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Evaluation of Grain Sorghum (Sorghum bicolor (L.) Moench.) Accessions in a Collection Nursery in the Steppe Zone of Northern Kazakhstan

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ABSTRACT

Climate variability and recurrent drought constrain crop production in Northern Kazakhstan. This study evaluated grain sorghum (Sorghum bicolor (L.) Moench) germplasm to identify early-maturing, productive, stress-tolerant accessions with high grain and fodder quality. Thirty accessions were assessed during 2021–2024 at the A.I. Barayev Research and Production Centre for Grain Farming, Akmola Region, using Dergachevsky as the standard. Phenology, biomass, grain yield, yield stability, drought tolerance, disease response, and grain composition were evaluated; metabolizable energy and feed units were calculated. Growing seasons ranged from very dry conditions in 2023 (hydrothermal coefficient 0.2) to favorable moisture in 2024 (1.2). Early-maturing accessions reached wax maturity in 89–94 days with lower thermal requirements. K-5501 (Slavyanka), K-5499 (Bakalavr), K-5502 (Granat), K-5538 (Slavyanskoe pole 591), and K-5539 (Kinelskoe 63) yielded 41.7–65.8 g m^{-2} of grain, compared with 38.5 g m^{-2} for Dergachevsky. Several accessions exceeded the standard in green biomass and dry matter by up to 27.3%. K-5501, K-5499, and K-5538 combined high productivity with favorable stress tolerance and ecological stability. Six accessions had superior energy and protein value, while six hybrid lines exceeded the standard grain yield by 17.0%–22.5%. Overall, six accessions were selected as breeding sources for developing early, productive, and environmentally resilient sorghum cultivars adapted to increasing climatic variability.

Keywords: Grain sorghum *(Sorghum bicolor (L.) Moench),* Grain yield, Accession, Green biomass, Dry matter, Crude protein.

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INTRODUCTION

Climate change is increasingly accompanied by soil and atmospheric droughts (Chadalavada *et al.*, 2021). Under the extreme conditions of the steppe zone of Northern Kazakhstan, selecting crops that can adapt to environmental variability while maintaining relatively high yields is particularly important. Evidence from pea trials in Northern Kazakhstan also shows that grain yield under no-till is associated with June precipitation and available soil moisture (Mamykin *et al*., 2026). Sorghum is well suited to these conditions because of its high productivity, salt tolerance, heat tolerance, drought resistance, and ability to resume growth after prolonged drought (Kibalnik *et al.*, 2023).

The expanding use of sorghum requires new breeding material for early-maturing, stress-tolerant cultivars. Such cultivars could expand sorghum cultivation and improve the use of regional soil and climatic resources (Prasad *et al.*, 2021; Yahaya & Shimelis, 2021; Hernández *et al.*, 2023). Air temperature and precipitation are the principal hydrothermal factors affecting plant growth and development (Ualkhanov *et al*., 2024).

A major breeding priority is therefore to develop early- and medium-maturing material with a shorter growing season, uniform seed maturation, and high grain and fodder productivity. Researchers emphasize identifying the optimum growing-season duration for each region because it may be more advantageous than either shorter or longer periods (Kostylev *et al.*, 2025). Achieving this objective depends largely on selecting suitable initial material from domestic and international accessions and breeding lines.

This study aimed to evaluate a collection of grain sorghum for early maturity, productivity, resistance to environmental stress factors, and the quality of fodder biomass and grain, and to identify valuable forms that could serve as sources for practical breeding.

MATERIALS AND METHODS

Considering the short frost-free period in Northern Kazakhstan, the study aimed to develop new grain sorghum breeding material using early-maturing, highly productive, and stress-tolerant accessions.

The research was conducted from 2021 to 2024 at the A.I. Barayev Research and Production Centre for Grain Farming in the steppe zone of Northern Kazakhstan, Akmola Region, 70 km from Astana (51°39′ N, 71°01′ E).

The region has a sharply continental and highly arid climate characterized by substantial annual variation in hydrothermal conditions. Based on 50 years of observations, mean annual

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precipitation ranged from 318.0 to 319.2 mm. Rukavitsina *et al.* (2026) provide detailed agroclimatic and soil characteristics. The experimental soil was southern carbonate chernozem with a heavy loam texture.

