CROP BREEDING AND APPLIED BIOTECHNOLOGY

ARTICLE

The potential of the VIR grain amaranth collection for cultivation in the northern regions

Diana Sokolova[1*]

Crop Breeding and Applied Biotechnology
25(2): e52252527, 2025
Brazilian Society of Plant Breeding.
Printed in Brazil
http://dx.doi.org/10.1590/1984-70332025v25n2a07

Abstract: *Amaranth is a promising agricultural crop with a huge potential for growth intensity, yield, and high content of complete protein in grain and leaf biomass. This potential is based on this plant's nutritional and biochemical properties, primarily the high quality of the protein and its balanced amino acid composition, as well as the content of squalene. The collection of amaranth germplasm maintained at VIR is unique in its origin and diversity. The paper presents the morphological characteristics of early-ripening genotypes of grain amaranth forms and notes the key phases of ontogenesis and features of growth and development under the conditions of the North-Western region of Russia. This study demonstrates the good adaptability of the crop and the potential for expansion to more northern areas. The identified features and noted genotypes of the collection are essential for developing breeding programs to create early-ripening varieties.*

Keywords: Amaranthus *L, diversity, early ripening, phases of ontogenesis, seed productivity*

INTRODUCTION

Amaranth (*Amaranthus* L.) is a valuable and promising food crop with multiple uses distributed worldwide in temperate, subtropical and tropical zones. This ancient crop belongs to the Amaranthaceae family. The main uses of cultivated amaranth species are food (vegetable and grain products) and fodder. In addition, there are other uses: ornamental, pharmaceutical, and for the production of building materials (Evon et al. 2021). The leaves of young plants of all cultivated species can be consumed fresh as salad ingredients. Recently, the crop has been rapidly gaining popularity worldwide due to its high-quality protein composition **(**Shukla **et al. 2010, Sanz-Penella et al. 2012).** Amaranth is a record breaker in complete protein content with an optimal ratio of amino acids and a significant content of sulfur-containing amino acids and lysine **(**Tang and Tsao 2017). A full set of essential amino acids in amaranth leaves determines their high nutritional and pharmacological value **(**Sokolova **et al. 2021).** Its high nutritional value is also based on the content of basic trace elements, such as essential microelements, β-carotene, iron, calcium, vitamin C, folic acid etc (Priya **et al. 2007,** Gins **et al.** 2017). The amount of lipids in amaranth seeds varies between 1.9 and 9.7%. Palmitic, oleic, linoleic and linolenic fatty acids predominate, together accounting for more than 90% of the total fatty acid content. The fatty acid composition of amaranth oil is almost similar to that of cereals, but the main difference is the content of a relatively high level of the polyunsaturated hydrocarbon squalene ($C_{30}H_{50}$) (Bressani 1994). The

***Corresponding author:**
E-mail: dianasokol@bk.ru
ORCID: 0000-0002-9967-74543

Received: 19 February 2025
Accepted: 19 March 2025
Published: 12 April 2025

[1] N. I. Vavilov All-Russian Institute of Plant Genetic Resources (VIR), 42-44 Bolshaya Morskaya Street, 190000 St. Petersburg, Russian Federation

ever-increasing interest in this compound is explained by its combined therapeutic effect: antioxidant, hypolipidemic, antitoxic, and antidiabetic (Rao et al. 1998, Smith 2000). Squalene has a wide range of applications in medicine – as an adjuvant in vaccines, or an immunomodulator and antioxidant in complex therapy against a number of diseases, such as diabetes and coronary heart disease (Gonor et al. 2006, Huang et al. 2009).

Amaranth is distinguished for its rich genetic diversity, phenotypic plasticity, high adaptability to unfavorable growing conditions, and tolerance to high temperatures and droughts (Barrio and Anon 2010, Rastogi and Shukla 2013). It belongs to a small group of "pseudocereal" plants, such as buckwheat and quinoa (Saunders and Becker 1984, Teutonico and Knorr 1985). Cereal amaranth species include *A. cruentus* L. and *A. hypochondriacus* L. from Central and North Americas, and *A. caudatus* L. of South American origin (Covas 1993). The history of amaranth cultivation in these regions dates back 5,000 to 7,000 years (Arreguez **et al.** 2013). The Aztec and Mayan tribes used it from ancient times as a grain crop and in rituals (Montellano 1990, Smith 1996). Sufficient genetic diversity among the breeding material of any agricultural crop is a prerequisite for creating high-yielding varieties and hybrids. The first step is to screen the germplasm to identify the best genotypes with the desired traits to achieve this. Analysis of diversity and identification of key characteristics associated with yield is crucial for breeding. In this regard, a comprehensive study of amaranth, promotion of its improvement through breeding, and development of new cultivars will contribute significantly to raising the quality of human nutrition by employing plant materials enriched with useful and highly nutritious components.

Intensive cultivation technologies make it possible to achieve higher amaranth yields. Thus, in the experiments conducted in 1977-1989 in Minnesota, USA, the highest grain yield of promising cultivars reached 1.72 t ha^{-1} (Myers and Putnam 1988). However, today, modern varieties reach yields of 2.2-2.4 t ha^{-1} (State Register for Selection Achievements Admitted for Usage of the Russian Federation 2024).

