	0.2	-0.63**	0.46*	0.37	-0.74**	0		
S	0.19	0.52*	0.05	0.15	-0.1	-0.16	0.42	-0.03	
SC	0.5*	-0.37	-0.49*	0.34	0.5*	-0.48*	0.04	0.28	-0.35

Legend: NOI - number of internodes; TT - total tillering; PH (cm) - plant height; LA (cm^2) - leaf area; SD (mm) - Stem diameter (lower part); PL (cm) - Panicle length (inflorescence); HOGM - Harvest of green mass; F (%) - Foliage (%); S (%) - Stems (%); SC - Sugar content.
Significance levels: * *P*<0.05; ** *P*<0.01.

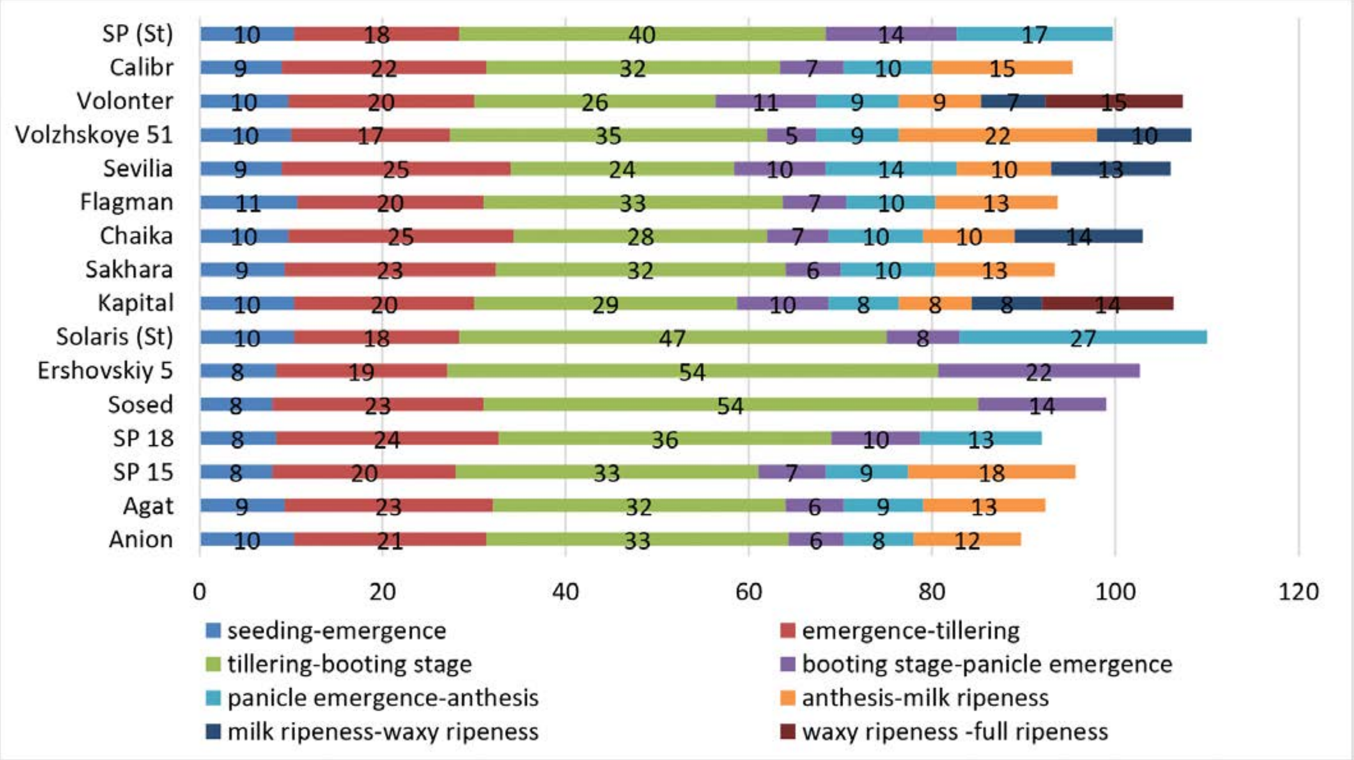


Figure 2. Duration of interphase periods in SS and SSH, 2020

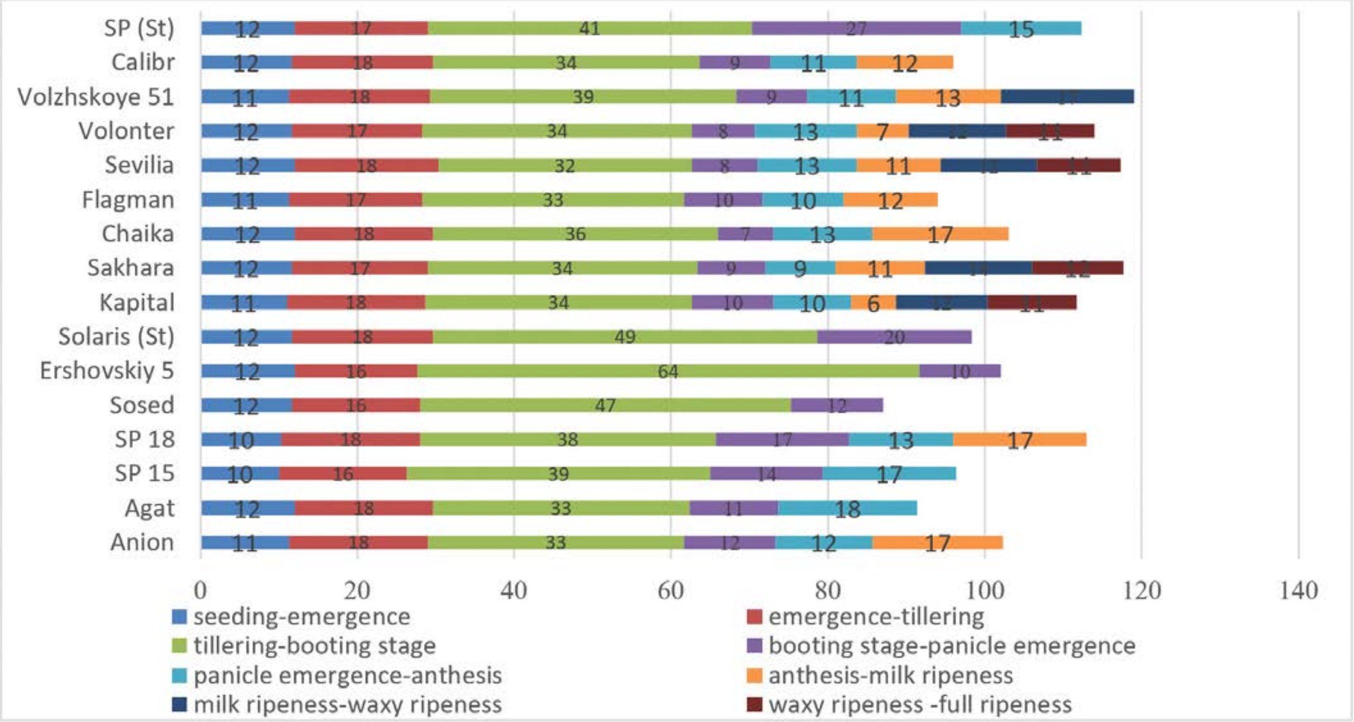


Figure 3. Duration of interphase periods in SS and SSH, 2021

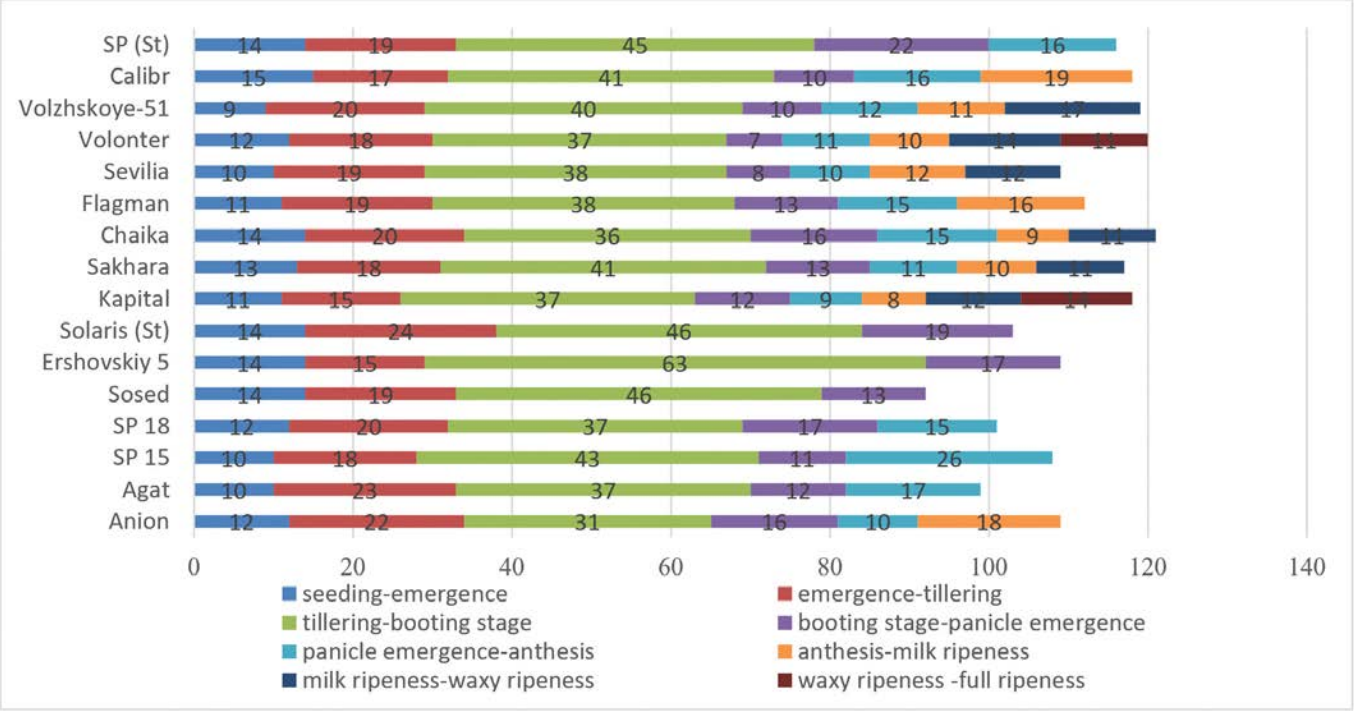