The study included 30 grain sorghum accessions of different ecological and geographical origins. The Russian cultivar Dergachevsky, recommended for cultivation in Akmola Region, was used as the standard. Phenological development, plant height, fresh biomass, and grain yield were assessed according to the guidelines for field experiments with fodder crops (Shpakov *et al.*, 2024). Stress tolerance ($Y_2 - Y_1$) was calculated according to Goncharenko, and environmental stability was determined using the method of Rosielle and Hamblin (1981).

The preceding crop was clean fallow. Field preparation included autumn tillage to 25–27 cm, spring moisture conservation, and pre-sowing cultivation to 7–8 cm. The collection nursery was sown manually in 60-cm rows at a depth of 5–6 cm. The plot area was 3.6 m^2, with two replications and a systematic plot arrangement. Sowing was conducted in late May, and full emergence occurred on June 4–6, 10–12 days after sowing.

Crude protein was determined using a UDK 139 semi-automatic Kjeldahl distillation unit (VELP Scientifica, Usmate, Italy) in accordance with ISO 5983-2:2016 (Federal Agency for Technical Regulation and Metrology., 2016). Organic matter was digested with sulfuric acid in the presence of a catalyst, then alkalized; ammonia was absorbed, and the sample was titrated. Nitrogen content was converted to crude protein using a factor of 6.25.

Crude fibre was determined according to ISO 6865:2015 (Federal Agency for Technical Regulation and Metrology., 2015; Federal Agency for Technical Regulation and Metrology., 2019) using a fully automated 12-position Fibretherm FT12 system (Gerhardt, Königswinter, Germany). The method involves acid and alkali treatment of plant material, after which the insoluble fibre fraction is filtered and weighed.

Crude fat was measured using an ST243 Soxtec instrument (Foss, Hillerød, Denmark) in a fully automated extraction and hydrolysis system.

Crude ash was determined as the residue remaining after combustion and ignition of the sample in ceramic crucibles at 550–650°C for 15 min, then cooled to room temperature (International Organization for Standardization., 2022).

Metabolizable energy content was calculated using the following formula:

$$ME = 13{,}1x(1{,}0\text{-}CFx1{,}05) \quad (1)$$

Where CF is the crude fibre content, and 13.1, 1.0, and 1.05 are constant coefficients.

Feed units were calculated using the formula specified in GOST 4808-87, *Hay: Specifications* (State Committee of the USSR for Standards., 1987):

$$\text{Feed units} = ME^2x0{,}0081, \quad (2)$$

Where 0.0081 is a constant coefficient.

Weather conditions varied considerably during the study period. Accumulated effective temperatures during the summer months were 2,489 °C in 2021, 2,416 °C in 2022, 2,603 °C in 2023, and 2,316 °C in 2024, compared with the long-term average of 1,941 °C.

In 2021, mean daily temperatures in May and August exceeded the long-term averages by 4.7 and 2.2 °C, respectively, while June and July were 0.1–0.5 °C warmer. Precipitation from May to August totaled 100.1 mm, 40.7% below the long-term average of 168.7 mm. The Selyaninov hydrothermal coefficient (HTC) was 0.4, compared with the long-term average of 0.8.

In 2022, temperatures in May–July were 1.2–3.2 °C above average, whereas August was 0.2 °C cooler. Precipitation was 44% below the long-term average, and the HTC was 0.4, indicating dry conditions.

In 2023, plant-available moisture in the 1-m soil layer decreased from 138 mm before sowing to 125 mm at emergence and 77 mm at tillering. Mean daily temperatures exceeded long-term averages by 1.6–4.5 °C, with the greatest deviation of 6.9 °C recorded in early June. Precipitation was substantially below average throughout the growing season, with deficits of 66.6%–88.1% during June–August. Consequently, 2023 was classified as extremely dry, with an HTC of 0.2. Nevertheless, sorghum efficiently utilized moisture and nutrients from deeper soil layers through its root system, which can reach 250–300 cm.