A unique amaranth collection, stored at the N.I. Vavilov All-Russian Institute of Plant Genetic Resources (VIR), currently includes 570 accessions from 62 countries. Broad genetic diversity of amaranth is interesting for research. The first accession, 'Sirukeerai' (*Amaranthus* sp., k-1), arrived from Bangalore Nursery and Gardens, India, in 1955 (Sokolova et al. 2024). The collection expanded with local cultivars and wild species in the following years through numerous missions and shipments from research centers, gene banks, botanical gardens, and breeding stations worldwide. The largest numbers of accessions came from Mexico, USA, Germany, and India. 80% of the collection is represented by *A. cruentus*, *A. hypochondriacus*, *A. caudatus*, *Amaranthus* sp., *A. hybridus* and *A. tricolor* species.

The Northwest region of the Russian Federation (RF) is a poorly studied area for amaranth cultivation. However, it is around the city of St. Petersburg (population over 6 million people) that interested large processing and pharmaceutical enterprises are concentrated, creating products to provide for the local population of the North-West region of the RF. The limiting environmental factors in this region are the short growing season, prolonged spring and recurring frosts. Therefore, the most valuable traits for amaranth breeding in this growing zone are early maturity and cold resistance. It is known that the optimal temperature for amaranth seed germination is 20-25 °C (Das 2016). Therefore, amaranth can be grown mainly in the southern regions. Screening the germplasm collection to identify early maturing and cold-resistant genotypes is necessary to develop breeding programs. An example confirming the possibility of growing grain amaranth in the northern regions is the early-ripening and cold-resistant variety 'Frant' (*A. cruentus*), created at VIR (State Commission of the Russian Federation 2022). This study aimed to screen the genetic diversity of grain amaranth from the VIR collection for early maturity and yield characteristics by conducting a comprehensive field study under the conditions of the Northwest region of RF.

MATERIAL AND METHODS

Planting material and experimental conditions

One hundred eighty-seven grain amaranth accessions from VIR collection served as the material for this research. A comprehensive study was carried out under field conditions in 2024. Accessions of the species *A. hypochondriacus* L., *A. cruentus* L., *Amaranthus* sp. and *A. hybridus* L. were selected for the experiment. The experiment included accessions from 25 countries of origin. The largest numbers were from the center of origin of grain amaranth: Mexico (88) and the USA (25).

Experimental design

The accessions were grown in the experimental fields of Pushkin and Pavlovsk Laboratories of VIR (lat 59° 7111275' N, long 30° 43032647' E; Pushkin, St. Petersburg, RF) in 2024. The soils on the experimental field are predominantly soddy-podzolic and sandy loam. A randomized block planting pattern was used. The plantings were arranged in 15-meter rows using a 70 × 25 cm scheme (60 plants per block). Seeds were sown manually on June 1 into open ground to a depth of 1-1.5 cm. Fertilizers or plant protection products against pests or diseases were not applied during the growing season. Harvesting date: as the seeds ripen, until September 17 inclusive. The onset of the following stages of ontogenesis was recorded: "shoots", "appearance of the first true leaf", "beginning of budding", "start of inflorescence growth", "start of flowering", "mass flowering", "beginning of seed ripening" and "physiological seed maturity". Phenotyping was carried out based on the methodology for testing the distinctiveness, homogeneity, and stability of the State Commission of RF's amaranth and protecting breeding achievements (State Commission of the Russian Federation 2007).

Weather conditions

Weather conditions during the growing season were generally favorable for the growth and development of amaranth. The air temperature of each month exceeded the long-term average. The sum of active temperatures (> 10 °C) by the end of the growing season exceeded the average climatic norm by 25%. Precipitation in June was close to the long-term average. In August, there was heavy one-day rains, when 20.7-23.2 mm of precipitation fell per day (03.08, 17.08 and 23.08).

Statistical analysis

Statistical data processing was performed using MS Excel 2007, Statistica 10.0 software, and in the R software version R-4.2.1 (www.r-project.org, metan packages). Descriptive statistics (mean, standard error of the mean, coefficient of variation) were calculated for all parameters. Factor analysis was applied to assess the variability in the structure of relationships among the characters. Factor loadings were calculated using the principal components method. The values of the Pearson's correlation coefficient at $r < 0.3$ were considered as weak, $0.3 > r > 0.5$ as moderate, $0.5 > r > 0.7$ as conspicuous, $0.7 > r > 0.9$ as strong, and $r > 0.9$ as very strong.

