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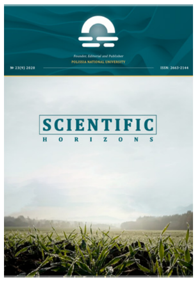

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Prospects for the cultivation of grain sorghum (*Sorghum bicolor* L. Moench) in the arid region of the Kazakh Aral Sea region: Literature review

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Abstract. The purpose of the present study was to substantiate effective breeding and agronomic solutions for improving the resistance of sorghum to climatic stresses in the conditions of the Aral Sea region. Based on an analysis of literature sources, the study showed that the agricultural sector of the Kyzylorda region of the Republic of Kazakhstan faces a persistent water shortage caused by both natural and anthropogenic factors. A considerable reduction in water inflows to the lower reaches of the Syr

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Darya, degradation of irrigation infrastructure, and deterioration of water quality create conditions under which conventional water-intensive crops such as rice become economically and environmentally unviable. A review of sources confirmed that, along with technical measures such as the introduction of water-saving technologies, the transition to more drought-resistant crops, including sorghum, is becoming increasingly significant. Sorghum was demonstrated to have unique physiological adaptations to water and heat stress due to its morphological and anatomical characteristics, growth phases, and ability to retain green mass. In the Aral Sea region, this crop is considered a key element in the strategy for adapting crop production to changing climatic conditions. Furthermore, sorghum has a wide range of applications, from food and feed to bioenergy, which highlights its agro-economic value. The literature review also noted growing interest in the genetic and breeding potential of sorghum: international gene banks hold more than 42,000 samples, including unique genotypes from Africa and Asia, which opens prospects for the creation of sustainable and high-yielding varieties. Thus, the findings of the literature review confirmed the pronounced adaptability of sorghum to the conditions of the Aral Sea region, its strategic significance in conditions of water stress, and the relevance of further breeding and agronomic developments aimed at its widespread introduction into the region's agriculture

Keywords: stress tolerance; genetic diversity; biopreparations; agrotechnical methods; water use efficiency

INTRODUCTION

The relevance of the present study is conditioned by the need to increase the resilience of agricultural crops, particularly sorghum, to extreme climatic conditions such as drought and hot temperatures. In the context of global climate change and increasing frequency of droughts in various regions of the world, the efficient use of water resources and ensuring food security are becoming priority tasks. Sorghum, due to its marked resistance to drought and hot conditions, is a promising crop that can play a key role in ensuring food security in arid regions. The problematic of the present study lies in the complexity of breeding drought- and heat-tolerant sorghum varieties, as high yield and tolerance to extreme conditions are often mutually exclusive traits. Furthermore, breeding for these traits requires consideration of many factors, such as genetic potential, interaction with the environment, and adaptive capabilities. Despite advancement in sorghum breeding, there is a need to develop more effective screening methods and genomic tools to accelerate the improvement of varieties with enhanced drought tolerance and heat tolerance.

L. Tokhetova *et al*. (2022) addressed the problem of creating source material for breeding for adaptability to stress factors. The researchers emphasised the value of developing sorghum varieties that can effectively adapt to extreme climatic conditions, including drought and hot temperatures. B.N. Nasiev and A.M. Zhilkybay (2022) focused on biological crop cultivation technologies in Western Kazakhstan. According to the researchers, the use of such methods can greatly increase plant resistance to drought, which is a vital aspect for the creation of sustainable sorghum varieties in arid regions. M. Masatbaev and N. Khozhanov (2021) investigated the influence of climatic factors on soil humus components. The researchers pointed out that the changing climatic conditions affect crop productivity and that, to maintain the sustainability of sorghum, it is necessary to create varieties capable of adapting to these changes.

S. Hossain *et al*. (2022) paid special attention to sorghum as a promising crop, considering it an essential element for food security in the context of climate change. These researchers noted that the creation of drought-resistant sorghum varieties is becoming a priority for countries facing water shortages. B.A. Pandian *et al*. (2022) considered not only the resistance of sorghum to herbicides but also emphasised the need to improve its resistance to climatic stresses. The researchers noted that selection for heat and drought tolerance is a crucial part of the breeding process, which contributes to the adaptability of sorghum under extreme climatic conditions. P.K. Subudhi *et al*. (2024) highlighted the key achievements in sorghum improvement, with the researchers emphasising that, for the successful cultivation of this crop under climate change, it is necessary to continue work on the development of varieties that are resistant to hot conditions and drought.