In May 2024, temperatures were 1.3 °C below average, while precipitation was 2.4 times higher than normal. From June to August, precipitation reached 232.2 mm, compared with the long-term average of 136.3 mm, and the mean daily temperature was 20.5 °C. These conditions favored sorghum growth, and the season was classified as satisfactory, with an HTC of 1.2.

Overall, the contrasting hydrothermal conditions during 2021–2024 enabled a comprehensive evaluation of the sorghum collection under both favorable and unfavorable environments.

RESULTS AND DISCUSSION

The accessions differed markedly in phenological development. The emergence-to-flowering period lasted 62–67 days in early-maturing, 68–72 days in medium-maturing, and 73–77 days in late-maturing accessions. K-5501 (Slavyanka), K-5498 (Avans), K-5499 (Bakalavr), K-5538 (Slavyanskoe Pole 591), and K-5559 (Ayushka) flowered 2–3 days earlier than the standard. Early accessions reached wax maturity in 89–94 days, 2–5 days earlier than Dergachevsky, whereas medium- and late-maturing accessions required 95–101 and 102–109 days, respectively **(Table 1).** Their heat requirements were also lower: 2,316–2,378 °C compared with 2,391–2,483 °C and 2,492–2,603 °C for the later groups. This confirms the lower thermal demand of early sorghum reported by Begna (2025); however, under Northern Kazakhstan conditions, early accessions also produced more grain because autumn frosts frequently prevented complete maturation of later genotypes.

Table 1. Duration of phenological phases (mean values for 2021–2024).

Cultivar	Origin	Duration of periods (days)	
		Emergence–flowering	Emergence–wax maturity
Dergachevsky, standard	Russia	67	94
Early-maturing			
K-5538, Slavyanskoe Pole 591	Russia	65	89
K-5501, Slavyanka	Russia	65	91
K-5498, Avans	Russia	65	94
K-5499, Bakalavr	Russia	64	89
K-5559, Ayushka	Russia	62	91
K-5539, Kinelskoe 63	Russia	65	93
Medium-maturing			
K-5536, Zersta 90	Russia	68	95
K-5502, Granat	Russia	69	96
K-5497, RSK Kaskad	Russia	72	101
Late-maturing*			
K-5535, Zhetysu 1	Kazakhstan	75	109
K-5556, Volzhskoe 615	Russia	73	102

Note: In 2023, the plants reached the beginning of the wax maturity stage; in 2021, 2022, and 2024, they reached full flowering.

The frost-free period from emergence to full wax maturity was 93–95 days in 2021, 2022, and 2024 and 103 days in 2023. Growth was slow during the first month after emergence (0.4–0.6 cm day^{-1}) but increased after the five- to six-leaf stage to 3.3–4.2 cm day^{-1} in early accessions and 2.9–3.6 cm day^{-1} in later groups. At wax maturity, plant height ranged from 118 to 156 cm in early, 127 to 178 cm in medium, and 135 to 179 cm in late accessions; K-5499 (Bakalavr) and K-5536 (Zersta 90) were the tallest.

Fresh biomass and dry matter yields varied substantially among accessions **(Table 2)**. A separate study of sweet sorghum in Northern Kazakhstan identified growing-season conditions as the main factor influencing green biomass yield (Bogapov *et al*., 2026). K-5556 (Volzhskoe 615) and K-5527 (Solnyshko) recorded the highest values, while several early- and medium-maturing accessions also exceeded the standard. Overall, the best accessions surpassed Dergachevsky by up to 26.3% in fresh biomass and 27.3% in dry matter, indicating that later maturity favored fodder biomass production.

Table 2. Yield of sorghum accessions in the collection nursery, mean values for 2021–2024.

Cultivar	Crop yield			
	Fresh biomass		Dry matter	
	g/m²	% of standard	g/m²	% of standard
Dergachevsky, standard	2278,3	100	867,5	100
Early-maturing				
K-5559, Ayushka	2540.4	111.5	952.7	109.8
K-5499, Bakalavr	2698.5	118.4	1014.8	117.0
K-5539, Kinelskoe 63	2486.0	109.1	922.6	106.4
K-5501, Slavyanka	2608.7	114.1	986.5	113.7
K-5538, Slavyanskoe Pole 591	2550.0	111.9	986.5	113.7
K-5502, Granat	2389.4	100.4	899.8	100.3
Medium-maturing				
K-5497, RSK Kaskad	2796.7	117.7	1061.9	118.3
K-5536, Zersta 90	2739.5	115.2	1032.8	115.1
K-5498, Avans	2817.6	118.5	1064.5	118.6
K-5527, Solnyshko	2991.4	125.9	1134.8	126.4
Late-maturing				
K-5535, Zhetysu 1	2548.6	107.2	970.4	108.1
K-5556, Volzhskoe 615	3004.8	126.3	1142.6	127.3
$LSD_{0.05}$	202.6		81.2	