RESULTS AND DISCUSSION

Early ripening

Flowing seeds into the soil on June 1 and harvesting up to and including September 17 resulted in mature seeds from 104 accessions (55.6% of the total). The average duration of the growing season for matured accessions was 101 days. Similar data were obtained in a study of 105 samples of grain amaranth germplasm in southern India: the duration of the growing season ranged from 79 to 100 days (Lokeshkumar and Murthy 2017). These accessions were grouped according to the duration of the growing season into three groups: 1 (ultra-early ripening) - 87-96 days from sowing, 2 (early ripening) - 97-106 days, 3 (mid ripening) - 107-114 days. Eighty-three accessions that did not form mature seeds were classified as late-ripening and cannot be considered for cultivation in the Northwest region of the RF. Of these, by September 17, 15 samples (17.8%) had not reached the stage of beginning of flowering, 55 samples (65.5%) had not reached the stage of beginning of seed ripening, and 12 samples had not reached the stage of physiological seed ripening. Based on the results of assessing the level of early ripening, 23 ultra-early-ripening, 58 early-ripening and 23 mid-ripening amaranth samples were identified as capable of forming mature seeds in 87–114 days. Representatives of the species *A. cruentus* showed themselves to be more early ripening than *A. hypochondriacus*. The ultra-early- and early-ripening groups included 58 accessions of the species *A. cruentus* (63% of the total number of experimental accessions of the species) and a total of 24 accessions of the species *A. hypochondriacus* (33% of the total number of samples of the species). Both species are of Central and North American origin. Most authors agree that all grain amaranths originated from the progenitor species *A. hybridus* (Das 2012, Akin-Idowu et al. 2016). A unique feature of *A. cruentus* is the presence of one copy of chromosome 2, which occurred as a result of its division and leading to the haploid set n=17 (Ma et al. 2021, Singh et al. 2023, Amosova et al. 2024). We suggest that the formation of the *A. cruentus* species may have occurred due to the movement of *A. hybridus* to high-mountain regions. Thus, the oldest finds of amaranth were registered in a cave in the highland area of Peñas de la Cruz, Department of Antofagasta de la

Sierra (3,665 MASL) (Arreguez et al. 2013). The discovered seeds date back to the beginning of the Middle Holocene (5500-6000 BC). Phylogenetic data may explain the significantly greater plasticity and cold resistance of *A. cruentus*. Osei-Kwarteng et al. (2022) reported higher photosynthetic rates and carbon assimilation efficiency in *A. cruentus*, which may also explain the species' significantly greater ecological plasticity.

Duration of phenological phases

The duration of the phenological phases "sowing-shoots" and "shoots - appearance of the first true leaf" varied slightly and averaged 6 and 10 days, respectively (Table 1). The "mass flowering – beginning of ripening" period for all samples also did not differ significantly and averaged 19 days. These phases of ontogenesis are typical for grain amaranths and did not affect the level of early maturity. The following key phenophases were identified, the duration of which significantly ($p < 0.05$) influenced the duration of the growing season: «appearance of the first true leaf - beginning of budding»,

Table 1. Duration of phenological phases of amaranth according to ripeness groups. Values with different letters in the column 'Mean' are significantly different at $p < 0.05$

Phenological phases	Mean days	Min - Max	SD	CV (%)
Ultra-early ripening				
sowing-shoots	6.0 a	5.0 – 9.0	1.1	18.1
shoots - appearance of the first true leaf	10.0 a	7.0 – 12.0	1.3	13.0
appearance of the first true leaf - beginning of budding	35.7 a	29.0 – 42.0	4.2	11.8
beginning of budding - start of inflorescence growth	4.2 a	2.0 – 6.0	0.9	21.4
start of inflorescence growth - start of flowering	5.7 a	3.0 – 9.0	1.8	31.5
start of flowering - mass flowering	5.2 a	3.0 – 8.0	1.9	36.7
mass flowering - beginning of ripening	19.7 a	15.0 – 26.0	3.2	16.3
beginning of ripening - physiological seed maturity	6.0 a	5.0 – 8.0	0.9	15.6
Early ripening				
sowing-shoots	5.8 a	5.0 – 10.0	1.1	18.5
shoots - appearance of the first true leaf	10.4 a	6.0 – 13.0	1.2	11.3
appearance of the first true leaf - beginning of budding	41.5 b	31.0 – 47.0	3.5	8.4
beginning of budding - start of inflorescence growth	4.8 a	2.0 – 7.0	1.2	24.4
start of inflorescence growth - start of flowering	6.0 a	3.0 – 10.0	1.7	28.0
start of flowering - mass flowering	5.1 a	3.0 – 10.0	1.8	35.9
mass flowering - beginning of ripening	16.6 a	8.0 – 32.0	4.8	28.8
beginning of ripening - physiological seed maturity	11.8 b	5.0 – 18.0	3.4	28.8
Mid ripening				
sowing-shoots	6.2 a	5.0 – 10.0	1.3	21.6
shoots - appearance of the first true leaf	10.0 a	7.0 – 12.0	1.5	15.0
appearance of the first true leaf - beginning of budding	42.3 b	31.0 – 50.0	3.7	8.7
beginning of budding - start of inflorescence growth	5.3 a	3.0 – 7.0	1.0	19.6
start of inflorescence growth - start of flowering	7.6 b	4.0 – 13.0	2.5	32.2
start of flowering - mass flowering	5.9 a	4.0 – 8.0	1.6	26.6
mass flowering - beginning of ripening	19.4 a	10.0 – 36.0	6.9	35.5
beginning of ripening - physiological seed maturity	11.2 b	4.0 – 20.0	5.5	49.3
Late ripening				
sowing-shoots	6.3 a	5.0 – 11.0	1.4	21.9
shoots - appearance of the first true leaf	10.2 a	6.0 – 14.0	1.5	14.8
appearance of the first true leaf - beginning of budding	47.9 c	30.0 – 73.0	9.9	20.8
beginning of budding - start of inflorescence growth	6.0 b	3.0 – 13.0	2.0	32.7
start of inflorescence growth - start of flowering	10.1 c	3.0 – 21.0	4.4	43.5
start of flowering - mass flowering	7.2 b	3.0 – 13.0	1.8	25.8
mass flowering - beginning of ripening	22.5 a	9.0 – 40.0	7.2	31.8
beginning of ripening - physiological seed maturity	-	-	-	-