According to H. Hao *et al*. (2021), genomic technologies open new opportunities for sorghum breeding, providing valuable tools for the creation of varieties that are resistant to climate stress. The researchers emphasised that the use of such technologies can markedly accelerate the process of sorghum improvement in the context of global climate change. W. Yali and T. Begna (2022) highlighted the progress of sorghum breeding in Ethiopia, where the crop is crucial for food security. The researchers acknowledged the achievements in breeding but noted that further success required addressing issues of drought and heat tolerance. In their study of the state of cereal crops in Bangladesh, A.K.M.G. Sarwar and J.K. Biswas (2021) showed that sorghum is becoming a prominent feed crop despite challenges such as insufficient drought resistance. The researchers stressed the need to develop more drought-tolerant sorghum varieties to increase its productivity under extreme climatic conditions. T.W. Hermann *et al*. (2023) covered the genetic diversity of sorghum and its potential for improving varieties in Burkina Faso. These researchers emphasised the significance of developing sweet sorghum varieties that are resistant to drought and hot temperatures, which is particularly relevant for a region with unfavourable climatic conditions. According to H. Zheng *et al*. (2023), sorghum could become an essential element of global food security and bioenergy. The researchers noted that, due to its resistance to extreme climatic conditions, sorghum has immense potential for use as a food and energy crop. A. Ashesh *et al*. (2025) examined the current challenges and prospects for sorghum development, pointing out the need to use the latest technologies to create varieties that can adapt to climate change and ensure food security.

The purpose of the present study was to assess the resistance of sorghum genotypes to climatic stresses and the potential for breeding to improve their adaptability. The objectives of the study were to assess the resistance of various sorghum genotypes to drought and hot conditions, as well as to analyse the effectiveness of modern breeding methods to improve their adaptability. A literature review was conducted using data from scientific publications covering the climatic and agroecological conditions of the Aral Sea region, the biological characteristics of sorghum, its stress resistance, areas of application, genetic resources, and modern breeding approaches. The analysis was based on the findings of studies conducted both in Kazakhstan and in other countries with arid climates (including Ethiopia, Bangladesh, Burkina Faso, etc.).

CLIMATIC AND SOIL CONDITIONS IN THE ARAL SEA REGION

Water scarcity in the Kyzylorda region of the Republic of Kazakhstan is a persistent problem that worsens year after year. The region is located in the lower reaches of the transboundary Syr Darya River and is completely dependent on water supplies from Uzbekistan and Kyrgyzstan. In a dry climate with high evaporation rates and degraded irrigation infrastructure, water supply is becoming a critical factor for the region's agricultural sector. According to the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan, in 2023, less than 6.9 bn m^3 of water flowed into the lower reaches of the Syr Darya, which is 2.1 bn m^3 less than in the same period in 2022. This represents a deficit of around 23%-25% compared to the normative values for the agricultural season. The water accumulation indicator in key regulatory structures was particularly alarming: at the end of summer 2023, there was 770 million m^3 less water in the Shardara Reservoir and the Koksarai Counter-Regulator than in the previous year (National report on…, 2023).

The water shortage directly affected the area under crops. In 2023, rice cultivation in the Kyzylorda region was reduced by more than 7,000 hectares compared to 2022. While in 2021-2022 the area under rice cultivation averaged 87-89 thsd ha, in 2023 it decreased to about 81.5 thousand hectares, according to data from the regional administration (Mass rice harvesting…, 2022). This is a necessary measure aimed at redistributing limited water resources in favour of less water-intensive crops and ensuring drinking water supplies for the population. The Syr Darya, as the main water artery of the region, also faces environmental challenges. Depletion of the riverbed, overgrowth with algae, and pollution from agricultural and industrial discharges all reduce water quality and increase losses during transport. According to environmental monitoring data, water losses in irrigation canals reach up to 40%, especially in old concrete and open channels that require modernisation. Drought and high soil salinity are other key limiting factors threatening agriculture in the region. Due to high mineralisation and water regime disturbances, over 35% of the region's agricultural land is subject to secondary salinisation, which critically affects crop yields and limits crop choice.

Against the backdrop of these problems, a set of measures aimed at adapting agriculture to water stress has been launched in the region. Firstly, cropland is being reallocated – instead of rice, sorghum, barley, millet, and maize, which are more drought-resistant, are increasingly being planted. Specifically, in 2023, about 4,000 ha were allocated for sorghum, which is almost twice as much as in 2021. Secondly, farmers are recommended to introduce drip and subsurface irrigation, which can save up to 30%-50% of water compared to conventional methods. Additionally, Kazakhstan is actively pursuing international cooperation with neighbouring countries on water distribution in the Syr Darya basin. However, the problem continues to be systemic: irregular discharges, lack of coordinated water supply schedules, and lack of uniform accounting and monitoring standards hinder the achievement of a sustainable water balance in the region.

