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Original Article

Evaluation of the agronomic traits and correlation analysis of phenotypes of proso millet (*Panicum miliaceum* L.) germplasm in Kazakhstan

Avaliação das características agronômicas e análise de correlação de fenótipos de gemoplasma de painço (*Panicum miliaceum* L.) no Cazaquistão

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Abstract

Proso millet is a valuable short-term crop of universal use cultivated all over the world. However, due to the lack of genetic improvement, the yield of this crop does not provide stable in-come for farmers. The research is aimed to test proso millet germplasm of different geographical origin under different agro-climatic regions in Kazakhstan. 90 accessions of proso millet originated from 19 countries were tested in the conditions of the North (A.I. Baraev Scientific Production Centre of Grain Farming) and the West (Agricultural Experimental Station) Kazakhstan from 2022 to 2023. The main agronomic traits such as plant height, number of seeds per panicle, seed weight per panicle and productive tillering, 1000 seed weight and yield per m^2 were measured. Correlation analysis was conducted based on the obtained data. High correlation was established between the SWPP and NSPP traits (r=0.73-0.92) in Northern and Western Kazakhstan conditions in 2022-2023 years. The world collection with higher values of 1000 seed weight showed a lower number of seeds per panicle, while the correlation was negative (r= - 0.48). The findings can be used in future proso millet breeding programs to develop new and improved genotypes with desirable productive traits adaptable to different environments.

Keywords: proso millet, germplasm, morphological traits, correlation analysis.

Resumo

O painço é uma valiosa cultura de curto prazo de uso universal, cultivada em todo o mundo. No entanto, devido à falta de melhoramento genético, o rendimento dessa cultura não proporciona uma renda estável aos agricultores. A pesquisa tem como objetivo testar germoplasma de painço de diferentes origens geográficas em diferentes regiões agroclimáticas do Cazaquistão. Noventa acessos de painço originários de 19 países foram testados nas condições do Norte (Centro de Produção Científica de Cultivo de Grãos A.I. Baraev) e do Oeste (Estação Experimental Agrícola) do Cazaquistão de 2022 a 2023. As principais características agronômicas, como altura da planta, número de sementes por panícula, peso de sementes por panícula e perfilhamento produtivo, peso de 1.000 sementes e produtividade por metro quadrado foram medidos. A análise de correlação foi realizada com base nos dados obtidos. Foi estabelecida uma alta correlação entre as características SWPP e NSPP (r=0,73-0,92) nas condições do norte e oeste do Cazaquistão nos anos 2022-2023. A coleção mundial com maiores valores de peso de 1.000 sementes apresentou menor número de sementes por panícula, enquanto a correlação foi negativa (r= - 0,48). As descobertas podem ser usadas em futuros programas de melhoramento de painço para desenvolver genótipos novos e melhorados com características produtivas desejáveis e adaptáveis a diferentes ambientes.

Palavras-chave: painço, germoplasma, características morfológicas, análise de correlação.

1. Introduction

Proso millet (*Panicum miliaceum* L.), also called common millet or broomcorn millet, is an ancient domesticated valuable and forage crop. It is an annual herbaceous plant from the Panicum genus, and it has a chromosome number of 2n=36 with a basic chromosome number of ×=9 (De Wet, 1986). It was considered the mountainous

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regions of East Asia, China and neighbouring countries as the centre of origin and primary form of proso millet, because here were the maximum diversity varieties discovered as well as a large number of endemic original forms (Habiyaremye et al., 2017; Flajšman et al., 2019; Oñate Narciso and Nyström, 2023). From here proso millet was spread to various countries of Asia and Europe by nomads, and then brought to America (Kurtseva and Romanova, 2012; Lu et al., 2009). According to Harlan (1975) proposed that proso millet was probably domesticated in both China and Europe independently. The renewed investigations show that common millet agriculture arose in the semiarid regions of China about 10 000 years ago (Lu et al., 2009).

Proso millet is used for food in some parts of Asia and for feeding birds and animals in other countries (Rajput et al., 2014). In the Western world, *P. miliaceum* is considered a minor cereal due to its poor economic importance, and thus, it is usually used as feed or fodder for farm animals (Crawford, 2006; Lindquist et al., 2005). Nowadays, proso millet grains still represent an important cereal food and a source of proteins for millions of people living in arid and semiarid areas in emerging countries (Blümmel et al., 2003; Brunette et al., 2016).

Proso millet is a short season crop with low water requirement and high tolerance to heat, salt and drought. It is favored for extreme soil and climatic conditions as it yields reasonable harvest even in degraded soils under unfavorable weather conditions. The dry steppe zones are more suitable for proso millet growing, so in Kazakhstan it is cultivated mainly in two regions North and West Kazakhstan (Zeinullina et al., 2023). The breeding of proso millet in Russia, India and Kazakhstan is mainly aimed at high yield, large grain size, yellow seed coloring, and the breeding process is mainly based on morphological and biological traits (Kotlyar and Sidorenko, 2016; Dyusibayeva et al., 2016; Sidorenko et al., 2006). There are cereal and forage directions in proso millet breeding, as well as the creation of special-purpose varieties. Forage proso millet is a reliable, highly nutritious supplement in the diet of domestic animals, which contributes to solving a number of problems in the animal production, in particular, the use as an alternative substitute for corn in many industries (Hassan et al., 2021). Proso millet varieties for special purposes can be developed, their starch consists entirely of amylopectin only or, on the contrary, of amylose only (Zhirnova et al., 2021).