SD: standard deviation, CV (%): coefficient of variation

«beginning of budding - start of inflorescence growth», «start of inflorescence growth - start of flowering » and «start of flowering - mass flowering». The phase “appearance of the first true leaf – beginning of budding” varied in different maturity groups from 35.7 days (ultra-early ripening) to 47.9 days (late ripening). The vegetative stage is the longest in the ontogenesis of amaranth, as noted earlier (Das 2016). During this period, intensive growth of vegetative mass and increased plant height were observed. The period “start of inflorescence growth – start of flowering” in early-ripening genotypes occurred significantly faster and averaged 5.7 days, while in late-ripening genotypes it was 10.1.

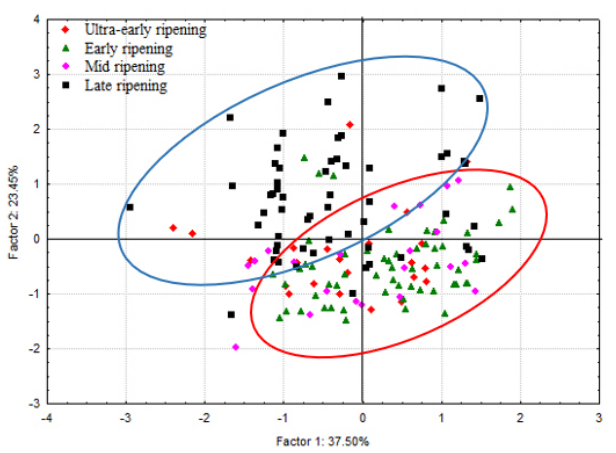
Morphological features

As a result of screening the metric characteristics of experimental genotypes, the following morphological features were identified (Table 2): 1 - characteristics that do not have significant differences ($p < 0.05$) and do not affect the level of early ripening (leaf length and width, leaf blade area, leaf petiole length, inflorescence length and plant height), 2 - traits that differed significantly ($p < 0.05$) depending on the time of ripening (total number of leaves on the plant, leaf surface area and stem diameter). On average, the photosynthetic surface area of late-ripening accessions was 44% higher than that of ultra-early-ripening genotypes. Differences between ultra-early-, early- and mid-ripening genotypes in terms of this indicator are not significant. The stem diameter of the late-ripening samples averaged 2.9 cm, which is 26-28% larger than the others. In the work of Dmitrieva (2021), when growing amaranth under the more southern conditions of Chuvashia (RF), the morphological characteristics of *A. cruentus* were studied, and the obtained data were similar in several characteristics to those of the late-ripening genotypes we described. A relationship was also observed between leaf area, stem diameter, and leaf number. It should be noted that, despite the general trend, exceptions were identified among all groups, as confirmed by the factor analysis results (Figure 1). Thus, among the ultra-early-ripening

Table 2. Metric characteristics of experimental amaranth accessions

Metric features	Ultra-early ripening		Early ripening		Mid ripening		Late ripening		LSD_{05}
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Number of leaves (pcs.)	35.1 a	20.0	33.1 a	12.9	38.2 a	16.4	62.2 b	26.9	6.02
Leaf length (cm)	17.0 a	4,0	17.5 a	3.0	16.4 a	4.3	16.9 a	3.5	0.96
Leaf width (cm)	8.8 a	2.3	10.3 a	2.1	9.2 a	2.5	8.4 a	2.1	0.61
Leaf area (cm^2)	108.0 a	43.3	128.9 a	42.3	109.6 a	47.6	102.4 a	42.6	12.01
Leaf surface area (cm^2)	3429.7 a	1868.0	4250.4 a	1944.5	4050.4 a	2218.1	6114.9 b	3186.7	731.06
Leaf petiole length, cm	8.8 a	2.3	10.7 a	2.3	10.1 a	2.7	9.6 a	2.3	0.65
Inflorescence length, cm	49.7 a	13.6	41.0 a	11.5	40.6 a	14.9	46.7 a	14.1	3.72
Stem diameter, cm	2.1 a	0.5	2.2 a	0.5	2.2 a	0.6	2.9 b	0.7	0.17
Plant height, м	1.7 a	0.2	1.6 a	0.2	1.6 a	0.3	1.6 a	0.2	0.06

SD - standard deviation, LSD - least significant difference, values with different letters are statistically different at $p < 0.05$.



