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Seed morphometry of *Rheum* L. (Polygonaceae) species from Kazakhstan and its implications in taxonomy and species identification

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Abstract. *Sumbembayev AA, Lagus OA, Nowak S. 2023. Seed morphometry of* Rheum *L.* (*Polygonaceae*) *species from Kazakhstan and its implications in taxonomy and species identification. Biodiversitas 24: 4677-4692.* In the article, the evaluation of morphometric and weight parameters of seeds of 7 species of the genus *Rheum* L. from Kazakhstan is presented, as well as an analysis of their biometric parameters from different ecological and geographical habitats. The purpose of the study was to determine the variability of the seeds of the studied taxa and the importance of the results in determining the taxonomic relationships within the genus. The external structure was described for all species of the genus. Seeds of all studied species are illustrated with photos and scale drawings, and their features are summarized in a table. Stable and taxonomically significant features were identified for the species of the section *Ribesiformia*, represented by *R. cordatum* and *R. maximowiczii*, allowing their identification. The correlation between seed metric parameters and environmental conditions of the site and growth area was established and found a significant relationship between morphometric data and most of the environmental factors studied. The low adaptive potential of rhubarb species in Kazakhstan and the species' narrow ecological range were found. The comparison of the results obtained with the taxonomic relationships and phylogeny of representatives of the genus are briefly discussed.

Keywords: Ecological and geographical confinement, Kazakhstan, morphometric characteristics, *Rheum*, seed morphology

INTRODUCTION

Among the tasks of modern botany, which are becoming increasingly important, are the issues of studying the morphological features of fruits and seeds. Knowledge of which is essential both for theoretical scientific studies and for practical work. Classical taxonomy is based mainly on the structure of the flower and makes insufficient use of data on fruits and seeds. Despite the apparent simplicity of the structure, the seeds amaze various morphobiological features of external features, as their ecological and geographical origin vary. Using these data would help refine and sometimes even clarify systematic relationships at different taxonomic levels, which could especially be crucial in identifying certain taxa. Therefore, at this stage, an important direction in the study of biological diversity is the study of morphometric and weight indicators of individual taxa. Fortunately, more and more work can be seen using seed structure data based on diverse methods for various taxonomical groups of plants (Gabr 2018; Martín-Gómez et al. 2019; Martín-Gómez et al. 2020; Rewicz et al. 2020; Rashid et al. 2021; Rewicz et al. 2022; Bai et al. 2023).

The genus *Rheum* L. is one of the largest in the family Polygonaceae Juss, whose range extends from west to east, from Bulgaria to temperate Asia and northern Indo-China (POWO 2023). The center of origin and genus diversity is The Qinghai-Tibetan Plateau and neighboring areas (Sun et al. 2012; Zhang et al. 2022). All representatives of the genus are well-known as valuable medicinal, food, and vitamin plants. The genus includes 56 generally accepted species (POWO 2023), of which 9 are listed for the flora of Kazakhstan (Abdulina 1999) and currently known growth for 7 *Rheum* species in Kazakhstan: *Rheum altaicum*, *R. compactum*, *R. nanum*, *R. wittrockii*, *R. tataricum*, *R. cordatum*, and *R. maximowiczii*. In addition, *R. compactum (R. altaicum)* and *R. wittrockii* are included in the list of the Red Book of Kazakhstan (2014) with the status of a rare species with a declining population.

Extensive research is being carried out on the biology of the genus *Rheum* in taxonomy (Jafari et al. 2012; Baradaran and Jafari 2014; İlçim and Karahan 2020), morphometry and biostatistics (Bhardwaj and Sood 2020), ontogeny (Kandari et al. 2012; Tabin et al. 2016; Shukla and Thapliyal 2021; Wani et al. 2022), karyology (Ruirui et al. 2010), and genetics (Sanchez et al. 2011; Zhao et al. 2017; Li and Wang 2020).