Now in the Republic of Kazakhstan proso millet is one of the main cereal crops. The germplas of millet includes samples of CIS countries, non-CIS countries, local varieties, including Wil local white - Bersiev millet. There are 21 varieties of millet for grain and 13 for fodder in the State Register of Breeding Achievements of the Ministry of Agriculture of the Republic of Kazakhstan. The collection of plants all over the world is considered as the main source of improvement of agricultural crops in the coming decades. Selection of samples with economically valuable features for breeding in most cases is based on world collections of cultivated plants (Zargar et al., 2023).

Germplasms are mainly studied in terms of the yield related traits, because this is the basis of any crop study. Comprehensive evaluation of germplasm based on the main agronomic traits and correlations between these traits are not only conducive to conservation and further research of high-quality germplasm but are also important for its genetic improvement (Zhang et al., 2019). Correlation studies of economically valuable traits provide an opportunity to precisely study the relationships between the yield and its individual elements. Detailed information on the actual contribution of each yield component will allow to select more appropriate breeding methods to improve crop yield (Salini et al., 2010).

The objective of this study was: 1) to conduct an overall agronomic characterization of proso millet germplasm during a two years field experiment (2022-2023) for identification of the most important germplasm; 2) to analyze correlations of the average phenotypic values in the two regions for precise study of the relationship between the yield and its individual elements. The genetic resources used to estimate the agronomic trait values had different ecological and geographical origins.

2. Materials and Methods

2.1. Experiment materials

A total of 90 proso millet collections were used as materials, originating from 19 countries (Supplementary Material): Afghanistan (n = 5), Australia (n = 2), Belarus (n = 2), Canada (n = 1), China (n = 3), France (n = 1), Hungary (n = 2), Argentina (n = 1), India (n = 5), Iran (n = 2), Kazakhstan (n = 22), Kyrgyzstan (n = 1), Pakistan (n = 1), Russian Federation (n = 20), Tajikistan (n = 3), Turkey (n = 12), Ukraine (n = 5), USA (n = 1), Uzbekistan (n = 1) (Figure 1).

2.2. Field experiment details

In the present investigation the field evaluation and the characterization of the collection was conducted for two consecutive years in the 2022 and 2023 growing seasons. For evaluation of agronomic traits of collection, the dry steppe zones of North and West Kazakhstan were selected. The field experiments were carried out from May to September in the collection nursery of the A.I. Baraev Scientific Production Center of Grain Farming (SPCGF) (Shortandy village-1, Shortandy district, Akmola region) of the Akmola region and in the Agricultural Experimental Station (AAES) of the Aktobe region, in the dry steppe zone of Kazakhstan. The experiment was performed according to the All-Russian Institute of Plant Growing guidelines and the Field Experiment Methodology (Agafonov and Kurtsev, 2011). Plants were seeded on dark chestnut soils in 1 m^2 area with a plant-to-plant spacing of 10 cm, the plot arrangement was systematic. For two years, the experimental layout was a randomized complete block design with two replications for each sample. The meteorological data for the growing experimental period 2022-2023 was gathered at the local weather station (Table 1).

The meteorological conditions during the study period were characterized by quite uniform temperature regime, so the average daily air temperature for May-August 2022 period was 17.5 °C, in 2023 - only a small difference -18.1 °C. Akmola region of the North Kazakhstan region is located in

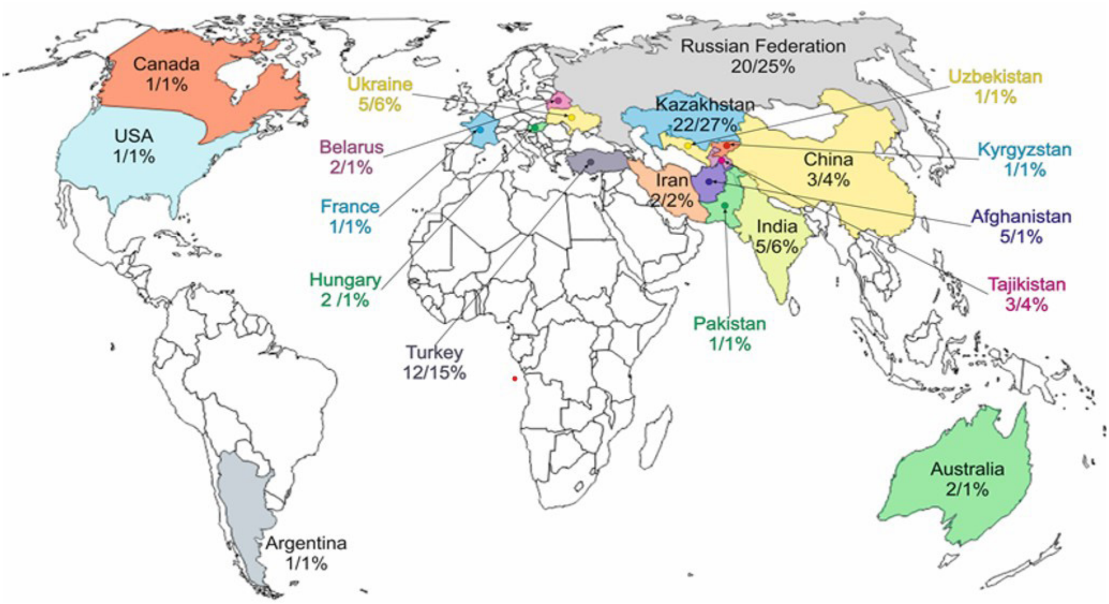

Figure 1. Geographical origin of proso millet germplasm.