BIOLOGICAL AND AGRONOMIC FEATURES

Grain sorghum, *Sorghum bicolor* L. Moench, is a staple food for millions of people living in approximately 30 countries in the subtropical and semi-arid regions of Africa and Asia (Rashwan *et al.,* 2021). Heat and water shortages during flowering are severe stress factors that considerably affect the yield of spring crops worldwide. These conditions are becoming particularly relevant in the context of global climate change, which is projected to cause global average temperatures to rise by 3.3°C-5.7°C by the end of the 21st century under the SSP5-8.5 scenario (Dhakar *et al.,* 2023). Such warming exacerbates extreme weather events such as droughts and abnormal heat, creating further challenges for agriculture. Although sorghum is considered a crop well-adapted to hot and dry climates due to its physiological resilience, it is not completely protected from the effects of terminal drought and heat stress. These factors are still among the most significant abiotic constraints to stable crop production, including sorghum.

The impact of heat stress on sorghum yield is determined by several key aspects: the timing of stress onset, its intensity and duration (Smith *et al*., 2023). For example, if stress occurs during critical stages of plant development, such as flowering or grain formation, it can substantially reduce the final yield. The primary damage is manifested in a reduction in the number of grains per plant, which is a direct consequence of the disruption of pollination and fruit set (Yeraliyeva *et al*., 2017). Therewith, an increase in the weight of individual grains is usually unable to fully compensate for the overall losses, which leads to a decrease in the overall productivity of the crop. Thus, despite sorghum's high adaptability to unfavourable conditions, its yield continues to be vulnerable to a combination of hot temperatures and moisture deficiency, which requires further research and the development of resistant varieties.

Sorghum development undergoes 12 distinct stages of organogenesis, each of which plays a significant role in the development of the plant and its yield (Dubery *et al*., 2024). These stages are described in detail below: in the first stage – seed germination – the seed absorbs moisture from the soil, internal biochemical processes are activated, and embryo growth begins; this stage is critically dependent on soil temperature and moisture, as water deficiency or too low temperatures can slow down or even stop germination. This is followed by the second stage – emergence of seedlings and formation of the third leaf – when, after germination, the first shoots appear, followed by the formation of the first true leaves, including the third, which marks the beginning of active development of the aboveground part of the plant; at this stage, sorghum begins to photosynthesise and strengthen its root system. The third stage, tillering, is characterised by the active formation of lateral shoots, which increases the potential productivity of the plant; this process requires sufficient nutrients and water, while stressful conditions can limit the number of shoots. In the fourth stage, tillering continues, strengthening the plant's structure; sorghum becomes more resistant to external factors but is still sensitive to drought, which can reduce the number of productive shoots. The fifth stage, the booting phase, marks the beginning of vertical stem growth, when the leaves fold into a tube, preparing the plant for the reproductive stage; this is a transitional stage that requires a stable water supply for normal development. In the sixth stage – continued booting – stem growth continues, the plant elongates and strengthens; sorghum actively accumulates resources for the upcoming flowering, which makes it vulnerable to moisture or nutrient deficiencies. The seventh stage, stem growth, is associated with intensive elongation and thickening of the stem, as well as biomass accumulation; this stage is vital for the development of a powerful base that will support the future panicle and grains. The eighth stage – the heading stage – begins with the formation of the panicle, the reproductive organ of sorghum; this process is sensitive to temperature fluctuations and water deficiency, which can affect the quality and quantity of future grains. The ninth stage, the flowering phase, is crucial, as this is when pollination and grain setting occur; hot temperatures or drought at this time can lead to sterile flowers and a significant reduction in yield. In the tenth stage – grain formation and growth – after successful pollination, grain development begins; the plant directs resources to increase the size and number of grains, which depends on the availability of water and nutrients. The eleventh stage – grain filling – is characterised by the accumulation of nutrients such as starch and proteins in the grains, which determines their final weight and quality; lack of moisture at this stage can lead to immature or small grains. Finally, the twelfth stage – the wax and full ripeness phase – is the final stage, when the grains reach their optimum maturity; wax ripeness is characterised by partial drying, while full ripeness – by readiness for harvest, with environmental conditions at this stage affecting crop preservation (Fig. 1).