At the same time, a limited number of studies have been conducted on the study of *Rheum* species at the population level (Libert and Englund 1989; Song et al. 2015; Khan et al. 2019), especially in Kazakhstan (Dagarova et al. 2017) - being a peripheral part of the range. Morphometry of generative organs (Eshibaev et al. 2021; Sumbembayev et al. 2021; Aidarkhanova et al. 2022; Orazov et al. 2022; Sumbembayev et al. 2022; Vesselova et al. 2022) and seeds, in particular, can serve as a qualitative systematic trait. According to the analysis of carpological studies (Zhao et al. 2008; Sharma and Sharma 2017; Kong et al. 2018; Tan et al. 2019; Bhardwaj and Sood 2020), rhubarb fruits and seeds have differences that, together with other diagnostic features, can be used to clarify systematic relationships and determine species.

On the other hand, phylogenetic relationships within the genus *Rheum* remained unresolved for a long time (Wang et al. 2005; Sun et al. 2012), and only phylogenomic studies seem to have answered the problem (Zhang et al. 2022). Unfortunately, although the sampling of species in phylogenomic studies is significant, it still does not cover all taxa whose systematic position may be dubious. Resolving phylogeny based on standard molecular markers may be difficult or impossible within the genus *Rheum* because of widespread hybridization and rapid radiation of taxa (Sun et al. 2012; Wan et al. 2014).

Unfortunately, data on seed morphology for many species of this genus are fragmentary or incomplete. However, the seed features are used as a trait in the determination keys, so they can probably be an unappreciated source in intrageneric classification or determination of species distinctiveness. Especially since the taxonomic distinctiveness of some species is not fully accepted; an example is *R. altaicum* Losinsk, which is given as a synonym of *R. compactum* L. (Tupitsyna 2012; POWO 2023).

Stable and clear systematics and the ability to easily identify taxa correctly are crucial, especially for species with the potential for human use. To such a group belongs the genus *Rheum*, where the occurrence of plant metabolites with medicinal potential, among other things, has been confirmed in several species (Ghorbani et al. 2019; Kolodziejczyk-Czepas and Liudvytska 2021; Mohtashami et al. 2021). Most species are valuable food and vitamin plants (Lang et al. 2020). At the same time, many rhubarb species remain difficult to identify correctly, and the taxonomic status of some of them remains unclear.

The purpose of this study is to evaluate the morphometric and weight parameters of seeds of species of the genus *Rheum* L. and to analyze their biometric parameters from different ecological and geographical habitats in the study region to clarify the systematic relationships of this genus.

MATERIALS AND METHODS

The object of the study was the seeds of 7 species of the genus *Rheum*, collected in natural populations of Kazakhstan in different ecological and geographical habitats throughout the distribution area in Kazakhstan (Figure 1).

Seed material was collected in stages during 2020-2022 from the whole territory of Kazakhstan (Table 1). *Rheum altaicum* and *R. compactum* were collected from research project expeditions. Seed material was collected from well-bearing individuals without traces of diseases and pests. The seeds of the remaining five species were obtained for study from the seed fund of the Institute of Botany and Phytointroduction. Well-formed seeds were selected for analysis; it should be noted that the seed collection of the studied rhubarb species was carried out in the most typical places of growth.

The collected material was subsequently stored dry in paper bags. All collected samples were measured for the seeds' length, width, and thickness; the weight of 1,000 seeds was determined.