Maturity group and year strongly influenced grain yield **(Table 3)**. In the extremely dry 2023 season, early accessions yielded 46.5–73.0 g m^{-2} because they reached wax maturity with sufficient accumulated heat and used stored soil moisture before the most severe summer drought. Averaged across 2021–2024, K-5501 (Slavyanka), K-5499 (Bakalavr), K-5502 (Granat), and K-5538 (Slavyanskoe Pole 591) produced 45.2–65.8 g m^{-2}, exceeding the standard (38.5 g m^{-2}) by 17.4%–70.9%; K-5539 (Kinelskoe 63) exceeded it by 8.3%. All medium- and late-maturing accessions yielded less grain than the standard. The selected early accessions had higher yields, with a 1,000-grain weight of 23–25 g and 910–1,030 grains per panicle, compared with 18 g and 820 grains in Dergachevsky, supporting the importance of these yield components reported by Kostylev *et al.* (2025).

Table 3. Plant height and grain yield of sorghum accessions, mean values for 2021–2024.

Cultivar/accession	Plant height (cm)	Grain yield, g/m²					
		2021	2022	2023	2024	mean	% of standard
Early-maturing							
Dergachevsky, standard	132	29.4	36.5	47.3	40.0	38.5	100
K-5559, Ayushka	136	29.7	31.9	46.5	36.8	36.2	94.0
K-5499, Bakalavr	156	40.7	41.5	55.3	49.6	46.8	121.6
K-5539, Kinelskoe 63	132	33.4	38.5	52.4	42.5	41.7	108.3
K-5501, Slavyanka	118	60.7	62.4	73.0	67.3	65.8	170.9
K-5538, Slavyanskoe Pole 591	137	37.5	41.2	52.3	49.6	45.2	117.4
K-5502, Granat	126	38.6	42.3	55.9	46.0	45.7	118.7
Medium-maturing							
K-5497, RSK Kaskad	147	30.8	33.7	42.9	36.5	36.0	93.5
K-5536, Zersta 90	178	26.5	30.7	40.5	34.0	32.9	85.4
K-5560, Ros	141	22.3	23.7	35.6	27.1	27.2	70.6
K-5498, Avans	145	17.3	14.6	31.8	25.0	22.2	57.7
K-5527, Solnyshko	—	24.9	25.2	32.0	27.4	27.4	71.2
Late-maturing							
K-5556, Volzhskoe 615	142	10.8	13.7	18.4	15.8	14.7	38.2
K-5535, Zhetysu 1	135	11.8	12.4	16.7	10.8	12.9	33.5
$LSD_{0.05}$	10.3					4.5	

Adaptive-capacity indicators confirmed the value of several early accessions **(Table 4)**. K-5501, K-5499, and K-5538 combined high yield with smaller yield variation than the standard and stress-tolerance values of −12.3 to −14.8. Among medium-maturing accessions, K-5527 had the most favorable stress-tolerance value (−7.1), although its grain yield was lower. Genetic flexibility was highest in K-5501, K-5499, and K-5502 (47.2–66.8), while K-5501, K-5499, and K-5538 had comparatively low Ymax − Ymin values, indicating greater environmental stability. These results agree with the interpretation that a smaller difference between yields under contrasting environments reflects broader adaptive capacity (Levakova, 2019; Bezuglaya *et al.*, 2021).

Table 4. Grain yield and adaptive capacity indicators of grain sorghum accessions, mean values for 2021–2024.