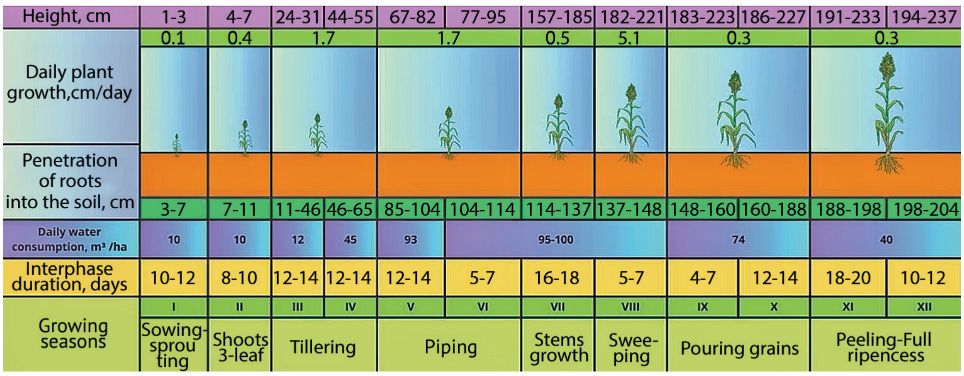

***Figure 1**. Features of grain sorghum plant development*

***Source:** compiled by the authors based on A.K. Rashwan et al. (2021), R. Dhakar et al. (2023), A. Smith et al. (2023), R. Kopecká et al. (2023), I. Dubery et al. (2024)*

Abiotic stresses: drought, hot temperatures, salinisation, and flooding continue to be the primary factors limiting crop growth and productivity under climate change (Kopecká *et al.,* 2023). Despite sorghum's high tolerance to extreme conditions such as heat, drought, saline soils, and excess moisture, in arid and semi-arid regions the plant often faces water shortages after flowering. The drought tolerance of sorghum is conditioned by both morphological and anatomical characteristics (the presence of a dense waxy coating on the leaves, their curling, and a well-developed root system) and physiological mechanisms, including osmotic regulation involving osmo-protectors and the 'stay green' ability.

FOOD USE OF SORGHUM IN FEED PRODUCTION AND BIOENERGY

Sorghum has been one of the key crops for centuries, providing food for millions of people in various parts of the world, especially in Africa, South Asia, and Latin America. In India, for instance, sorghum flour is traditionally used to make chapati, thin flatbreads that form the staple of the daily diet for a sizeable portion of the population, especially in rural areas (Meena *et al.*, 2022). In African countries, sorghum is widely used to prepare a variety of dishes, from thick porridges and flatbreads to bread, soft drinks, and even popcorn, highlighting its versatility and accessibility (Adebo, 2020). In Indonesia, this crop ranks third among cereals in terms of cultivation volume, behind only rice and maize, which indicates its significance in the local agro-economy. Although sorghum consumption is gradually declining in some regions due to competition from cheaper and more accessible products such as wheat or rice, it continues to play an indispensable role in food security, especially in arid and semi-arid areas (Pichura *et al.*, 2024). This is conditioned by its outstanding drought tolerance, ability to grow on poor soils and stable yields even under limited water supply.

Recently, sorghum has been gaining popularity in high-income countries such as the United States, Brazil, South Africa, and Kenya, where it is beginning to be perceived not just as a traditional crop for the poor, but as a valuable functional food product. Sorghum grain has a series of unique properties that make it particularly attractive to health-conscious consumers. It is gluten-free, making it an ideal choice for people with coeliac disease or gluten intolerance. Furthermore, sorghum is rich in antioxidants, micronutrients (such as iron, magnesium, and phosphorus), and polyphenols, which help reduce inflammation and strengthen the immune system. These qualities make sorghum a valuable component of a balanced diet, and its use in the food industry – from gluten-free baked goods to nutritious bars – is rapidly expanding in the global market.

Apart from its food uses, sorghum plays a prominent role in animal feed production, which is particularly significant for regions with limited natural resources (Sprynchuk *et al.*, 2023). Its green mass, haylage, silage, and grain are used to prepare high-quality compound feed, providing nutrition for livestock in semi-arid areas where other feed crops, such as maize, may be unable to withstand extreme conditions (Hadebe *et al.*, 2021). The advantages of sorghum in this area include its undemanding soil requirements, ability to use minimal amounts of water efficiently, and high biomass productivity. However, there are certain challenges associated with its use. These include the relatively short shelf life of green mass and grain due to high moisture content, vulnerability to pests such as birds and insects, and the need for technological solutions to increase nutritional value and improve yields. For instance, grain processing or the selection of resistant varieties can help overcome these limitations, making sorghum an even more competitive crop.