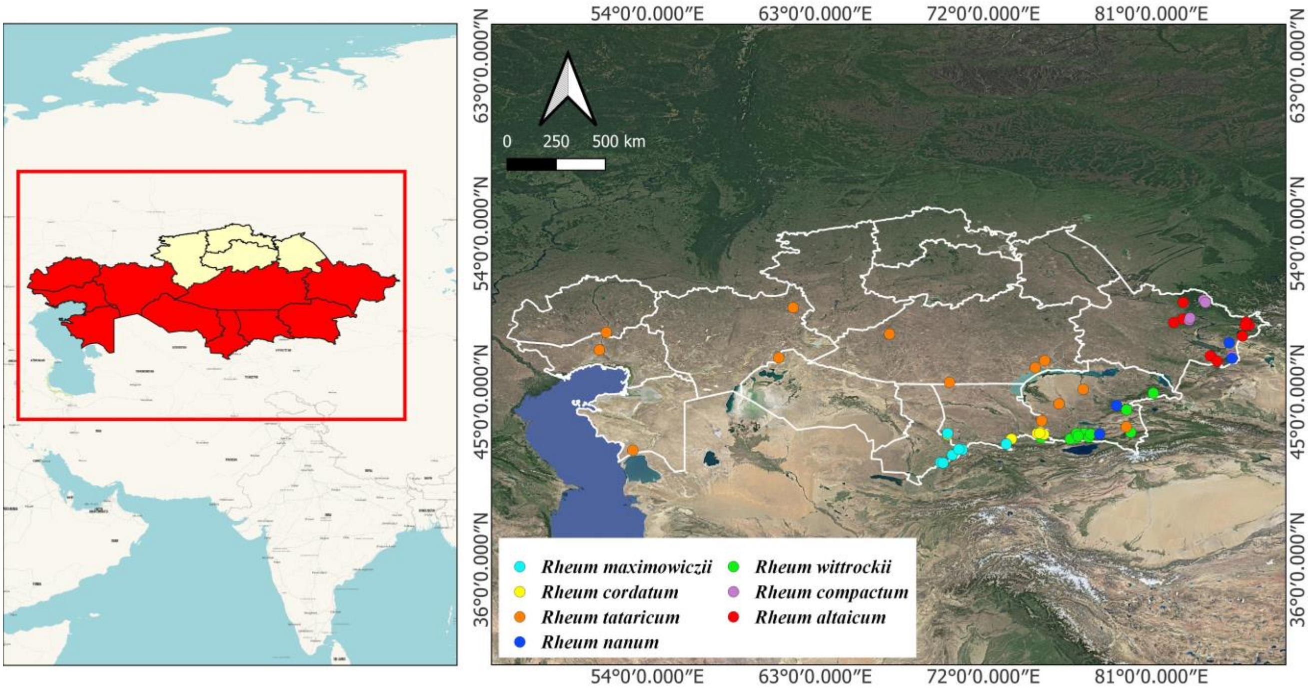

Figure 1. Location of populations of the studied species of the genus *Rheum* L. in Kazakhstan

Table 1. Characteristics of the locations of the population of species of the genus *Rheum* in Kazakhstan