Figure 4. Duration of interphase periods in SS and SSH, 2022

DISCUSSION

Choosing the right forage sorghum genotype is crucial due to its distinct yield potential, forage quality, and agronomic traits compared to maize. These differences affect biomass accumulation, environmental adaptability, and overall system performance. Our trials revealed significant genotype variability linked to rainfall and genetic diversity, consistent with Ngidi et al. (2024) and Sinha and Kumaravadivel (2016). Most traits showed significant differences, except total tillering in certain years and sugar content in 2020. Forage sorghum grows well on clay or loam soils with a pH (in KCl) above 5 and does not require high soil fertility. Soil conditions in the experimental field were suitable for sorghum growth. Forage sorghum can yield satisfactorily with as little as 200 mm of rainfall during the growing season (Blum and Sullivan, 1986), although optimal production requires 450–650 mm (Hadebe et al., 2017). Northern Kazakhstan is characterised by low rainfall (up to 350 mm annually), limited heat, and a short frost-free period (Karatayev et al., 2022). In central Northern Kazakhstan, the growing season lasts 85–95 days, with thermal resources of about 2500 °C and annual precipitation of 250–300 mm, of which 140–160 mm falls between May and August (Baisholanov et al., 2024). Moisture availability during the growing season is considered "optimal and sustainable".