	Factor 1	Factor 2
Number of leaves	-0.33	**0.82**
Leaf length	**0.83**	0.25
Leaf width	**0.91**	-0.11
Leaf area	**0.97**	0.07
Leaf surface area	0.47	**0.79**
Leaf petiole length	0.57	-0.02
Inflorescence length	-0.22	0.49
Stem diameter	0.21	**0.77**
Plant height	0.21	0.17

Figure 1. Factor analysis of metric features of amaranth groups. Factor Loadings (Varimax raw).

genotypes, the heavy-leaved *A. cruentus* (k-185, Romania) and *A. cruentus* (k-26, Kazakhstan) were noted, and among the late-ripening genotypes, the weak-leaved - *A. cruentus* (k-64, Germany) and *Amaranthus* sp. (tk-859, Russia).

Growth speed

The tall height of amaranth plants makes harvesting difficult, so low-growing genotypes have a significant advantage. Comparative analysis of plant height did not reveal significant interspecific differences and differences between maturity groups. On average, the height of the plants was 1.6 m, which is comparable to the results of amaranth studies in Romania and India (Lokeshkumar and Murthy 2017, Toader et al. 2020). The early-ripening *A. cruentus* (temp. k-793, Maldives), the late-ripening *A. hypochondriacus* (k-22, India), and *A. hypochondriacus* (k-256, Mexico) reached a maximum height of 2.2 meters. The minimum height of 1.1 meters was found in mid-ripening accessions from the USA *Amaranthus* sp. (k-431) and *A. cruentus* (k-432), as well as in late-ripening accessions *Amaranthus* sp. (tk-844, Hungary), *Amaranthus* sp. (k-163, Romania) and *A. hypochondriacus* (k-249, Mexico).

Amaranth is a plant with C4 photosynthesis. The difference between C3 and C4 plants lies in their carbon fixation strategies, the product of which is the four-carbon oxaloacetic acid rather than the three-carbon 3-phosphoglyceric acid. It is assumed that this type of photosynthesis appeared in dicotyledons about 20 million years ago (Gowik and Westhoff 2010). This provides a high rate of photosynthesis at low stomatal conductance, even at low temperatures (Pyankov et al. 2010). C4 plants have a characteristic leaf structure (Kranz life structures) and easily tolerate high temperatures and lack of moisture. In C4 photosynthesis there is almost no photorespiration process. It is believed that in phylogenesis, it was C4 photosynthesis that influenced the ability of amaranth to adapt from the humid climate typical of the Andean highlands to a temperate tropical climate (Sage et al. 2007). Considering the above, it was of interest to trace the intensity of plant growth during different periods of ontogenesis under conditions atypical for this crop in the North-Western region (RF). In the first month of the growing season all genotypes were characterized by extremely slow growth: from germination to July 1 (~ 23-26 days of vegetation), the plants reached 13-16 cm in height. The increase amounted to 8.3-9.5% of the maximum height. This crop feature was noted earlier and is associated with tiny seeds with a small supply of nutrients (the weight of 1000 amaranth seeds does not exceed 1 gram) (Toader et al. 2020, Dmitrieva 2021). Over the next 12 days, as the plant's photosynthetic surface area increased, the height reached 26-31 cm (+8.2-9.5%). Over 11 days from July 12 to 23, the height of the plants reached 62-67 cm (+20.6-24.1%), adding 1.9-2.2 cm daily. The period from July 23 to August 6 (14 days) was characterized by the maximum growth rate: daily growth was 4.4-5.3 cm. In an article by Toader et al. (2020), when studying two varieties of *A. cruentus* under the conditions of the southern regions of Romania, the authors noted a daily growth rate of about 2-3 cm. In the Northwest region of the RF, such

Table 3. Seed productivity indicators of experimental amaranth accessions

Indicators		Ultra-early ripening	Early ripening	Mid ripening	LSD_{05}
Yield per plant (g)	Mean	7.2 a	12.1 b	14.7 c	3.77
	SD	2.3	4.8	9.6	
	Min - Max	1.9-13.5	5.6-25.7	2.6-48.8	
	CV (%)	32.5	39.3	65.4	
Number of seeds per plant (pcs)	Mean	10124 a	14996 b	18040 c	4453
	SD	3391	6265	10231	
	Min - Max	2832-18750	7022-34719	3239-51900	
	CV (%)	33.5	41.8	56.7	
Weight of 1000 seeds (g)	Mean	0.72 a	0.82 a	0.80 a	0.07
	SD	0.10	0.12	0.09	
	Min - Max	0.50-0.86	0.60-1.25	0.58-0.94	
	CV (%)	13.4	14.8	10.8	
Grain yield (kg ha^{-1})	Mean	1447.6 a	2421.8 b	2938.5 b	755.0
	SD	469.9	952.5	1921.7	
	Min - Max	385.2-2700.0	1110.3-5138.5	518.3-9757.1	
	CV (%)	32.5	39.3	65.4	

CV (%) - coefficient of variation, SD - standard deviation, LSD - least significant difference. Values with different letters are statistically different at $p < 0.05$.

a growth rate in agricultural crops is not encountered and, as we assume, is associated with the characteristics of C4 photosynthesis and the photoperiod duration (Das 2016). It should be noted that late-ripening amaranth genotypes significantly exceeded early-ripening ones regarding the increase in photosynthetic surface area. By August 20, it was 6114.9 cm^2, exceeding the indicators of early maturing samples by 2 times. This observation is of interest for creating amaranth varieties for fodder use.