Species, population	Location	Geographical coordinates, altitude	L*	T*	M*	R*	N*	S*	Habitat
Family Polygonaceae Juss. Subfamily: *Polygonoideae* Tribe: *Rumiceae* Dumort Genus: *Rheum* L., Sp. Pl.: 371 (1753)									
Section: *Rheum* *Rheum altaicum* Losinsk.									
Pop 1	East Kazakhstan region, Manrak ridge	47.457680 84.182219 1,800 m asl.	9	6	4	7	5	6.5	Southern slope of Mount Chorbas
Pop 2	East Kazakhstan region, Saur-Tarbagatai mountain range, Shilikty valley	47.175871 84.516614 800 m asl.	9	6	4.5	7	4.5	6	Rocky slopes
Pop 3	East Kazakhstan region, Zharma district, Eastern part of the Kalba ridge, Sarytau mountains	49.494167 83.055556 742 m asl.	9	5.5	5	6.5	6	4.5	Multi-grass rocky slopes
Pop 4	East Kazakhstan region, Zharma district, Eastern part of the Kalba ridge, near the village of Tainty	49.235556 82.191111 1,134 m asl.	9	5.5	5	5.5	6	4	On the ledges of the southern slope
Pop 5	East Kazakhstan region, Katon-Karagai district, South Altai Tarbagatai ridge	49.095278 86.2325 1,890 m asl.	8	5	6	4.5	7.5	3.5	Southeastern slope, shrub-forb meadows
Pop 6	East Kazakhstan region, Katon-Karagai district, South Altai Tarbagatai ridge	49.261944 86.065833 1,859 m asl.	8.5	5	6	5	7.5	3.5	Southeastern foothills, forb-grass meadows
Pop 7	East Kazakhstan region, Katon-Karagay district, Sarymsakty ridge, in the area of the Burkhat mountain pass	49.093056 86.028333 1,870 m asl.	8.5	5	6	4.5	7.5	3.5	Northeast rocky slope
Pop 8	East Kazakhstan region, Sekisovka village, Mount Calendar	50.321052 82.695514 980 m asl.	8	5	6	4	7.5	4.5	Northern slope, part of black taiga, with rock outcrops
Pop 9	East Kazakhstan region, Azutau ridge, Kyzylashchi tract	48.516171 85.875351 1,500 m asl.	9	5	5.5	5	7	4	Western steppe slope
Pop 10	East Kazakhstan region, Zharma district, Eastern part of the Kalba ridge, Taldy tract	49.428889 82.666944 896 m asl.	8.5	5.5	5	5	6	5	On the granitoid of the southwestern slope
Pop 11	East Kazakhstan region, Manrak ridge	47.453824 84.153396 1,120 m asl.	9	6	5	7	5	6.5	Northwestern slope
Rheum compactum L.									
Pop 1	East Kazakhstan region, northern slopes of the Kalba ridge, 2 km west of Shibyndy-kol lake	49.373201 83.018656 755 m asl.	8.5	5.5	5	5	6	5	On rocky slopes
Pop 2	East Kazakhstan region, Saur ridge, Baimurza mountain pass	47.434849 85.300912 1,404 m asl.	9	5	5	6.5	5	5.5	Southeastern slopes
Pop 3	East Kazakhstan region, Zharma district, Eastern part of the Kalba ridge, Tainty village	49.486944 83.066111 830 m asl.	8.5	5.5	6	5	6	5	Northeast slope
Pop 4	East Kazakhstan region, Ivanovsky Ridge, neighborhood of the village of Poperechnoye	50.441372 83.793038 850 m asl.	8	5.5	6	4	7.5	3.5	Pine forest, upper forest boundary, between rocks
Pop 5	East Kazakhstan region, Ivanovsky ridge	50.320233 83.889247 1,545 m asl.	8.5	5	6	4	7.5	3.5	Pine forest, on the rocks
Rheum wittrockii Lundstr.									
Pop 1	Zhetysu region, southern part of the Dzungar Alatau ridge, left bank of the Koksu river, near the canyon	44.564736 79.665080 1,102 m asl.	8	5	6	4.5	6.5	4	On the rocks, in the spruce-birch forest