During the trial, rainfall was low (89.6 mm in 2020, 109.7 mm in 2021, and 218.8 mm in 2022), yet green biomass yields exceeded the regional average (Zhapayev et al., 2023). Most rainfall occurred in July, during the tillering–booting stage, which is critical for biomass accumulation. Water stress at booting impacts grain yield and silage quality. Leaf growth ceases after the onset of reproduction.

Sorghum's satisfactory performance is due to its C4 physiology, which maintains photosynthesis under drought through reduced stomatal conductance (Lopes et al., 2011), and its deep root system, enabling efficient water uptake (Chen et al., 2020). Its lodging resistance and erect growth habit under dry conditions further support biomass production (Li et al., 2025). The number of internodes, which equals the number of leaves, indicates the length of the growing season. Genotypes with fewer internodes mature earlier, making this trait valuable in environments with limited heat and short frost-free periods. This correlation relates to thermal time to panicle formation and leaf formation rate (Tirfessa et al., 2023).

Genotypes with a greater number of tillers tend to achieve higher biomass yields (Gonulal, 2020). However, they often require a longer growing period to reach maturity. Under the current environmental conditions – limited heat availability and a short frost-free season – genotypes with lower tillering should be favoured to ensure a timely harvest. As Kim et al. (2010) stated, tillering in sorghum is a very plastic trait that is influenced not only by the genotype but also by environmental factors. The plant height measured before harvest and the main stem diameter are important structural characteristics that contribute significantly to the total biomass of the plant. Plant height is influenced by the length of the individual internodes, the internode production rate and the duration of vegetative growth. The duration of vegetative growth affects height, as internode production ceases with flower induction, while elongation continues until anthesis (Hilley et al., 2016). In sweet sorghum, internode diameter is an important component of stem yield. A significant correlation between the position of internodes and the leaf stage at which thickening occurred indicates uniform development along the stem (Nakamura et al., 2011). Genotypes with optimal stem height and diameter should be selected for specific climatic conditions to ensure efficient biomass accumulation. Sorghum stem form influences stem volume and tolerance to lodging.

Sugar yield of sweet sorghum is closely related to stem biomass yield (Tsuchihashi and Goto, 2004; Sato et al., 2008), but in our study, it was only significantly positively correlated with plant height. In sorghum, which is often grown as a forage crop, the stem is an important organ for harvesting. The stem yield is closely related to the stem volume. Therefore, increasing the stem volume can increase the sugar yield and dry weight of the stem. In contrast, the hybrid of sweet sorghum and sudangrass showed a completely different pattern of association with morphological traits and only showed a positive correlation with the number of internodes and stem diameter. For bioethanol production, the ideal genotypes would have a higher biomass in combination with high sugar yields (Mathur et al., 2017), which was not the case in our study. For both sweet sorghum varieties and hybrids, significant differences in yield and sugar yield were found between genotypes in certain years; however, no significant correlation was found between these two parameters. Notably, the varieties Sevilia, Kapital and Sahara showed consistently higher sugar content in stem juice across the entire study period, indicating their potential suitability for bioethanol production under the agroecological conditions studied. Significant differences in the duration of the vegetation period were found between analysed genotypes of the sweet sorghum and sorghum × sudangrass hybrids. The early maturing varieties Kapital and Volonter consistently reached full seed maturity within 101 and 103 days, respectively, demonstrating their high adaptability to local agroecological conditions and their potential as parental lines in breeding programs. The varieties Sevilia and Sahara also reached full physiological maturity, confirming their agronomic stability. In contrast, the sorghum × sudangrass hybrids showed variable maturation, which limits their use for grain production. However, their vigorous vegetative growth makes them suitable for forage purposes. Although the genotypes Ershovskiy 5, Sosed and Solaris do not produce seeds under the climatic conditions of Kazakhstan, they are capable of producing high green biomass, which emphasises their potential as a valuable forage crop. Green biomass showed weak to moderate correlations with the measured traits, suggesting that no single parameter can reliably predict biomass yield. These results emphasise the need for comprehensive phenotypic assessments in conjunction with environmental adaptability assessments to ensure sustainable biomass production. For example, Rana and Kher (2015) found that green biomass yield was highly positively and significantly correlated with stem diameter, leaf length, leaf width and dry matter yield.