Yield of amaranth seeds

Seed yield averaged 2269.3 kg ha^{-1}. The group of mid-ripening accessions had higher indicators – on average 2938.5 kg ha^{-1}. It should be noted that there is significant variation in productivity indicators within each ripening group, except 1000-seed weight (CV=10.8-14.8%) (Table 3). The highest yield was shown by varieties of the species *A. cruentus* of Mexican origin: k-423 – 9760.3 kg ha^{-1} и k-424 – 7121.1 kg ha^{-1}. These accessions were characterized by light yellow seed color and the largest 1000 seed weight among mid-season biotypes: 0.94 g and 0.88 g, respectively. Similar yields were observed in a 2020 study growing the 'Golden Giant' and 'Bolivia 153' varieties in southern Romania (Toader et al. 2020). At the same time, the growing season was longer and amounted to 124 and 127 days, respectively. This fact seems interesting and may indicate the influence of the length of daylight hours under the conditions of the Northwest of the RF (Das 2016). Among the early-ripening accessions, the following stand out in terms of seed yield: *A. cruentus* (k-202, Venezuela) – 5,140 kg ha^{-1}, *A. cruentus* (k-218, Mexico) – 4,930 kg ha^{-1}, *A. cruentus* (k-391, Brazil) – 4,890 kg ha^{-1} and 'Frant' (k-318, Russia) – 4,400 kg ha^{-1}. Among the ultra-early-ripening genotypes, the maximum yield of 2701.2 kg ha^{-1} was shown by the *A. cruentus* accessions from Uzbekistan (k-55).

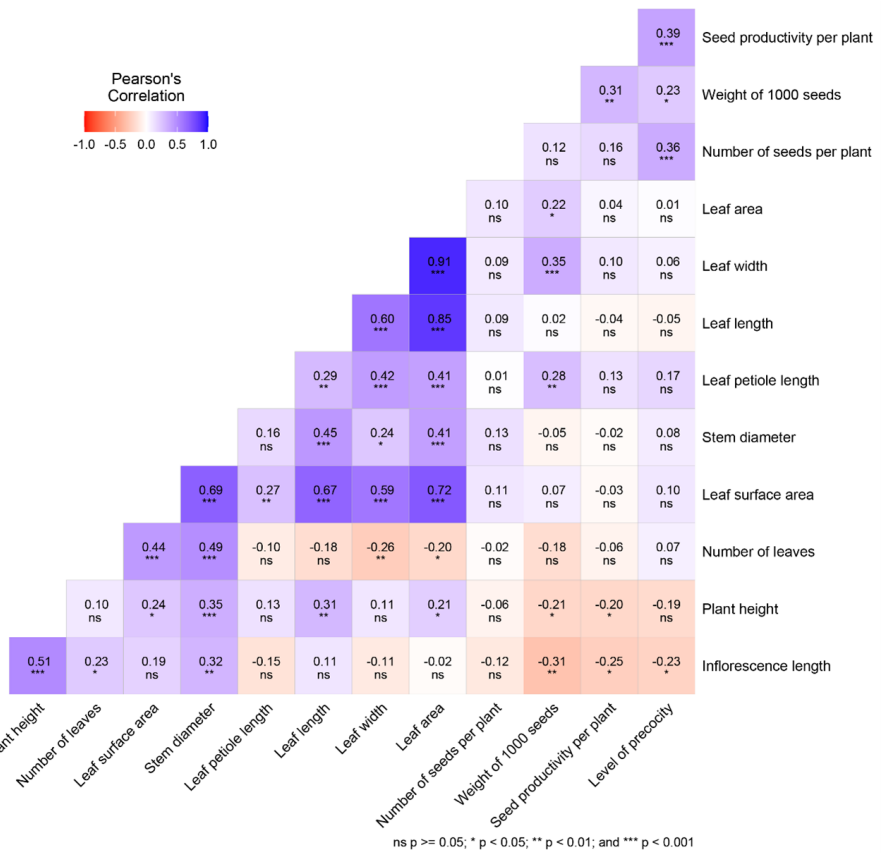


Figure 2. Correlation matrix of morphological features of amaranth accessions under the conditions of the North-West region of the Russian Federation.