Pop 2	Almaty region, Ili-Alatau ridge, Almaty Reserve	43.258978 77.379256 1,120 m asl.	8.5	5.5	6	5.5	6.5	4	Highlands, on the south side of the slope descending into the alpine meadow
Pop 3	Almaty region, Ili-Alatau ridge, right bank of the Middle Talgar River, right side of the Myn-Dzhilki gorge	43.305538 77.385700 1,534 m asl.	8.5	5.5	5.5	5.5	6	5.5	On the rocky slopes of the gorge
Pop 4	Almaty region, Eastern part of the Kungei Alatau ridge, Kurmekty gorge	43.007738 76.651086 2,700 m asl.	8.5	5	5.5	5	6	3.5	On the southwest slope
Pop 5	Almaty region, Talgar district, Big Almaty gorge, above the dam, 2 km below from the turn to the right	43.294167 76.986944 2,171 m asl.	8	5	6	5.5	6	4	Apple orchard, powerful forbs
Pop 6	Almaty region, Talgar district, Ile-Alatau Natural Park	43.102778 77.646667 1,685 m asl.	7.5	5.5	6	6	6	4.5	On the bridge of the Big Almaty Lake, under the canopy of trees
Pop 7	Almaty region, Talgar district, Ile-Alatau Natural Park	43.269694 77.740278 1,540 m asl.	8	5.5	5.5	6	6	5	Turgen Gorge, between bushes
Pop 8	Almaty region, Talgar district	43.164203 77.076030 2,018 m asl.	8	5	5.5	5	6.5	4.5	Gorge Kim-Asar
Pop 9	Almaty region, Uigur district, Ketmentau ridge	43.363333 79.8925 1,542 m asl.	8.5	5.5	5.5	6	6	5	Aktam gorge
Pop 10	Almaty region, Alakol district, territory of Zhongar Alatau Natural Park	45.464722 81.100278 1,943 m asl.	9	5.5	6	6	5	5	Kepeli river valley
Pop 11	Almaty region, Talgar district, Ili-Alatau ridge	43.055278 76.973611 2,619 m asl.	8.5	5	6	6	5.5	5	Big Almaty Gorge
Pop 12	Almaty region, Talgar district, Ili-Alatau ridge	43.070833 75.09 2,640 m asl.	8.5	5	6	6	5.5	5	Big Almaty Gorge
Section: *Deserticola* Maxim. Series: Racemiferae A. Los. *Rheum nanum* Siev.									
Pop 1	East Kazakhstan region, Saur Ridge, Sarytologoy tract	47.320397 85.310184 954 m asl.	9	5.5	5	6.5	4	6.5	At outlets of tertiary clays
Pop 2	Zhetysu region, southwestern spurs of the Dzhungar Alatau ridge	44.799253 79.128879 1,120 m asl.	9	5.5	6	6	5.5	6	Left bank of the middle course of the Bizhe River, near junction No. 53, on a rocky slope
Pop 3	Almaty region, Enbekshikazakh district, Syugaty depression	43.27 78.222222 1,025 m asl.	9	5.5	6	5.5	6	6	Secondary vegetation in place of arable land
Pop 4	East Kazakhstan region, Kurchum ridge, vicinity of the village Kalguty	48.154885 85.161653 521 m asl.	9	6	5	6.5	5	7	Rubble slope
Section: *Orbicularia* A. Los. *Rheum tataricum* L.fil.									
Pop 1	Aktobe region, Southern slope of the Turgai plateau, 18 km south of Arys-Kul Lake, 34 km east of Zhusaly station	50.045422 61.810328 305 m asl.	9	6	4	7	4.5	8	*Artemisia-Anabasis* desert
Pop 2	Karaganda region, Ulytau mountains	48.624987 66.973358 687 m asl.	9	5.5	5	6.5	4.5	7.5	On the steppe slopes
Pop 3	Karaganda region, Central Betpak-dala desert, Kok-Ashik tract	46.037976 70.187071 565 m asl.	8.5	6.5	3.5	7	3.5	8	In the depressions of the relief
Pop 4	Almaty region, Chu-Ili mountains	43.980911 75.121613 857 m asl.	9	6	6	6.5	5.5	6.5	Valley of the river Utyugun, in the small hills