In recent years, scientists and agronomists have been paying particular attention to the bioenergy potential of sorghum, which opens new horizons for its use (Bakari *et al.,* 2023). Technical and sweet varieties of this crop can accumulate significant amounts of biomass rich in sugars and cellulose, making them a promising raw material for bioethanol and biogas production. Unlike many other bioenergy crops, such as maize or sugar cane, sorghum does not compete directly with food crops, as it can be successfully grown on marginal, low-fertility lands without requiring intensive irrigation or large investments in fertilisers (Bolokhovsky *et al.*, 2024). This makes it an economically viable and environmentally sustainable solution for resource-depleted regions. Furthermore, the use of sorghum in bioenergy contributes to reducing dependence on fossil fuels and greenhouse gas emissions, which is particularly relevant in the context of global climate change (Fig. 2).

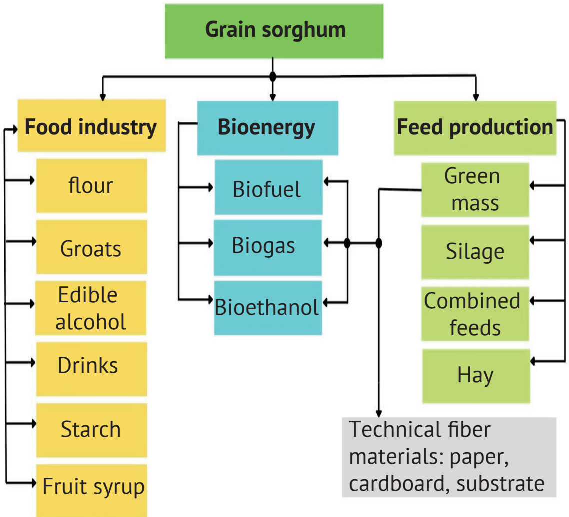

Figure 2*. Economic and industrial uses of grain sorghum*
Source: *compiled by the authors of this study based on O.A. Adebo (2020), Hadebe et al. (2021), K. Meena et al. (2022), S.T.H. Bakari et al. (2023)*

Thus, sorghum is a multifunctional crop that, thanks to its versatility and adaptability, can simultaneously address food, feed, and energy security challenges. In the context of a growing global population, declining arable land and increasing climate challenges, sorghum is poised to become a strategic crop, ensuring the stability and development of agricultural systems in the most challenging regions of the world.

GENETIC RESOURCES AND SELECTION

Genetic resources of sorghum preserved in global collections represent an extensive pool of more than 42,000 accessions (Mace *et al.*, 2020). One of the leaders in this field is the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, which holds approximately 38,000 germplasm samples covering approximately 80% of the genetic diversity of sorghum (Mangshin *et al.*, 2024). These samples have been carefully studied and preserved using both short-term and long-term storage methods, which allows them to stay viable for future research and breeding. Among the largest repositories, two key centres stand out: ICRISAT and the US Department of Agriculture's National Plant Germplasm System (USDA-NPGS), each with more than 41,000 samples, including historical lines, local ecotypes, wild species, and breeding results (Cuevas & Prom, 2020). In India, the National Bureau of Plant Genetic Resources has a collection of approximately 20,000 samples, while in China, the Institute of Germplasm Resources of Agricultural Crops has over 16,874 samples (Singh *et al.*, 2020). The Australian Centre for Tropical Crop and Forage Genetic Resources, on the other hand, focuses on a unique collection of local wild sorghum species, making it a valuable source for studying the wild genome of this crop and its potential for adaptation to extreme conditions. Furthermore, sorghum has gained attention in recent years due to its ability to grow on marginal lands where conventional crops such as wheat or maize are ineffective, making it a valuable asset for countries with limited agricultural resources.

Sorghum was first domesticated in North-East Africa, in a region stretching from Sudan to Ethiopia, which established this territory as the centre of its evolution (Barron *et al.*, 2020). It is here that the greatest diversity of ancient wild species is preserved, as well as a wealth of genetic lines formed over thousands of years of interaction between humans and nature. The USDA-NPGS collection, which includes nearly 41,000 samples, contains 7,217 specimens from Ethiopia and 2,552 from Sudan, highlighting their significance as primary sources. However, the genetic structure of these regions differs: in Sudan, the principal collection is represented by five ancestral populations, while in Ethiopia there are eleven, indicating a more complex genetic diversity of Ethiopian samples. Therewith, the genetic distance between samples (Ibrahim, 2021) from Sudan is greater than in Ethiopia, suggesting greater variability in the Sudanese collection. This contrast is explained not only by natural factors, but also by the historical migration routes of sorghum and the different approaches of local communities to its cultivation. Modern research shows that sorghum from these regions has unique characteristics, such as resistance to soil salinisation and the ability to maintain productivity with minimal irrigation, making them particularly valuable for breeding in the context of global warming.