Table 1. Location, environment, and weather data during agronomic seasons for the two study regions in Kazakhstan.

Site/Region	SPCGF (Akmola Region)		AAES (Aktobe Region)	
Latitude/Longitude	51.41'/70.59'		50.27'/57.20'	
Soil type	dark chestnut (3.6-4.1% humus)		black soil and dark chestnut (2.74% humus)	
Conditions	Rainfed		Rainfed	
Year	2022	2023	2022	2023
Annual rainfall, mm	125.2	72.2	155.9	167.9
Mean temperature, °C	17.5	18.1	34.7	19.9
Max temperature, °C	21.1	24.4	37.9	24.4
Min temperature, °C	13.2	11.8	30.0	14.6

the zone of insufficient moisture, the precipitations vastly vary both from year to year and throughout the year. Over the entire study period (2022–2023), the annual amount of precipitation in summer ranged from 72.2 mm in 2023 to 125.2 mm in 2022. Dry weather in May led to insufficient soil moisture, which contributed to the slowdown in the emergence of proso millet. In 2022 and 2023, this indicator was at the level of long-term averages.

In the Aktobe region, the Western region of the country, slight temperature fluctuations were observed over the years. The average monthly value for 2022 was 34.7 °C, and for 2023 – 19.9 °C, respectively. However, in terms of total precipitation in 2023, during the five months of the millet growing season, 167.9 mm fell, which was almost the same as in 2022 and amounted to only 155.9 mm.

2.3. Data collection

Twenty-five plants from each genotype were randomly selected to measure plant height (PH), number of seeds per panicle (NSPP), seed weight per panicle (SWPP, g) and productive tillering (PT) at maturity stage. After harvesting, 1000-seed weight (TSW) and yield per m^2 (Y) was measured. The mean value of the 25 plants were obtained. In order to provide a complete and precise assessment of growth and development features of proso millet cultivars, two groups of traits were analyzed: traits related to plant adaptation and productivity component traits. The plant adaptation traits included sprouting-budding period from emergence to tiller development (ETD, days), tube emergence from fifth leaf emergence to the panicle initiation (FLPI, days), flowering-maturity period (FMD, days), sowing-maturity vegetation period (SMD, days), vegetation period (VP, days), plant height (PH, cm). To characterize the yield components, 25 promising plants from each sample were selected from the experimental plot considering such traits as number of seeds per panicle (NSPP, pcs), seed weight per panicle (SWPP, g), productive tillering (PT, pcs/1 plant), (NPS, pcs), 1000 seed weight (TSW, g) and yield per square meter (Y, g/m^2) (Kotlyar and Sidorenko, 2016).

2.4. Statistical analysis

Excel 2007 was used to analyse the obtained data. For primary data analysing correlation coefficients were calculated using R Studio (IDE) for Windows (R version 3.6.0, 2019) software. For the data obtained from the experiment, the following parameters were calculated: mean, minimum, maximum value, range and standard deviation. The mean values of 90 genotypes for six quantitative traits were analyzed with correlation coefficient, multivariate hierarchical clustering and principal component analysis (PCA).

3. Results

3.1. Assessment of morphological and agronomic traits

The germplasm was tested across growing seasons 2022 and 2023 in the region of the North (A.I. Baraev Scientific Production Centre of Grain Farming) and the West (Aktobe Agricultural Experimental Station) Kazakhstan. During the 2022-2023 growing seasons, the field productivity of 90 proso millet varieties in two different regions of Kazakhstan (SPCGF and AAES) was analyzed by phenotypic trait screening. Phenotypic variability between the two regions including the least important seven traits was recorded in the study of proso millet world collection, which consisted of 61 foreign proso millet varieties and 29 local proso millet varieties. These records revealed that in 2022 the mean PH value ranged from 55.9-89.9 cm in soil and climatic conditions of SPCGF and this value was 55.3-97 cm in AAES. In 2023, there was a significant genotype-related variation from 63.1 to 95.6 in SPCGF and from 67.4 to 99.2 in AAES, but in both regions the height of proso millet plants did not show variability and amounted to 63.1-95.6; 67.4-99.2, respectively (Table 2).

The following traits had the most significant correlation between the plants and the growing conditions: number and weight of grains from the main panicle. Thus, the field observations showed that the fluctuation in 2022 in SPCGF conditions was 467 pcs, and the one in the western region was 302 ± 12.1 pcs. Productive tillering under SPCGF conditions showed no year-to-year variation and averaged 1.0-1.5 pcs/1 plant, in contrast, there was significant variation for this trait under AAES conditions: from 1.1 to 3.8 pcs/1 plant in 2022 and from 0.8 to 3.8 pcs/1 plant in 2022.

Experimental data obtained in the course of our research show that the plants cultivated in different regions of Kazakhstan in contrasting soil and climatic conditions do not differ in the such yield properties as seed weight per panicle and 1000 seed weight. Thus, the average indicators affecting the productivity of proso millet in SPCGF conditions in 2022 included the following traits: seed weight per panicle - 2.7 g; 1000 seed weight - 6.1 g; in AAES conditions - 1.9 g; 5.8 g, respectively. In 2023, the panicle seed weight was 2.6 g, 1000 seed weight was 5.7 in SPCGF; 2.5 g and 6.4 g in AAES, respectively.