Pop 5	Mangistau region, Karakiya district, 107 km from the city of Aktau towards the Senek village	42.398611 53.228611 247 m asl.	9	8	3	7.5	3	8	Steppe northwestern slopes
Pop 6	Atyrau region, Makhambet district, vicinity of Bolek village	47.771389 51.433333 -20 m asl.	8.5	7.5	3.5	7	4	7	In the depressions of the relief
Pop 7	Aktobe region, Shalkar district, railway station Chokusu	47.3525 61.038889 178 m asl.	8.5	8	4	7	4	7.5	In the lowering of the relief
Pop 8	West Kazakhstan region, Akzhaiyk district, 10 km north of the Inderbor village	48.712778 51.804444 -9.7 m asl.	8.5	7	4.5	7.5	4.5	7	hollows
Pop 9	Karaganda region, Aktogay district, 16 km to the south of the Balkhash city	46.825 74.775 385 m asl.	8.5	6	4.5	6.5	4	7	Steppe forbs
Pop 10	Karaganda region, Aktogay district, from the city of Balkhash 55 km to the north-west	47.2 75.284444 495 m asl.	9	6	4.5	6.5	4	7	Steppe grass communities
Pop 11	Almaty region, Karatal district, 70 km from Mount Ushtobe, 1 km from the village of Naimansuek, 29 quarter of the Karatal forestry	45.669167 77.339444 380 m asl.	8.5	6	5	6.5	4	6.5	Among the *Halóxylon* bushes
Pop 12	Almaty region, Balkhash district, 5-6 km from the Bura village	44.889444 76.050556 394 m asl.	8.5	6	4	6.5	3.5	6.5	Among the *Halóxylon-Halimodendron* thickets
Pop 13	Almaty region, Enbekshikazakh district, Boguty mountains	43.655833 79.653889 921 m asl.	9	6	4	6.5	3.5	6.5	Rubble plain
Section: *Ribesiformia* A. Los.									
Rheum cordatum Losinsk.									
Pop 1	Zhambyl region, Kurdai district, Southern spurs of the Chu-Ili mountains, on the road from Krasnogorka to Georgievka	43.308006 74.880737 956 m asl.	9	6	5.5	6	5.5	6	Forb steppe meadows
Pop 2	Zhambyl region, Karatau ridge, Ilekty-sai gorge	43.232865 70.078340 1,320 m asl.	9	6	5	6	5.5	5.5	On the rocky slopes of the gorge
Pop 3	Almaty region, Zhambyl district, Chu-Ili mountains, further from the weather station	43.375833 75.053056 1,020 m asl.	8.5	6	5.5	6	5.5	6	Along the mountain stream
Pop 4	Zhambyl region, Merken district, Kyrgyz ridge, Merke tract	43.008056 73.501667 2,316 m asl.	8.5	5.5	5	6.5	5.5	5	Koyansai Gorge, on slopes
Pop 5	Zhambyl region, Kordai district, Zhety-Zhol mountains	43.251389 75.239444 1,593 m asl.	8.5	6	5	6	5	5.5	Sulutor gorge
Pop 6	Zhambyl region, Southern spurs of the Chu-Ili mountains, the Kurdai city	43.316421 75.012151 1,454 m asl.	9	6	5	6	5.5	5.5	Forb steppe communities
Rheum maximowiczii Losinsk.									
Pop 1	Zhambyl region, Karatau mountains, Berkara gorge	43.308759 70.083517 1,787 m asl.	9	6	5	6	5.5	5.5	Rocky slopes
Pop 2	South Kazakhstan region, Western part of the Tien Shan mountain range, Karzhantau ridge, Churgunus river gorge	41.750285 69.710376 1,854 m asl.	9	6	4	6	6	5.5	On clay-gravel screes
Pop 3	South Kazakhstan region, Western part of the Tien Shan mountain range, Karzhantau ridge, upper reaches of the Naut gorge	41.722196 69.841066 2,024 m asl.	9	6	5	6	6	5	Along the eastern rocky slope
Pop 4	South Kazakhstan region, Western part of the Tien Shan mountain range, Ugam ridge, Aksar-say peak	42.144992 70.328126 2,007 m asl.	9	6	5	6	5.5	5	The grassy southern slope of the mountains