Preservation of the genetic pool of sorghum requires comprehensive approaches and international cooperation to protect this resource (Reshetnikov *et al.*, 2023). Working with such collections involves their replenishment, maintenance, dissemination, study, and practical application. One of the challenges continues to be the standardisation of approaches to sample evaluation, as countries use different protocols and methods. Documentation has also been a long-standing problem, but major centres such as the USDA-NPGS and ICRISAT have taken steps to modernise their databases to provide access to detailed information on collections, including genome and phenotypic data. In 2007, sorghum experts developed a global strategy for the *ex situ* conservation of sorghum genetic diversity to standardise conservation efforts and facilitate the exchange of resources between countries (Enyew *et al.*, 2022). With growing populations and the increasing impact of climate change threatening food security, these collections are becoming increasingly significant for combating the biotic and abiotic stresses affecting humanity's ability to feed itself. Presently, the stewardship of these resources is more relevant than ever, providing a basis for the development of sustainable varieties in the face of global challenges. Moreover, sorghum is increasingly viewed as a dual-purpose crop: apart from food and feed, its biomass is used to produce biofuels, highlighting the need to preserve genetic diversity to support not only agriculture but also the energy sector (Havrysh *et al.*, 2022). This makes sorghum a strategic resource for sustainable development in an era of environmental and demographic change (Table 1).

***Table 1**. Major sorghum gene bank collections worldwide*

Region/Country	Institute/Organisation	Wild relatives	Cultivars	Total (% of total)
		Africa		
Ethiopia	Institute of Biodiversity Conservation (IBC)		9,772	9,772(4.1)
Kenya	National Gene Bank of Kenya, Crop Plant Genetic Resources Centre – Muguga KARI-NGBK	92	5,774	5,866(2.2)
Zambia	SADC Plant Genetic Resources Centre (SPRGB)	27	3,692	3,719(1.6)

Table 1. Continued

Region/Country	Institute/Organisation	Wild relatives	Cultivars	Total (% of total)
Americas				
USA	Plant Genetic Resources Conservation Unit (PGRCU)	199	43,511	43,710(18.5)
Brazil	Centre for Genetic Resources Preservation Embara Milo et Sorgho		10,812	10,812(4.6)
Mexico	Biotechnologia (CENARGEN) Uguala		5,500	5,500(2.3)
Asia				
India	International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	461	39,092	39,553(16,8)
India	ICAR National Bureau of Plant Genetic Resources	11	20,555	20,566
China	Institute of crop science, Chinese Academy of Agriculture Science	27	23,059	23,086
Japan	Department of Genetic Resources National Institute, ICS-CAAS	–	18,263	18,263(7.7)
Pakistan	Agrobiological Science (NIAS) Plant Genetic Resources Programme (PGRP)	–	–	–
Europe				
France	Laboratoire de Génétique et Amélioration des Céréales, (LGAC)	27	7,278	7,305(3.0)
Australia				
Australia	Australian Tropical Crops and Forages Genetic Recources Centre (ATCFA)	346	4,144	4,491(2.0)

Source: *compiled by the authors based on E. Mace et al. (2020), H. Cuevas and L. Prom (2020), K. Singh et al. (2020), A. Barron et al. (2020), M.E. Ibrahim (2021), M. Enyew et al. (2022), G.B. Mangshin et al. (2024)*

Thus, sorghum genetic resources accumulated in international collections represent a strategically significant basis for the sustainable development of the agricultural sector. Their diversity, encompassing both cultivated forms and wild relatives, offers enormous potential for the selection of varieties capable of adapting to adverse climatic conditions, drought, poor soils, and new diseases.

PROSPECTS FOR SELECTION AND AGRICULTURAL TECHNICAL SOLUTIONS. POTENTIAL FOR UTILISING FOREIGN GENETIC RESOURCES

The prospects for sorghum breeding in the Aral Sea region were based on the use of genetic resources collected in international collections and were aimed at creating varieties that are resistant to drought, heat, and other abiotic stresses (Sirany *et al.*, 2022). Foreign gene pools, specifically samples from the ICRISAT and USDA-NPGS collections, provided breeders with access to unique lines with high adaptability to extreme conditions (Pujiharti *et al.*, 2022). These collections contained both wild forms and breeding lines, providing broad potential for the development of hybrids capable of producing stable yields in arid climates (Liu, 2023). Breeding programmes introduced genomic technologies, including the use of molecular markers, which accelerated the selection process and increased the accuracy of developing stable varieties (Bvenura & Kambizi, 2022). Attention was also paid to the introduction of hybrid models involving foreign material, aimed at increasing productivity under conditions of limited water supply and high temperatures (Weldemichael *et al.,* 2024).