Although there was a significant difference in the number of main panicle seeds by region (460 seeds in SPCGF and 706 seeds in AAES), the variation by year showed almost similar results: SPCGF 2022 - 86-1348 seeds, AAES 2022 - 56-1348 seeds; SPCGF 2023 - 216-1020, AAES 2023 - 60-1020 seeds.

Evaluation of the mean value of grain yield (Y) of proso millet varieties revealed that over these two years the

Table 2. Mean and range of the main agronomic traits based on the data of the three-year field experiment.

Agronomic traits	Measure	Regions	2022		2023	
			Mean ± SD	Range	Mean ± SD	Range
PH	cm	SPCGF	73.4 ± 4.2	55.9-89.9	78.6 ± 1.9	63.1-95.6
		AAES	73.3 ± 2.9	55.3-97.0	82.1 ± 2.1	67.4-99.2
PT	pcs/1 plant	SPCGF	1.17 ± 0.05	1.0-1.5	1.22 ± 0.01	1.0-1.5
		AAES	1.40 ± 0.07	1.1-3.8	1.15 ± 0.01	0.8-3.8
NSPP	pcs	SPCGF	467 ± 19.5	186-1348	460 ± 10.9	216-1020
		AAES	302 ± 12.1	56-1348	706 ± 16.6	60-1020
SWPP	g	SPCGF	2.70 ± 0.9	1.2-8.4	2.6 ± 0.09	1.4-6.9
		AAES	1.90 ± 0.01	0.35-6.05	2.55 ± 0.08	0.28-6.0
Y	g/m^2	SPCGF	430 ± 18.3	189-986	469 ± 14.6	225-1248
		AAES	211 ± 8.5	49-455	260.2 ± 0.7	49.0-668.0
TSW	g	SPCGF	6.1 ± 0.1	4.1-8.2	5.7 ± 0.09	4.0-7.2
		AAES	5.8 ± 0.12	2.7-7.6	6.45 ± 0.18	1.9-8.6
VP	days	SPCGF	93.9 ± 2.1	82-106	90.4 ± 2.1	80-101
		AAES	75.8 ± 2.3	67-108	76.6 ± 1.7	68-98

Note: PH = plant height, cm; PT = productive tillering, pcs/1 plant; NSPP = number of seeds per panicle, pcs; SWPP = seed weight per panicle, g; Y = yield per square meter, g/m^2; TSW = 1000 seed weight, g; VP = vegetation period, days.

yield of the northern region showed almost twice higher than one of the western region of the country. For the two regions, the difference in productivity was 219 g/m^2 for the year 2022 and 209 g/m^2 for the year 2023. As a result of the study of seed productivity of proso millet plants per square meter the most productive genotypes were identified, such as: Saratovskoe 3 (608.5 g/m^2), PI 209790 (635.3 g/m^2), K - 2241 (636.0 g/m^2), Shortandinskoe 7 (713 g/m^2), PI 177481(720.3 g/m^2), PI 211058 (738.5 g/m^2), K-2468 (1206.2 g/m^2), they managed to give a stable yield regardless of climatic conditions in different years of research.

The study of the length of the vegetation period (VP) in proso millet plants showed that according to the growing season can be divided into three groups: fast-ripening (67-70 days); moderate-ripening (71-99 days); late-ripening forms (100 days and more). In 2022 in Akmola region the VP of local varieties presented by 15 genotypes was shorter than the VP of the local standard variety Saratovskoye 6, this represents 17% of the entire collection. However, in 2023, the VP of 3 varieties only was shorter than the standard, which is 3.3%. The foreign collection was evaluated regardless of the year of research, and no genotypes with shorter VP than the local standard were identified. In Aktobe region in both 2022 and 2023, 18 varieties of domestic showed shorter VP than the local standard Pamyati Bersieva. Studies conducted in this region showed that in 2022 34 genotypes among the foreign collection were distinguished by short vegetation compared to the local standard, which amounted to 38% of the entire collection. A similar situation occurred in 2023, 27 genotypes of the foreign collection were shorter than the local standard Pamyati Bersieva.

According to the results of phenological studies in SPCGF conditions in 2021 the average VP was 93.9 ± 2.1 days, and in 2023 it was shorter by 3.5 days and amounted to 90.4 ± 2.1. In the AAES region in 2022 the vegetation period was significantly shorter, almost by 18.1 days and amounted to 75.8 ± 2.3 days. In this region in 2023, no significant change in VP length was observed, it amounted to 76.6 ± 1.7 days, it was shorter by 13.8 days than the results obtained under SPCGF conditions the same year.

3.2. Analysis of correlations between morphological quantitative traits

Correlation analysis related to climatic conditions of proso millet germplasm are limited investigated compared to the major crops. In our research, correlation coefficients between the main economically valuable traits of proso millet varieties were studied. Thus, under SPCGF conditions, the data obtained in 2022 indicate that the yield of local proso millet genotypes Y is not related to productive tillering PT (r=-0.52) (Figure 2).