Pop 5	Zhambyl region, Western part of the Tien Shan mountain range, Talas Ala-Tau ridge, Kishi-Kaindy river valley	42.431419 70.865580 1,700 m asl.	9	6	5	6	6	5.5	Southern rocky slopes
Pop 6	Zhambyl region, Western part of the Tien Shan mountain range, Talas Alatau ridge	42.458534 70.685936 1,685 m asl.	9	6	5	6	5.5	6	Rocky slopes of the right bank of the Baldybrek River
Pop 7	Zhambyl region, Merken district, Merke river valley	42.736111 73.227222 1,239 m asl.	8	6	5	5.5	6	6	under the crowns of *Celtis* on the southern slope, next to the cave

Note: *Verbal definitions of the scales of Ellenberg indicator values:

L - Light (scale 1-9):
1. deep shade plant, occurring where the incident diffuse radiation is less than 1% of that in an open area, rarely at more than 30%
2. between 1 and 3
3. shade plant, usually occurring where the incident diffuse radiation is less than 5% of that in an open area, but also at sunnier sites
4. between 3 and 5
5. semi-shade plant, only exceptionally occurring in full light, but usually at more than 10% of the diffuse radiation incident in an open area
6. between 5 and 7; rarely at less than 20% of diffuse radiation incident in an open area
7. half-light plant, mostly occurring at full light, but also in the shade up to about 30% of diffuse radiation incident in an open area
8. light plant, only exceptionally occurring at less than 40% of diffuse radiation incident in an open area
9. full light plant, occurring only in fully irradiated places, not at less than 50% of diffuse radiation incident in an open area

T - Temperature (scale 1-9):
1. cold indicator, only in high mountain areas, i.e., the alpine and nival belts
2. between 1 and 3 (many alpine species)
3. cool indicator, mainly in subalpine areas
4. between 3 and 5 (especially high montane and montane species)
5. moderate heat indicator, from lowland to montane belt, mainly in submontane-temperate areas
6. between 5 and 7 (lowland and colline species)
7. heat indicator, occurring in relatively warm lowlands
8. between 7 and 9
9. extreme heat indicator

M - Moisture (scale 1-12):
1. strong drought indicator, viable at sites that frequently dry out and confined to dry soils
2. between 1 and 3
3. missing on damp soil
4. between 3 and 5
5. indicator of fresh soils, focus on soils of average moisture, missing on wet soils and on soils that frequently dry out
6. between 5 and 7
7. humidity indicator, focus on well-moistened, but not wet soils
8. between 7 and 9
9. wetness indicator, focus on often soaked, poorly aerated soils
10. aquatic plant that survives long periods without soil flooding
11. aquatic plant rooted underwater, but at least temporarily with leaves above the surface, or a plant floating on the water surface
12. permanently or almost permanently submerged aquatic plant

R - Reaction (scale 1-9):
1. indicator of strong acidity, never occurring in slightly acidic to alkaline conditions
2. between 1 and 3
3. acidity indicator, occurring mainly in acidic conditions, exceptionally in neutral conditions
4. between 3 and 5
5. indicator of moderate acidity, occurring rarely in strongly acidic as well as in neutral to alkaline conditions
6. between 5 and 7
7. indicator of slightly acidic to slightly basic conditions, never occurring in very acidic conditions
8. between 7 and 9, occurring mostly in calcium-rich conditions
9. base and lime indicator, always occurring in calcium-rich conditions

N - Nutrients (scale 1-9):
1. occurring at nutrient-poorest sites
2. between 1 and 3
3. occurring at nutrient-poor sites more frequently than at average sites and exceptionally at rich sites
4. between 3 and 5
5. occurring at moderately nutrient-rich sites and less frequently at poor and rich sites
6. between 5 and 7
7. occurring at nutrient-rich sites more often than at average sites and only exceptionally at poor sites
8. pronounced nutrient indicator
9. concentrated at very nutrient-rich sites