In parallel with breeding, agronomic approaches aimed at reducing climate risks were developed. Specifically, sowing dates were adjusted to prevent critical growth phases of sorghum from coinciding with periods of extreme heat (Dhar *et al.*, 2024). Measures were taken to improve soil water retention, deep loosening and mulching, which helped maintain productivity even with minimal irrigation (Soni *et al.*, 2023). Special attention was paid to the use of biopreparations and organic stimulants that improve plant resistance to stressful conditions (Somegowda *et al.,* 2021). At the farm level, adaptation measures were proposed, including the use of locally adapted varieties, agrochemical optimisation of nutrition, and minimum tillage technologies. These solutions helped to increase production efficiency and adapt it to the realities of climate change (Khalifa & Eltahir, 2023). The introduction of breeding and agronomic solutions together ensured the formation of a sustainable sorghum cultivation system in the Priaall, factoring in both global scientific developments and the specifics of local conditions (Yadav & Singh, 2024).

The use of such collections helped to expand the adaptive characteristics of the crop through the introduction of ecotypes that are resistant to hot temperatures, drought, and salt stress. First and foremost, attention was paid to genotypes that had been tested under arid farming conditions, which corresponded to the ecological conditions of the Aral Sea region. The potential of the foreign gene pool lay not only in its stability, but also in its high plasticity, ability to form yields under limited resources, and suitability for hybridisation with locally adapted forms (Biswas *et al.*, 2021). The introduction of breeding models was based on the integration of conventional and modern approaches, including molecular selection, marker-associated selection, and preliminary assessment of phenotypic stability. Considering the climatic characteristics of the region, there was a need to develop sorghum varieties that combine drought and heat tolerance, early maturity, and increased biomass (Dixit & Ravichandran, 2024). Such varieties had to meet the requirements of both food and technical uses. In the breeding model, special attention was paid to genotypes capable of demonstrating stable productivity under sharp temperature fluctuations and minimal water supply. The use of genomic resources obtained from international banks ensured a prominent degree of diversity of the source material, which was an essential condition for breeding success (Eduru *et al*., 2021).

Apart from breeding work, considerable attention was paid to agronomic practices aimed at optimising sorghum growing conditions (Liu *et al*., 2022). One effective technique was to adjust sowing dates according to temperature forecasts and hydrothermal conditions, which helped to avoid the flowering and grain filling phases coinciding with extreme heat. This practice helped to stabilise yields in years with unfavourable climatic conditions. Deep loosening, minimal soil cultivation and mulching were also used to improve moisture retention and reduce evaporation (Choudhary *et al*., 2025). At the farm level, it was recommended to introduce organic farming technologies and use biopreparations – microbiological growth stimulants, anti-stress complexes, and bioprotective agents. Their use ensured increased plant resistance to drought, improved nutrient uptake and increased the overall biological potential of crops. These measures not only reduced dependence on conventional agrochemicals but also formed sustainable agroecosystems capable of adapting to climate fluctuations. Thus, breeding and agronomic solutions aimed at adapting sorghum to the conditions of the Aral Sea region were based on a comprehensive approach: the use of foreign gene pools, the introduction of breeding models involving sustainable forms, the optimisation of sowing and plant nutrition technologies, and the active application of adaptive farming practices. All this formed a scientifically sound and practically applicable strategy for the sustainable cultivation of sorghum in arid regions.

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The nutritional value of sorghum and its role in functional nutrition have also been the focus of recent research, where the crop is considered not only as a source of energy but also as a component of a healthy diet (Mwamahonje *et al*., 2024). However, despite considerable attention to nutritional aspects, climate resilience is either not considered at all or only mentioned fragmentarily in these studies. This suggests the need to integrate biochemical, physiological and agronomic approaches into a single programme for sustainable crop cultivation. Active progress is also being made in the field of breeding, where marker-assisted selection methods are being used and genomic technologies are being introduced, which is helping to accelerate the creation of new varieties with target traits (Parikh *et al*., 2021). However, without considering the conditions of their subsequent cultivation, such varieties may not reach their full potential. The use of biopreparations adapted to regional conditions has contributed to increasing plant resistance to abiotic stresses, reducing dependence on chemical fertilisers and pesticides, and forming more sustainable agroecosystems. Thus, the inclusion of agrotechnical solutions in the strategy for sustainable sorghum cultivation not only enhances the effect of breeding achievements but also ensures the practical applicability of the findings obtained in real agricultural production conditions.