Accession/cultivar	Yield variation (min–max), g/m²	Stress tolerance ($Y_2 - Y_1$)	Genetic flexibility $\frac{y_1 - y_2}{2}$	Environmental stability y_1-y_2
Dergachevsky, standard	29.4–47.3	−17.9	38.4	17.9
Early-maturing				
K-5559, Ayushka	29.7–46.5	−16.8	38.1	16.8
K-5499, Bakalavr	40.7–55.3	−14.6	48.0	14.6
K-5539, Kinelskoe 63	33.4–52.4	−19.0	42.9	19.0
K-5501, Slavyanka	60.7–73.0	−12.3	66.8	12.3
K-5538, Slavyanskoe Pole 591	37.5–52.3	−14.8	44.9	14.8
K-5502, Granat	38.6–55.9	−17.3	47.2	17.3
Medium-maturing				
K-5497, RSK Kaskad	30.8–42.9	−12.1	36.8	12.1
K-5536, Zersta 90	26.5–40.5	−14.0	33.5	14.0
K-5560, Ros	22.3–35.6	−13.3	28.9	13.3
K-5498, Avans	14.6–31.8	−17.2	23.2	17.2
K-5527, Solnyshko	24.9–32.0	−7.1	28.4	7.1
Late-maturing				
K-5556, Volzhskoe 615	10.8–18.4	−7.6	14.6	7.6
K-5535, Zhetysu 1	10.8–16.7	−5.9	13.8	5.9

All accessions showed very high visual drought tolerance (4.8–4.9 points) during stem elongation–flowering. Bacterial leaf spot caused by *Pseudomonas holci* Kendrick was most severe in the humid 2024 season: infection reached 26.2%–40.0% in medium- and late-maturing accessions but only 6.4%–9.8% in early accessions. This pattern agrees with reports that bacterial spotting develops more strongly under humid than moisture-deficient conditions (Reshetnikov *et al.*, 2023; Wei *et al.*, 2023).

Grain composition also differed among accessions **(Table 5)**. Seven accessions contained 11.04%–13.10% crude protein and 8.83%–10.48% digestible protein, exceeding the standard by 0.25–2.31 and 0.20–1.85 percentage points, respectively. K-5499 (Bakalavr) had the highest crude and digestible protein contents, while K-5501, K-5502, and K-5527 had the highest crude fat contents (1.62%–1.87%). Metabolizable energy and feed-unit contents were consistently high across the collection,

ranging from 12.52 to 12.80 MJ kg^{-1} and 1.27 to 1.33 kg kg^{-1}. Considering protein, energy, and feed-unit values together, K-5539, K-5499, K-5501, K-5502, K-5498, and K-5556 were the most promising. Crude and digestible protein, energy, and feed-unit values have also been reported for Rumex K-1 and Jerusalem artichoke used in an experimental feed mixture (Bakhtiyarova *et al*., 2025).

Table 5. Chemical composition and nutritional value of sorghum grain, mean values for 2023–2024.

Cultivar/catalogue number	Crude protein (%)	Crude fibre (%)	Crude ash (%)	Crude fat (%)	NFE (%)	Nutritional value per 1 kg of dry matter		
						Digestible protein (%)	ME, MJ	Feed units, kg/kg
Early-maturing								
Dergachevsky, standard	10.79	3.43	1.62	0.74	83.42	8.63	12.60	1.29
K-5539, Kinelskoe 63	11.94	2.19	2.29	1.31	83.27	8.85	12.68	1.30
K-5499, Bakalavr	13.10	2.97	1.97	1.56	80.40	10.48	12.70	1.31
K-5501, Slavyanka	12.75	4.32	2.84	1.62	78.47	10.20	12.52	1.27
K-5502, Granat	11.13	3.25	1.70	1.87	82.05	8.90	12.79	1.32
Medium-maturing								
K-5497, RSK Kaskad	10.77	3.48	1.34	1.23	83.18	8.62	12.72	1.31
K-5536, Zersta 90	10.91	1.77	2.33	0.91	84.08	8.73	12.64	1.29
K-5498, Avans	12.58	2.98	2.11	1.24	81.09	10.06	12.63	1.29
K-5527, Solnyshko	11.18	2.83	1.84	1.85	82.30	8.94	12.79	1.33
Late-maturing								
K-5556, Volzhskoe 615	11.04	2.21	1.86	1.19	83.70	8.83	12.72	1.31
K-5535, Zhetysu 1	9.71	2.79	1.44	1.48	84.58	7.77	12.80	1.33

Ten crossing combinations were produced from accessions with valuable traits and evaluated for drought tolerance, plant height, synchronous flowering and maturation, early maturity, and grain yield. The hybrids K-1-23, K-2-23, K-4-23, K-5-23, K-8-23, and K-9-23 exceeded the Dergachevsky standard (56.4 g m^{-2}) by 9.6–12.7 g m^{-2}, or 17.0–22.5%, and therefore represent promising material for further breeding.