Negative correlation was also observed between the number of seeds per panicle and the 1000 seed weight (r= - 0.38). It is revealed that among samples of foreign

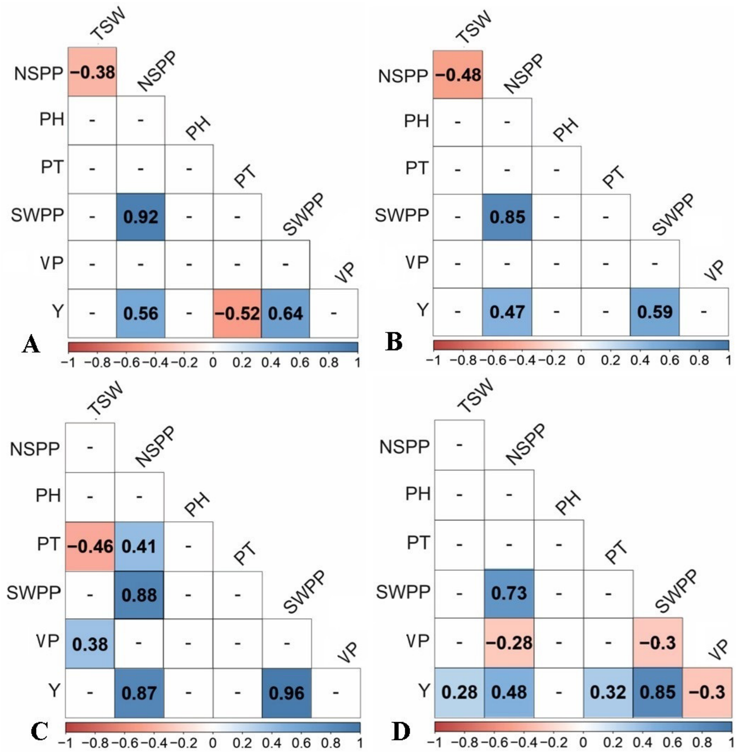

Figure 2. Correlation coefficients (r) among the agronomic traits in the conditions of SPCGF in Akmola region: (A) Local collection in 2022; (B) World collection in 2022; (C) Local collection in 2023; (D) World collection in 2023. Note: Correlations with $p < 0.05$ are highlighted in colour. The colour indicates either positive (blue) or negative (red) correlation.

collection plants with higher values of 1000 seed weight TSW had lower number of seeds in panicle NSPP (r= - 0.48). In 2023, under the conditions of SPCGF region, no close relationship was observed between PT and TSW (r=-0.46) among local genotypes, and between VP and NSPP, SWPP (r=-0.28, - 0.3) between Y and VP (r=- 0.3) among foreign samples. During the two-year studies of SWPP and NSPP (r=0.73-0.92), VP and TSW (r=0.38), PT and NSPP (r=0.41) showed high trait dependence among domestic varieties in 2022. We observed an increase in Y yield with increasing NSPP (r=0.47-0.87), SWPP (r=0.59-0.96). In 2022 TSW (r=0.28) and PT (r=0.32) also affected the productivity of foreign collection.

Under AAES conditions, negative correlation coefficients between the main valuable traits of proso millet genotypes were observed between NSPP and TSW (r=- 0.38) in 2022, and between VP and TSW (r=-0.35) in 2023. In this region, a positive relationship was established between traits SWPP and NSPP (r=0.48-0.84), SWPP and TSW (r= 0.42-0.45). Mean phenotypic values of productivity components showed that Y is positively correlated with TSW (r=0.28-0.50), NSPP (r=0.38-0.59) and SWPP (r=0.40-0.66) in this region (Figure 3).

In general, grain yields depend on a number of factors, including the ability of plants to synthesize and distribute assimilates, form elements of yield structure, and the timing of development and maturation phases. A number of traits, including the number of grains in the panicle or ear, yield potential, flowering and grain filling dates, are considered as a complex indicator explaining 76% of variation in grain yield (r = 0.70, p = 0.86), which can be used in breeding programs for grain crops with high productivity under drought.

During the research of the relationship between interphase periods and traits in 2022 under SPCGF conditions, only positive correlations were found between the following traits: ORI - FLR (r=0.37), SOR - ETS (r=0.38), SOR - FLR (r= 0.87), SOR - ORI (r= 0.34), SOR - SHT (r=0.23). However, under AAES conditions in the same year, negative relationship was observed between SOR - SHT traits (r= - 0.23), moreover, SHT - ETS, SHT - FLR traits were also negatively correlated and their coefficients were r=-0.43, 0.89, respectively (Figure 4).

In 2023, the studied traits showed significant close relationship in both regions: SOR - FLR (r= 0.84), SOR - ORI (r= 0.28). The traits FLR - ETS (r= - 0.41) and SHT - FLR (r= - 0.24) showed insignificant negative correlation in this year. According to the results of PCA analysis of the main quantitative traits (NSPP, SWPP, Y, PT), it was shown that the coordinates of basis vectors were distributed into four main groups (Figure 5).