Against this background, the development of localised sorghum cultivation models adapted to the conditions of regions such as the Aral Sea region is becoming particularly relevant. The introduction of genetically stable varieties must be accompanied by targeted agrotechnical measures – the selection of optimum sowing dates, soil cultivation depth, nutrition and water supply schedules, the use of bioprotective agents, and adapted microbiological complexes. This approach allows for the maximum use of the potential of both conventional and innovative agricultural technologies, creating a sustainable sorghum cultivation system in conditions of increased climatic risks.

CONCLUSIONS

The study identified key areas for sustainable development of the agricultural sector in the context of growing water scarcity in the Kyzylorda region of the Republic of Kazakhstan. It was found that water stress associated with reduced water volumes in the lower reaches of the Syr Darya, degradation of irrigation infrastructure and high evaporation rates directly affect crop selection, crop structure, and agronomic practices. These conditions have predetermined the need to search for alternatives to conventionally cultivated water-intensive crops, such as rice, and confirmed the potential of sorghum as a drought-resistant crop.

The study showed that sorghum has pronounced morphological and physiological adaptations, including a dense waxy coating on the leaves, a deep root system, and the ability to retain green mass, which ensures its survival and productivity under conditions of limited water supply. It was found that drought and heat stress are particularly critical during flowering, which requires the development of varieties that are resistant to terminal drought. Analysis of the phases of sorghum organogenesis confirmed the significance of each stage of crop development and its sensitivity to external conditions, especially during the reproductive phase. From a practical standpoint, the study provided an opportunity to substantiate the need to switch to sorghum cultivation in the Aral Sea region as part of a strategic adaptation to climate change. The study confirmed that the use of modern agronomic solutions – optimisation of sowing dates, introduction of drip and subsurface irrigation systems, use of biopreparations and adapted nutrition schedules – can substantially increase the sustainability and profitability of production. Furthermore, the study highlighted the potential of using the international sorghum gene pool, including materials from gene banks in India, the United States, and African countries, which expands the possibilities for local selection and adaptation of varieties. Thus, the findings obtained not only confirmed the effectiveness of sorghum under water stress conditions but also provided a basis for the development of adaptive agricultural strategies at the regional level.

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CONFLICT OF INTEREST

None.

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Перспективи вирощування зернового сорго (*Sorghum bicolor* L. Moench) у посушливому регіоні Казахстанського Приаралля: огляд літератури

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Анотація. Метою цього дослідження було обґрунтування ефективних селекційних та агрономічних рішень для підвищення стійкості сорго до кліматичних стресів в умовах Приаралья. На основі аналізу літературних джерел дослідження показало, що сільськогосподарський сектор Кизилординської області Республіки Казахстан стикається з постійним дефіцитом води, спричиненим як природними, так і антропогенними факторами. Значне скорочення надходження води в пониззя Сирдар'ї, деградація іригаційної інфраструктури та погіршення якості води створюють умови, за яких традиційні водоємні культури, такі як рис, стають економічно та екологічно нежиттєздатними. Огляд джерел підтвердив, що поряд з технічними заходами, такими як впровадження водозберігаючих технологій, перехід до більш посухостійких культур, включаючи сорго, набуває все більшого значення. Було продемонстровано, що сорго має унікальні фізіологічні адаптації до водного та теплового стресу завдяки своїм морфологічним та анатомічним характеристикам, фазам росту та здатності утримувати зелену масу. У Приаральї ця культура вважається ключовим елементом стратегії адаптації виробництва сільськогосподарських культур до змін кліматичних умов. Крім того, сорго має широкий спектр застосування, від продуктів харчування та кормів до біоенергетики, що підкреслює його агроекономічну цінність. В огляді літератури також відзначається зростаючий інтерес до генетичного та селекційного потенціалу сорго: міжнародні банки генів зберігають понад 42,000 зразків, включаючи унікальні генотипи з Африки та Азії, що відкриває перспективи для створення стійких та високоврожайних сортів. Таким чином, результати огляду літератури підтвердили виражену адаптивність сорго до умов регіону Аральського моря, його стратегічне значення в умовах водного стресу та актуальність подальших селекційних та агрономічних розробок, спрямованих на його широке впровадження в сільське господарство регіону

Ключові слова: стресостійкість; генетичне різноманіття; біопрепарати; агротехнічні методи; ефективність використання води