CONCLUSION

Evaluation of the grain sorghum collection in Northern Kazakhstan identified six promising early-maturing accessions: K-5499 (Bakalavr), K-5501 (Slavyanka), K-5539 (Kinelskoe 63), K-5502 (Granat), K-5538 (Slavyanskoe Pole 591), and K-5559 (Ayushka). They reached wax maturity within 94 days, required fewer thermal resources, and exceeded the standard by 9.1%–18.4% in fresh biomass and dry matter yield and by 8.3%–70.9% in grain yield. These accessions also showed high stress tolerance, genetic flexibility, and environmental stability.

Several medium- and late-maturing accessions produced high fodder biomass but lower grain yields than the standard. K-5539, K-5499, K-5501, K-5502, K-5498, and K-5556 recorded the best grain quality. Early-maturing accessions are therefore recommended for breeding for grain and fodder productivity, whereas later-maturing forms are more suitable for fodder production. The selected parental material also produced promising early-maturing hybrids with high productive and adaptive potential.

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REFERENCES

Bakhtiyarova, S., Kapysheva, U., Makashev, Y., Zhaksymov, B., Makashev, Y., Kalekeshov, A., Junussova, A., & Bimenova, Z. (2025). Novel feed mixture from non-traditional forage plants for young farm animals. *International Journal of Agriculture and Biosciences, 14*(6), 1231–1239. doi:10.47278/journal.ijab/2025.108

Begna, T. (2025). Phenotypic variability analysis of key sorghum (Sorghum bicolor (L) moench) genotypes under dry lowland areas. *Reproduction and Breeding, 5*, 79-87. doi:10.1016/j.repbre.2025.03.007

Bezuglaya, T. S., Samofalova, N. E., Ilichkina, N. P., Dubinina, O. A., & Kameneva, A. S. (2021). Adaptive potential of the new winter durum wheat varieties and lines in the conditions of the Rostov region. *Grain Econ. Russ., 3*, 27-33. doi:10.31367/2079-8725-2021-75-3-27-33

Bogapov, I., Baidalin, M., Kibalnik, O., Baidalina, S., Akhet, A., Salikova, Z., Nogoyev, Y., & Alshinbayeva, Z. (2026). Agronomic and bioconversion assessment of sweet sorghum as a sustainable bioethanol feedstock in Northern Kazakhstan. *International Journal of Design & Nature and Ecodynamics, 21*(8), 2467–2475. doi:10.18280/ijdne.210826

Chadalavada, K., Kumari, B. D. R., & Kumar, T. S. (2021). Sorghum mitigates climate variability and change on crop yield and

quality. *Planta, 253*, 113. doi:10.1007/s00425-021-03631-2

Federal Agency for Technical Regulation and Metrology. (2015). *GOST ISO 6865-2015 Animal Feeding Stuffs. method for determination of Crude Fibre Content. Standartinform, Moscow, Russia*.

Federal Agency for Technical Regulation and Metrology. (2016). *GOST ISO 5983-2-2016 Feeds, Compound Feeds, Feed Raw Materials. determination of Mass Fraction of Nitrogen and Calculation of Mass Fraction of Crude Protein. Part 2. Block Digestion and Steam Distillation method. Standartinform, Moscow, Russia*.

Federal Agency for Technical Regulation and Metrology. (2019). *GOST 13496.4-2019 Fodder, Mixed Fodder and Raw Mixed Fodder. methods of Nitrogen and Crude Protein determination. Standartinform, Moscow, Russia*.