In the dendrogram based on the results of phenotypic traits clustering, three main groups were determined, and then were divided into subclusters (Figure 6). The first group was the most numerous with 58 varieties, then followed by the second group, which included 32 genotypes. In clusters I

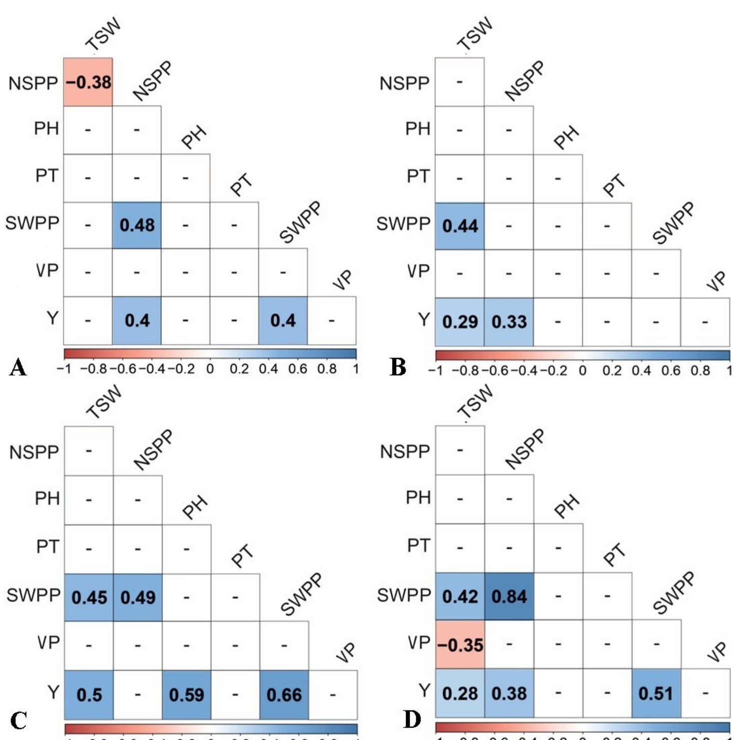

Figure 3. Correlation coefficients (r) among the agronomic traits in the conditions of AAES in Aktobe region: (A) Local collection in 2022; (B) World collection in 2022; (C) Local collection in 2023; (D) World collection in 2023. Note: Correlations with $p < 0.05$ are highlighted in colour. The colour indicates either positive (blue) or negative (red) correlation.

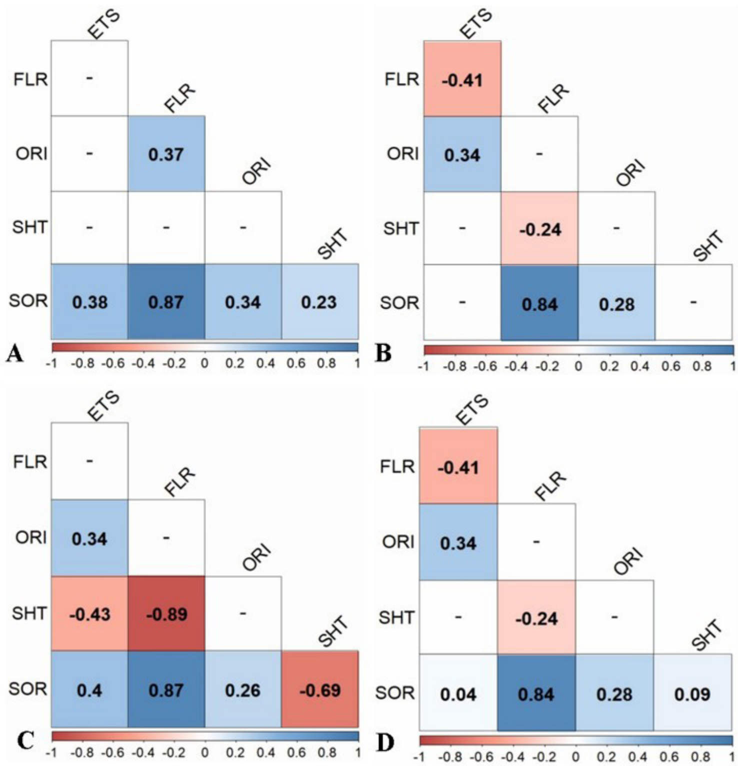

Figure 4. Correlation coefficients (r) among the growth stages: in Akmola region during 2022 (A) and 2023 (B); in the conditions of AAES in Aktobe region SPCGF 2022 (C) and 2023 (D). Note: ORI = origin; SHT = shoots-tillering; ETS = exit to the tube - sweeping (g), FLR = flowering-ripening, SOR = sowing - ripening. in the conditions of SPCGF. Correlations with $p < 0.05$ are highlighted in colour. The colour indicates either positive (blue) or negative (red) correlation.

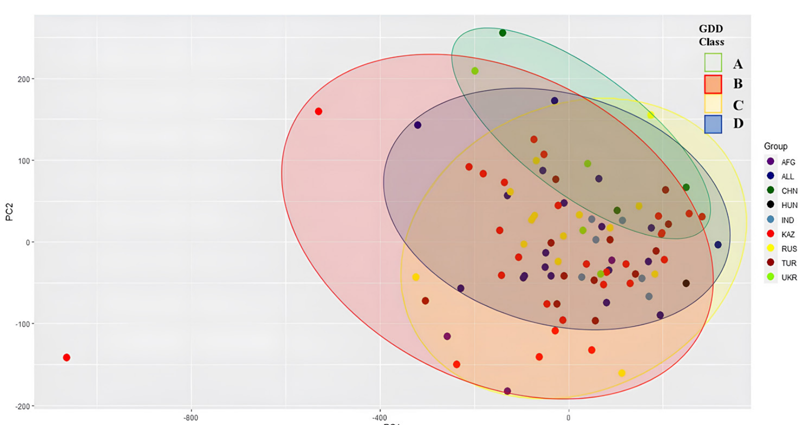

Figure 5. Principal component analysis of the proso millet germplasm based on the main agronomic traits: (A) UKR; (B) KZ; (C) RU; (D) USDA collection.

and II, 10 and 8 varieties were grouped together, respectively. Clusters IV, VI, III and VIII each contained two very similar genotypes. Cluster XI consisted of 6 genotypes, cluster XII had 9, cluster XIV had 10, and the remaining clusters (V, VII, IX, X, and XIII) were found with sole varieties. In the second group, clustering allowed to divide the studied objects into 5 subclusters: XV - 10, XVII - 6, XVI and XVIII - 5, XX - 4 and with clusters XIX and XXI with sole varieties.