CONCLUSIONS

The screening of sorghum genotypes enables the identification and introduction of highly productive and drought-tolerant varieties and hybrids that can ensure stable biomass yields under variable climatic conditions. Sorghum cultivation in northern Kazakhstan and neighboring regions largely depends on rainfall, which is often irregular and unevenly distributed throughout the growing season. Over the course of three years, it was demonstrated that germplasm of imported sweet sorghum and sorghum × sudangrass hybrids can be successfully grown under the agroecological conditions of northern Kazakhstan. The highest productivity of green biomass was observed in the sweet sorghum genotypes Volzhskoye 51 and Calibr, as well as in the sorghum × sudangrass hybrid SP15, which are recommended for forage production. For bioethanol production, on the other hand, the varieties Sevilia, Kapital, and Sahara are particularly suitable. The early-maturing varieties Kapital and Volonter consistently reached full seed maturity and are considered promising sources for the development of early-maturing parental lines and for stable forage production. The most consistent positive correlations were observed with the number of internodes and leaf area.

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REFERENCES

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.
DOI: https://doi.org/10.3390/cli13010003

Blum, A., Sullivan, C. Y. (1986) The comparative drought resistance of landraces of sorghum and millet from dry and humid regions. Annals of Botany, 57 (6), 835-846.
DOI: https://doi.org/10.1093/oxfordjournals.aob.a087168

Boga, H. (2020) Climate Smart Sorghum Production Training and Resource Guide. Available at: https://www.snv.org/assets/downloads/f/191310/c844cfa3b9/snv-20craft-20climate-20smart-20sorghum-20production-20training-20and-20resource-20guide.pdf [Accessed 26 July 2025].

Bollam, S., Romana, K. K., Rayaprolu, L., Vemula, A., Das, R. R., Rathore, A., Gandham, P., Chander, G., Deshpande, S.P., Gupta, R. (2021) Nitrogen use efficiency in Sorghum: exploring native variability for traits under variable N-Regimes. Frontiers in Plant Science, 12, 643192. DOI: https://doi.org/10.3389/fpls.2021.643192

Bulekov, T. A., Limanskaya, V. B., Bulekova, A. A., Davletova, A. M., Kasimova, G. V. (2023) Agrotechnics of sorghum in grass-field crop rotation for the conditions of the West Kazakhstan region. IOP Conference Series: Earth and Environmental Science, 1154 (1), 012053.
DOI: https://doi.org/10.1088/1755-1315/1154/1/012053

Ciampitti, I. A., Prasad, P. V. V. (2019) Sorghum: State of the art and future perspectives. Agronomy Monographs, 58. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Available at: https://scholar.google.com/scholar_lookup?title=Sorghum+State+of+the+Art+and+Future+Perspective [Accessed 26 July 2025].

Chen, X., Wu, Q., Gao, Y., Zhang, J., Wang, Y., Zhang, R., Zhou, Y., Xiao, M., Xu, W., Huang, R. (2020) The role of deep roots in sorghum yield production under drought conditions. Agronomy, 10 (4), 611.
DOI: https://doi.org/10.3390/agronomy10040611

Chiluwal, A., Bheemanahalli, R., Perumal, R., Asebedo, A. R., Bashir, E., Lamsal, A., Jagadish, S. K. (2018) Integrated aerial and destructive phenotyping differentiates chilling stress tolerance during early seedling growth in sorghum. Field Crops Research, 227, 1-10.
DOI: https://doi.org/10.1016/j.fcr.2018.07.011