The weight of 1000 seeds averaged 0.78 g. This indicator ranged from 0.5 g for the ultra-early-ripening variety *A. hypochondriacus* (k-295. Mexico) to 1.25 g for the early-ripening *A. cruentus* (k-219, Mexico). Black seeds predominated in color among ultra-early-ripening forms. This is due to the predominance of this seed color in the species *A. cruentus* L., which accounted for 69.7% of the ultra-early-ripening samples. Correlation analysis showed a positive relationship between the level of early maturity and the yield of seeds per plant ($r = 0.39$, $p < 0.01$) and their quantity ($r = 0.36$, $p < 0.01$) (Figure 2). Plant height correlated with inflorescence length ($r = 0.51$, $p < 0.01$), stem diameter ($r = 0.35$, $p < 0.01$) and leaf length ($r = 0.31$, $p < 0.05$). Among mid-ripening accessions, the average number of seeds per plant was 18,040, which is 78% more than that of ultra-early-ripening accessions. It can be concluded that ultra-early-ripening amaranth accessions are inferior in yield and the choice of genotypes for cultivation in colder regions should be made among the noted early- and mid-ripening groups.

The study described the morphological characteristics of early-ripening genotypes of grain amaranth, noted the key phases of ontogenesis and the features of growth and development in relation to northern regions. The identified features are important for breeding programs to create early-ripening varieties. This study demonstrates good adaptability and plasticity of the crop, which is the potential for cultivating grain amaranth in more northern regions.

ACKNOWLEDGMENTS

This research was supported by the Russian Science Foundation under Project No. 24-26-00218 (Interaction of Phenotypic and Biochemical Characteristics of Grain Amaranth with Squalene Content in Seeds under the Conditions of the Northwest of the Russian Federation).

DATA AVAILABILITY

The datasets generated and/or analyzed in this study are available from the corresponding author upon reasonable request.

REFERENCES

Akin-Idowu P, Gbadegesin M, Orkpeh U, Ibitoye D and Odunola O (2016) Characterization of grain amaranth (*Amaranthus* spp.) germplasm in South-West Nigeria using morphological, nutritional, and random amplified polymorphic DNA (RAPD) analysis. **Resources 5**: 6.

Amosova AV, Yurkevich OY, Semenov AR, Samatadze TE, Sokolova DV, Artemyeva AM, Zoshchuk SA and Muravenko OV (2024) Genome studies in *Amaranthus cruentus* L. and *A. hypochondriacus* L. based on repeatomic and cytogenetic data. **International Journal of Molecular Sciences 25**: 13575.

Arreguez GA, Martínez JG and Ponessa G (2013) *Amaranthus hybridus* L. ssp. *hybridus* in an archaeological site from the initial mid-Holocene in the Southern Argentinian Puna. **Quaternary International 307**: 81-85.

Barrio DA and Anon MC (2010) Potential antitumor properties of a protein isolate obtained from the seeds of *Amaranthus mantegazzianus*. **European Journal of Nutrition 49**: 73-82.

Bressani R (1994) Composition and nutritional properties of amaranth. In Paredes-Lopez O (ed) **Amaranth biology, chemistry and technology**. CRC Press, Boca Raton, p. 185-206.

Covas G (1993) **Perspectivas del cultivo de los amarantos en la republica Argentina**. In INTA – Instituto Nacional de Tecnologia Agropecuaria, Buenos Aires, p. 1-10.

Das S (2012) Taxonomical observation on the grain amaranths and new varieties of *Amaranthus cruentus* (Amaranthaceae). **Nordic Journal of Botany 30**: 412-420.

Das S (2016) **Amaranthus: A promising crop of future**. Springer, Singapore, 208p.

Dmitrieva OF (2021) Study of the growth and development of *Amaranthus cruentus* L. at different dates and methods of sowing in the Chuvash republic. **Journal of Agriculture and Environment 1**: 1-6.

Evon P, de Langalerie G, Labonne L, Merah O, Talou T, Ballas S and Vé ronèse T (2021) Low-density insulation blocks and hardboards from amaranth (*Amaranthus cruentus*) stems, a new perspective for building applications. **Coatings 11**: 349.

Gins MS, Gins VK, Motyleva SM, Kulikov IM, Medvedev SM, Pivovarov VF and Mertvishcheva ME (2017) Metabolites with antioxidant and protective functions from leaves of vegetable amaranth (*Amaranthus tricolor* L.). **Agricultural Biology 52**: 1030-1040.

Gonor KV, Pogozheva AV, Derbeneva SA, Maltsev GY, Trushina EN and Mustaphina OK (2006) The influence of a diet with including amaranth oil antioxidant and immune status in patients with ischemic heart disease and hyperlipoproteinemia. **Problems of Nutrition 75**:30-33.

Gowik U and Westhoff P (2010) The path from C3 to C4 photosynthesis. **Plant Physiology 155**: 56-63.

Huang ZR, Lin YK and Fang JY (2009) Biological and pharmacological activities of squalene and related compounds: potential uses in cosmetic dermatology. **Molecules 14**: 540-554.

Lokeshkumar BM and Murthy N (2017) Genetic variability and divergence studies for yield component traits in grain amaranth (*Amaranthus* spp.). **International Journal of Current Microbiology and Applied Sciences 6**: 1276-1285.

Ma X, Vaistij FE, Li Y, Jansen van Rensburg WS, Harvey S, Bairu MW, Venter SL, Mavengahama S, Ning Z, Graham IA, Deynze AV, Peer YV and Denby KJ (2021) A chromosome-level *Amaranthus cruentus* genome assembly highlights gene family evolution and biosynthetic gene clusters that may underpin the nutritional value of this traditional crop. **The Plant Journal 107**: 613-628.