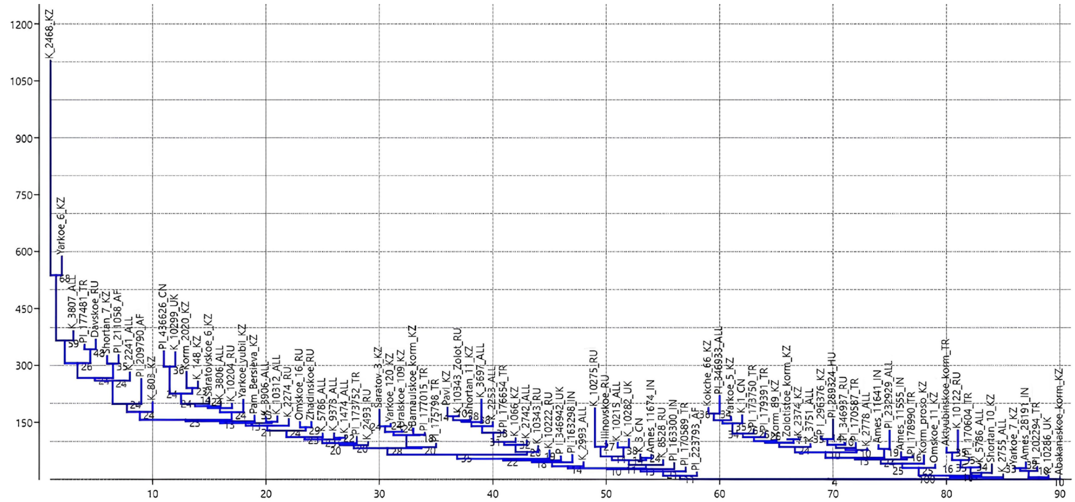

Figure 6. Clustering pattern of 90 proso millet accessions obtained through cluster analysis.

4. Discussion

This research presents the results of evaluation of valuable traits of 90 proso millet varieties of different origins, which were planted in the conditions of the Northern (SPCGF) and the Western region (AAES) of Kazakhstan during two consecutive years (2022 and 2023). Characterization of agronomic traits of the gene pool is considered an important stage in plant breeding. Selection of genotypes adaptable to different habitats and possessing desirable productive characteristics is important for future breeding pro-grams to create new high-yielding varieties (Sood et al., 2015).

In general, field trials under AAES 2023 conditions showed better values of agronomic indicators compared to 2022, particularly for the traits NSPP and SWPP. This can be related to the drought stress that occurred at the seedling emergence and tillering stage, which negatively affected seed formation in the first experimental year of 2022. The obtained experimental data was comparable with the results of other studies on proso millet gene pool evaluation (Calamai et al., 2020).

Based on the results of two-year studies, productive variability in *P. miliaceum* cultivars took into account the plant height trait as one of the most important properties characterizing the biological features of the crop variety. For example, the recorded ranges of plant height under SPCGF conditions were found to be between 55.9 and 89.9 cm in 2022; between 63.1 and 95.6 cm in 2023; under AAES conditions, the short plant height of proso millet plants was also pointed out: 55.3 to 97.0 cm and 67.4 to 99.2 cm, respectively. Similar data were also obtained for other millet crops, such as pearl millet (62-160 cm) and barnyard millet (79-156 cm), except kodo millet (34-101 cm) (Salini et al., 2010; Dhanalakshmi et al., 2019; Anuradha et al., 2018).

In general, the world cultivation of proso millet, including the Republic of Kazakh-stan, has declined over the last decade, especially due to its low grain yield (average world yield of 890 kg/ha) compared to the main agricultural cereal crops (Sage and Zhu, 2011). Although grain yield depends not only on genotype, but also on abiotic factors such as rainfall, temperature and applied agricultural technologies (Saleh et al., 2013), the results of the two-year field study showed that the selected high-yielding genotypes could achieve up to 1248 kg/ha grain yield. This corresponds to the previous studies reporting that utilization of a promising genotype results in higher average grain yield (Calamai et al., 2020). In order to get high yield, the crop should include good development of all plants, including the density of productive plant stand which must be optimal for the given environmental conditions and variety. It is proved that the indicator of the density of the productive stand has up to 50% influence on the yield, 25% on the number of grains in the spike, 25% on the 1000 seed weight (Panwar and Kapila, 1992).