Dolapčev Rakić, A., Prodanović, S., Sikora, V., Vasiljević, S., Župunski, V., Jevtić, R., Uhlarik, A. (2025) Potential for Enhancing Forage Sorghum Yield and Yield Components in a Changing Pannonian Climate. Agriculture, 15(13), 1439.
DOI: https://doi.org/10.3390/agriculture15131439

Druille, M., Williams, A. S., Torrecillas, M., Kim, S., Meki, N., Kiniry, J. R. (2020) Modeling Climate Warming Impacts on Grain and Forage Sorghum Yields in Argentina. Agronomy, 10, 964.
DOI: https://doi.org/10.3390/agronomy10070964

Gonulal, E. (2020) Performance of sorghum × Sudan grass hybrid (*Sorghum bicolor* L. × *Sorhgum sudanense*) cultivars under water stress conditions of arid and semiarid regions. Journal of Global Innovations in Agricultural Sciences, 8 (2), 78-82.
DOI: https://doi.org/10.22194/JGIASS/8.908

Hadebe, S. T., Mabhaudhi, T., Modi, A. T. (2017) Water use of sorghum (*Sorghum bicolor* L. Moench) in response to varying planting dates evaluated under rainfed conditions. Water SA, 43 (1), 91-103.
DOI: http://dx.doi.org/10.4314/wsa.v43i1.12

Handiso, Y. E., Mamo, M. A. (2022) Agronomic Response of Sorghum [*Sorghum bicolor* (L) Moench] Variety to Density, Nitrogen and Blended Fertilizer Rates for Yield Components and Seed Quality in Southern Ethiopia. International Journal of Biosciences, 21 (5), 172-183. DOI: http://dx.doi.org/10.12692/ijb/21.5.172-183

Hariprasanna, K., Patil, J. V. (2015) Sorghum: origin, classification, biology and improvement. In: Sorghum molecular breeding. pp. 3-20. DOI: https://doi.org/10.1007/978-81-322-2422-8_1

Hilley, J., Truong, S., Olson, S., Morishige, D., Mullet, J. (2016) Identification of Dw1, a regulator of sorghum stem internode length. PloS one, 11 (3), e0151271.
DOI: https://doi.org/10.1371/journal.pone.0151271

Karatayev, M., Clarke, M., Salnikov, V., Bekseitova, R., Nizamova, M. (2022) Monitoring climate change, drought conditions and wheat production in Eurasia: The case study of Kazakhstan. Heliyon, 8 (1), e08660. DOI: https://doi.org/10.1016/j.heliyon.2021.e08660

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” sweet sorghum (*Sorghum bicolor* (L.)). Biotechnology for the Environment, 1 (1), 1-13.
DOI: https://doi.org/10.1186/s44314-024-00001-6

Kim, H. K., Luquet, D., Van Oosterom, E., Dingkuhn, M., Hammer, G. (2010) Regulation of tillering in sorghum: genotypic effects. Annals of Botany, 106 (1), 69-78.
DOI: https://doi.org/10.1093/aob/mcq080

Li, J., Zhao, L., Fan, H., Zhao, F., He, D., Li, B., Wang, J., Xie, G., Hu, Z., Fan, C., Wang, L. (2025) A precise and high-throughput assay for stem structural characteristics deepens understanding of lodging resistance in sorghum. BMC Plant Biology, 25 (1), 386.
DOI: https://doi.org/10.1186/s12870-025-06396-y

Liubych, V. V., Storozhyk, L. I., Voitovska, V. I., Tereshchenko, I. S., Losieva, A. I. (2021) Agrobiological parameters of various varieties and hybrids of sweet sorghum. Plant varieties studying and protection, 17 (3), 193-198.
DOI: https://doi.org/10.21498/2518-1017.17.3.2021.242966

Lopes, M. S., Araus, J. L., Van Heerden, P. D., Foyer, C. H. (2011) Enhancing drought tolerance in C4 crops. Journal of experimental botany, 62 (9), 3135-3153. DOI: https://doi.org/10.1093/jxb/err105