Hernández, P. F. V., Mendoza Onofre, L. E., & Rosas Cárdenas, F. F. (2023). Responses of sorghum to cold stress: A review focused on molecular breeding. *Frontiers in Plant Science, 14*, 1124335. doi:10.3389/fpls.2023.1124335

International Organization for Standardization. (2022). *ISO 5984:2022. Animal feeding stuffs – Determination of crude ash*. Available from: https://www.iso.org/standard/77807.html

Kibalnik, O. P., Efremova, I. G., Semin, D. S., Starchak, V. I., Stepanchenko, D. A., & Kukoleva, S. S. (2023). The use the VIR world collection in the selection of new varieties and hybrids of sugar sorghum for arid regions of the Russian Federation. *Agrarian Science*, (366(1)), 78-82. doi:10.32634/0869-8155-2023-366-1-78-82

Kostylev, P. I., Kovtunov, V. V., & Kalyuzhny, A. A. (2025). Elements of the yield structure affecting the productivity of grain sorghum. *Journal of Agriculture and Environment*, (10(62)), 1-6. doi:10.60797/JAE.2025.62.2

Levakova, O. V. (2019). The study results of adaptive-ecological traits of the new varieties and promising lines of winter soft wheat in the Ryazan Region. *Grain Econ. Russ., 2*, 13-16. doi:10.31367/2079-8725-2019-62-2-13-16

Mamykin, E., Nazarova, P., & Utelbayev, Y. (2026). Pea productivity depending on the methods of mineral fertilizer treatment with the no-till system in the arid conditions of North Kazakhstan. *International Journal of Agriculture and Biosciences, 15*(6), 2620–2634. doi:10.47278/journal.ijab/2026.180

Prasad, V. B. R., Govindaraj, M., Djanaguiraman, M., Djalovic, I., Shailani, A., Rawat, N., Singla-Pareek, S. L., Pareek, A., & Prasad, P. V. V. (2021). Drought and high temperature stress in sorghum: Physiological, genetic, and molecular insights and breeding approaches. *International Journal of Molecular Sciences, 22*, 9826. doi:10.3390/ijms22189826

Reshetnikov, M. V., Butsenko, L. M., & Pasichnyk, L. A. (2023). Biological properties of the agent of soryz bacterial spot in Ukraine. *Microbiological Journal, 85*(6), 48-60. doi:10.15407/microbiolj85.06.048

Rosielle, A. A., & Hamblin, J. (1981). Theoretical aspects of selection for yield in stress environments. *Crop Science, 6*, 12-13.

Rukavitsina, I., Kushugulova, A., Filippova, N., Kozhakhmetov, S., Zuyeva, N., & Zhloba, L. (2026). Metagenomic insights into microbial community response to Melilotus officinalis green manuring in degraded steppe soils. *Agriculture, 16*(1), 36. doi:10.3390/agriculture16010036

Shpakov, A. S., Novoselov, Y. K., Kharkov, G. D., Volovik, V. T., Truzina, L. A., Prologova, T. V., Ulanov, A. N., Laretin, N. A., & Usoltseva, T. G. (2024). *Methodical Basis of Field Experiments with Fodder Crops. FGBOU DPO RAKO APK, Moscow, Russia. Pp. 332*.

State Committee of the USSR for Standards. (1987). *GOST 4808-87. Hay. Specifications. IPK Izdatel'stvo standartov, Moscow, USSR*.

Ualkhanov, B., Konopiyanov, K., Bekenova, L., Zhukova, N., & Mukhamadiyeva, A. (2024). Impact of new varieties on the yield and quality of wheat, oats, and Sudangrass in North-Eastern Kazakhstan. *International Journal of Design & Nature and Ecodynamics, 19*(1), 81–91. doi:10.18280/ijdne.190110

Wei, G., Zhao, W., Hu, A., Ren, M., Huang, Y., & Xu, H. (2023). Identification of a new pathogenic fungi causing sorghum leaf spot Disease and its management using natural product and microorganisms. *Microorganisms, 11*, 1431. doi:10.3390/microorganisms11061431

Yahaya, M. A., & Shimelis, H. (2021). Drought stress in sorghum: Mitigation strategies, breeding methods and technologies – A review. *Journal of Agronomy and Crop Science, 207*, 127-142. doi:10.1111/jac.12573