Changes in weather conditions during plant development, observed in recent decades due to global climatic transformations, require the development of new varieties adapted to these abiotic factors. For this reason, it is important to determine how they affect the 1000 seed weight and which growth phases are the most significantly affected. Crop yields are known to be affected by several important factors: temperature, precipitation and moisture. Lack or excess of moisture, heat or frost in certain phases of development can differently affect important valuable traits - 1000 seed weight, grain size, natural weight, plant height, disease incidence, yield, protein content and many other parameters. When selecting varieties for specific climatic conditions, it is necessary to take into ac-count their ecological needs. The expression of valuable agronomic traits depends on the weather situation in the phenophase of plant development. It is considered that the hydrothermal factor in May and June, as well as the prevailing temperature regime at the initial and final stages of organogenesis are particularly important. According to some studies cereals are significantly affected by air temperature during the first periods of growth. Hot, dry weather negatively affects both the forming of reproductive organs and the grain filling at the end of vegetation. Studying the impact of climate characteristics on plants at certain stages of development will make it possible to create varieties that are maximally adapted to local conditions. Ultimately, this will help to increase yield and stability in grain production.

Grain yield is a complex trait and its expression depends on the interaction of a number of productivity components. Determining the relationship between grain yield and other traits helps to improve breeding efficiency. The correlation coefficient measures the relationships between different traits and exactly determines the component that will improve genetic yield. At the genetic level, positive correlation occurs because of the link-age phase. All the six traits studied except vegetation season showed significant positive correlation with grain yield per square meter. Similar results were obtained by Panwar and Kapila (1992) and Chidambaram and Palanisamy (1995). Significant positive correlation implies high dependence between productivity elements and increase in one trait also leads to increase in the other. The highest significant positive correlation was observed between seed productivity and seed weight per panicle (0.98) followed by seed weight per panicle and number of seeds per panicle (0.92) under SPCGF conditions. When studying the relationship between quantitative traits (NSPP, SWPP, Y, PT) and the origin of genotypes with the use of PCA analysis, it can be shown that the distribution of basis vectors coordinates of Kazakh proso millet collection and Russian coincides. This can be explained by the fact that earlier the crop breeding was carried out within the USSR and they may belong to the same ecological-geographical type by origin; also, it should be taken into consideration that some soil-climatic zones of growth of Kazakhstan and Russia have similar conditions. The conditions of the vegetation season are important factors influencing the formation of crop yields, and different varieties may re-act differently to external influences. All these aspects should be taken into account when determining the main productivity indicators. Proso millet has a relatively short ripening period (3-4 months), which makes it an optimal crop both for northern regions and for sustainable rainfed agriculture (Saleh et al., 2013).

Testing of the *P. miliaceum* gene pool under SPCGF conditions during our study did not include a wide range of varieties with different classes of precocity as previously has been performed by Vetriventhan and Upadhyaya (2018), Sanon et al. (2014) and by other researchers based on local proso millet varieties grown in India, Africa, and also by Salini et al. (2010) based on numerous proso millet accessions.

Based on the results of our data analysis, we managed to distinguish three classes of precocity based on the number of days to ripeness. According to several authors, late ripening proso millet genotypes resulted in higher yields compared to early and medium ripening ones due to the longer growing cycle, leading to increased grain yield and bio-mass accumulation (Sood et al., 2015; Salini et al., 2010; Dhanalakshmi et al., 2019). On the contrary, Eric et al. (2016) reported the lowest grain yield of late ripening accessions because the plants flowered under moisture-limited conditions with less rainfall comparing to early season. These results suggest that crop breeding programs should attempt to develop new and improved varieties of different precocity classes suitable for different environmental conditions. Moreover, our data do not show any evidence of an effect of vegetation season length on yield traits except TSW under SPCGF conditions in 2023. At the same time, estimates of the heritability of individual traits suggest that the studied proso millet collection may be suitable for effective selection (Arunachalam et al., 2012). Thus, in fact, according to a number of authors, plant height, productive tillering, seed yield, 1000 seed weight, and vegetation season length in proso millet pre-sent a high genetic component and demonstrate valuable traits to be selected in breeding programs (Vetriventhan and Upadhyaya, 2019; Sood et al., 2015). On the contrary, selection for traits with moderate heritability such as grain yield and total dry biomass would be difficult to realize. This could be achieved by indirect selection using traits of high heritability characterized by high positive correlation with the traits to be improved (Salini et al., 2010; Dhanalakshmi et al., 2019).

5. Conclusions

Based on the results of the analysis of the relationship between the valuable traits of different varieties and samples of millet, the main criteria for selecting valuable forms in different climatic conditions of growth were determined. The correlation analyses, the role of individual agronomic traits and their contribution to the yield of proso millet genotypes was noted. According to the assessment of the average grain yield, the following genotypes were identified as promising: varieties Saratovskoe 3, Shortandinskoe 7; samples PI 177481, PI 209790, PI 211058, K-2241, K-2468, they demon-strated stable yield regardless of climatic conditions over the years of research. A tendency towards the formation of high yield was established in the relationship between the SWPP and NSPP traits with r=0.73-0.92; also, in 2023, the productivity of the world proso millet collection was affected by the 1000 seed weight (r=0.28) and productive tillering (r=0.32). These two identified agronomic traits (SWPP and NSPP) contribute to the development of new and improved genotypes adaptable to the conditions of Kazakhstan in the future breeding programs. Obtained results can be useful for the increase of yield productivity in proso millet depending on different climatic conditions and improve the efficiency breeding processes in the future.

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Supplementary Material

Supplementary material accompanies this paper.

Supplementary Table 1. A list of proso millet accessions origin information.

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