Montellano BRO (1990) **Aztec medicine, health, and nutrition**. Rutgers University Press, New Jersey, 441p.

Myers RL and Putnam DH (1988) Growing grain amaranth as a specialty crop. **Center for Alternative Crops and Products, University of Minnesota**. Available at <https://conservancy.umn.edu/items/d6b7c0a1-6c3e-45a8-bf8d-08ab79a5cdb6>. Accessed on January 30, 2025.

Osei-Kwarteng M, Ayipio E, MoualeuNgangue D, Buck-Sorlin G and Stützel H (2022) Interspecific variation in leaf traits, photosynthetic light response, and whole-plant productivity in amaranths (*Amaranthus* spp. L.). **PLoS ONE 17**: e0270674.

Priya VP, Celine VA, Gokulapalan C and Rajamony L (2007) Screening amaranth genotypes (*Amaranthus* spp.) for yield and resistance to leaf blight caused by *Rhizoctonia solani* Kuhn. **Plant Genetic Resources Newsletter 147**: 1-4.

Pyankov VI, Ziegler H, Akhani H, Deigele C and Lüttge U (2010) European plants with C4 photosynthesis: geographical and taxonomic distribution and relations to climate parameters. **Botanical Journal of the Linnean Society 163**: 283-304.

Rao CV, Newmark HL and Reddy BS (1998) Chemopreventive effect of squalene on colon cancer. **Carcinogenesis 19**: 287-290.

Rastogi A and Shukla S (2013) Amaranth: A new millennium crop of nutraceutical values. **Critical Revisions of Food Science Nutrition 53**: 109-125.

Sage RF, Sage TL, Pearcy RW and Borsch T (2007) The taxonomic distribution of C4 photosynthesis in Amaranthaceae sensu stricto. **American Journal of Botany 94**: 1992-2003.

Sanz-Penella JM, Laparra JM, Sanz Y and Haros M (2012) Bread supplemented with amaranth (*Amaranthus cruentus*): effect of phytates on in vitro iron absorption. **Plant Foods for Human Nutrition 67**: 50-56.

Saunders RM and Becker R (1984) Amaranthus: a potential food and feed resource. In Pomeranz Y (ed) **Advances in cereal science and technology**. American Association of Cereal Chemists, Saint Paul, p. 357-396.

Shukla S, Bhargava A, Chatterjee A, Pandey AC, Rastogi A and Kumar A (2010) Genetic interrelationship among nutritional and quantitative traits in the vegetable amaranth. **Crop Breeding and Applied Biotechnology 10**: 16-22.

Singh A, Mahato AK, Maurya A, Rajkumar S, Singh AK, Bhardwaj R, Kaushik SK, Kumar S, Gupta V, Singh K and Singh R (2023) Amaranth genomic resource database: An integrated database resource of amaranth genes and genomics. **Frontiers in Plant Science 14**: 1-13.

Smith ME (1996) **The Aztecs**. Blackwell, Oxford, 390p.

Smith TJ (2000) Squalene: Potential chemopreventive agent. **Expert Opinion on Investigational Drugs 9**: 1841-1848.

Sokolova D, Zvereva O, Shelenga T and Solovieva A (2021) Comparative characteristics of the amino acid composition in amaranth accessions from the VIR collection. **Turkish Journal of Agriculture and Forestry 45**: 68-78.

Sokolova DV, Solovieva AE, Zaretsky AM and Shelenga TV (2024) The potential of the amaranth collection maintained at VIR in the context of global plant breeding and utilization trends. **Vavilov Journal of Genetics and Breeding 28**: 731-743.

State Commission of the Russian Federation (2007) Methodology for testing the distinctiveness, homogeneity and stability of amaranth. Available at <https://gossortrf.ru/publication/metodiki-ispytaniy-na-oos.php>. Accessed on January 30, 2025.

State Commission of the Russian Federation (2022) Frant. Available at <https://gossortrf.ru/registry/gosudarstvennyy-reestr-selektsionnykh-dostizheniy-dopushchennykh-k-ispolzovaniyu-tom-1-sorta-rasteni/frant-amarant-metelchatyy/>. Accessed on January 30, 2025.

State Register for Selection Achievements Admitted for Usage of the Russian Federation (2024) Available at <https://gossortrf.ru/publication/reestry.php>. Accessed on January 14, 2025.

Tang Y and Tsao R (2017) Phytochemicals in quinoa and amaranth grains and their antioxidant, anti-inflammatory, and potential health beneficial effects: a review. **Molecular Nutrition & Food Research 61**: 1600767.

Teutonico RA and Knorr D (1985) Amaranth: composition, properties and applications of a rediscovered food crop. **Food Technology 1**: 49-60.

Toader M, Ionescu AM, Sonea C and Emil G (2020) Research on the morphology, biology, productivity and yields quality of the *Amaranthus cruentus* L. in the southern part of Romania. **Notulae Botanicae Horti Agrobotanici Cluj-Napoca 48**: 1413-1425.