Lu, Q., Yu, X., Wang, H., Yu, Z., Zhang, X., Zhao, Y. (2022) Quantitative trait locus mapping for important yield traits of a sorghum-sudangrass hybrid using a high-density single nucleotide polymorphism map. Frontiers in Plant Science, 13, 1098605.
DOI: https://doi.org/10.3389/fpls.2022.1098605

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.
DOI: https://doi.org/10.1186/s13068-017-0834-9

Meier, U. (2018) Growth Stages of Mono- and Dicotyledonous Plants: BBCH Monograph; Open Agrar Repositorium: Berlin, Germany. Available at: https://lozari.bg/wp-content/uploads/2023/04/crop-stages-BBCH.pdf [Accessed 26 July 2025].

Mohammed, A., Misganaw, A. (2022) Modeling future climate change impacts on sorghum (*Sorghum bicolor*) production with best management options in Amhara Region, Ethiopia. CABI Agriculture and Bioscience, 3 (1), 22.
DOI: https://doi.org/10.1186/s43170-022-00092-9

Muratova, A. Y., Golubev, S. N., Dubrovskaya, E. V., Pozdnyakova, N. N., Panchenko, L. V., Pleshakova, E. V., Chernyshova M. P., Turkovskaya, O. V. (2012) Remediating abilities of different plant species grown in diesel-fuel-contaminated leached chernozem. Applied Soil Ecology, 56, 51-57. DOI: https://doi.org/10.1016/j.apsoil.2012.01.002

Nakamura S, Nakajima N, Nitta Y, Goto Y (2011) Analysis of successive internode growth in sweet sorghum using leaf number as a plant age indicator. Plant Production Science, 14 (4), 299-306.
DOI: https://doi.org/10.1626/pps.14.299

Ngidi, A., Shimelis, H., Abady, S., Figlan, S., Chaplot, V. (2024) Response of *Sorghum bicolor* genotypes for yield and yield components and organic carbon storage in the shoot and root systems. Scientific Reports, 14 (1), 9499.
DOI: https://doi.org/10.1038/s41598-024-59956-x

Osman, H.E., Fadhlallah, R.S., Alamoudi, W.M., Eid, E.M., Abdelhafez, A.A. (2023) Phytoremediation potential of Sorghum as a bioenergy crop in Pb-amendment soil. Sustainability, 15 (3), 2178.
DOI: https://doi.org/10.3390/su15032178

Pataki, I., Katić, S., Mihailović, V., Milić, D., Vasiljević, S., Mikić, A. (2010) Use of hybridization (F1) in forage sorghum (*Sorghum bicolor* (L.) Moench) breeding. Field and Vegetable Crops Research, 47 (1), 225-229.

Rana, H. R., Kher, H. R. (2015) Study of variability, correlation and path analysis in forage sorghum [*Sorghum bicolor* (L.) Moench]. The Bioscan, 11 (Supplement 1), 259–263. Available at: https://thebioscan.com/index.php/pub/article/view/864 [Accessed 26 July 2025].

Rao, S.S., Elangovan, M., Umakanth, A.V., Seetharama, N. (2008) Characterizing phenology and growth stages of sorghum hybrids. In: Reddy Belum, V.S., Ramesh S., Ashok Kumar, A, Gowda C.L.L., eds. Sorghum improvement in the new millennium. Patencheru, Andhra Pradesh, India, pp. 16-22.

Roozeboom, K. L., Prasad, P. V. V. (2019) Sorghum growth and development. In: Ciampitti I. A., Prasad P. V. V., eds. Sorghum: A state of the art and future perspetives, 58, pp. 155-172. DOI: https://doi.org/10.2134/agronmonogr58.c8

Sato, A., Nakajima, N., Nakamura, S., Saito, M., Nitta, Y., Goto, Y. (2008) Effect of fertilizer application on characteristics of sweet sorghum (*Sorghum bicolor* (L.) Moench) internodes. Japanese Journal of Crop Science, 77 (Extra issue 2), 106-107.

Silva, K. J., Menezes, C. B., Tardin, F. D., Emygdio, B. M., Souza, V. F., Carvalho, G. A., Silva, M. J. (2013) Seleção de híbridos de sorgo granífero cultivados no verão em três localidades. Revista Brasileira de Milho e Sorgo, 12 (1), 44-53.

Sinha, S., Kumaravadivel, N. (2016) Understanding genetic diversity of sorghum using quantitative traits. Scientifica, 2016 (1), 3075023. DOI: https://doi.org/10.1155/2016/3075023

StatSoft, Inc. (2011) STATISTICA (Data Analysis Software System), Version 10. http://www.statsoft.com

Stickler, F. C., Wearden, S., Pauli, A. W. (1961) Leaf area determination in grain sorghum 1. Agronomy Journal, 53 (3), 187-188. DOI: https://doi.org/10.2134/agronj1961.00021962005300030018x

Tack, J., Lingenfelser, J., Jagadish, S.V.K. (2017) Disaggregating sorghum yield reductions under warming scenarios exposes narrow genetic diversity in US breeding programs. Proc. Natl. Acad. Sci. USA, 114, 9296–9301. DOI: https://doi.org/10.1073/pnas.1706383114

Taylor, J.R. (2019) Sorghum and millets: Taxonomy, history, distribution, and production. In: Sorghum and millets, pp. 1-21. DOI: https://doi.org/10.1016/B978-0-12-811527-5.00001-0

Tirfessa, A., McLean, G., Baker, P., Mortlock, M., Hammer, G., Van Oosterom, E. (2023) Differences in temperature responses among phenological processes in diverse Ethiopian sorghum germplasm can affect their specific adaptation to environmental conditions. Annals of Botany, 131 (4), 601-611. DOI: https://doi.org/10.1093/aob/mcad011

Tsuchihashi, N., Goto, Y. (2004) Cultivation of sweet sorghum (*Sorghum bicolor* (L.) Moench) and determination of its harvest time to make use as the raw material for fermentation, practiced during rainy season in dry land of Indonesia. Plant Production Science, 7 (4), 442-448. DOI: https://doi.org/10.1626/pps.7.442

Tu, M., Du, C., Yu, B., Wang, G., Deng, Y., Wang, Y., Chen, M., Chang, J., Yang, G., He, G., Xiong, Z., Li, Y. (2023) Current advances in the molecular regulation of abiotic stress tolerance in sorghum via transcriptomic, proteomic, and metabolomic approaches. Frontiers in Plant Science, 10 (14), 1147328. DOI: https://doi.org/10.3389/fpls.2023.1147328

Zhapayev, R., Iskandarova, K., Toderich, K., Paramonova, I., Al-Dakheel, A., Ismail, S., Srinivasa Rao, P., Omarova, A., Nekrasova, N., Balpanov, D., Ten, O., Ramanculov, E., Zelenskiy, Y., Akhmetova, A., Karabayev, M. (2015) Sweet Sorghum Genotypes Testing in the High Latitude Rainfed Steppes of the Northern Kazakhstan (for Feed and Biofuel). Journal of Environmental Science and Engineering B, 4, 25-30. Available at: https://davidpublisher.com/Public/uploads/Contribute/551a057838cb1.pdf [Accessed 26 July 2025].

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. Journal of water and land development, 56 (I-III), 118–126. Available at: https://www.jwld.pl/files/2023-01-JWLD-16.pdf?utm_source=chatgpt.com [Accessed 26 July 2025].

Zheng, H., Dang, Y., Diao, X., Sui, N. (2024) Molecular mechanisms of stress resistance in sorghum: Implications for crop improvement strategies. Journal of Integrative Agriculture, 23 (3), 741-768. DOI: https://doi.org/10.1016/j.jia.2023.12.023