S - Salinity (scale 0-9):
0. not salt tolerant, glycophyte
1. salt tolerant, mostly on low-salt to salt-free soils, but occasionally on slightly salty soils
2. oligohaline, often on soils with very low salt content
3. mesohaline, mostly on soils with low salt content
4. mesohaline, mostly on soils with low to moderate salt content
5. mesohaline, mostly on soils with a moderate salt content
6. meso/polyhaline on soils with moderate to high salt content
7. polyhaline on soils with a high salt content
8. euhaline on soils with a very high salt content
9. euhaline to hypersaline, on soils with a very high and in dry periods extremely high salt content

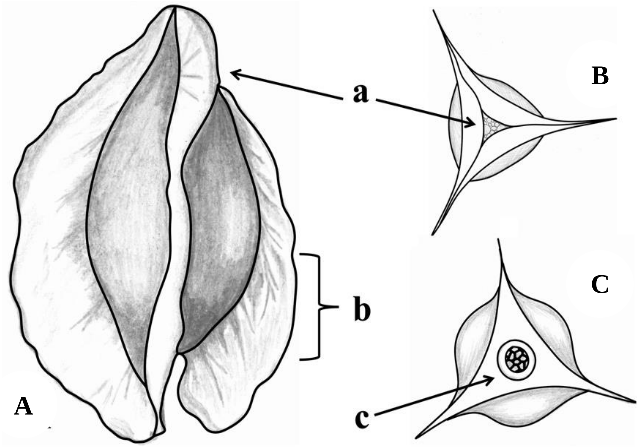

Figure 2. Scheme of the structure of the *Rheum* seeds: A: General view, B: Top view, C: Bottom view; a: Micropyle, b: Chalazal end, c: Seed scar

The description of the seed shape was carried out according to the generally accepted method of Martin (1946). Particular attention was paid to parts of the seed, such as the micropyle, chalazal end, and seed scar (Figure 2).

Morphometric measurements were made with an MK-25 micrometer in 20 repetitions for each parameter. The ecological conditions of the locations of the studied populations were assessed using the Elenberg ecological scales (Tichý et al. 2023). Determination of the levels of ecological scales was carried out directly on the spot in their specific natural habitats. The seed color palette is based on the MacAdam color chart (1974). The nomenclature of species is indicated according to POWO (2023), and the taxonomy of the genus and sectional division are indicated according to the fundamental works of Lozina-Lozinskaya (1936) and Li (1998).

Data for Principal Component Analysis (PCA), correlation analysis, ANOVA, and construction of a dendrogram of population similarity (cluster analysis) were processed using the R-studio program (version 1.3.1093).

Kazakhstan, as a study area, is characterized by the high amplitude of various environmental conditions: from the Caspian Sea in the west to the alpine meadows of the Altai Mountains in the east, from the forests of Siberia in the north to the deserted slopes of the Tien Shan in the south. As a result of expeditionary surveys, seeds of 7 *Rheum* species known in Kazakhstan were collected. Fifty-eight populations were recorded (Table 1) in different ecological and phytocenotic conditions.

RESULTS AND DISCUSSION

The uniqueness of the growing conditions of various *Rheum* species populations significantly affects seeds' morphological and metric characteristics. Considering the diversity of optimal climatic conditions for growing in Kazakhstan is important. Species grow in 10 administrative areas, from arid deserts to alpine meadows. The soil substrate and altitudinal zoning also have a great influence. Most populations of the studied species are concentrated in the east and southeast of the country and are almost absent in the north.

The study of the morphological features of seeds of 7 species of the genus *Rheum* L. revealed the interpopulation heterogeneity of seed material inherent in each species (Figure 3).

An important aspect of the study was to examine the seeds' morphometry according to 4 metric features: length, width, thickness, and weight of 1000 seeds (Table 2).

The analyses resulted in the description of the external structure in 7 species of the genus *Rheum* L. The main morphological parameters characterizing the external features of rhubarb seeds for practical use in clarifying the systematic relationships of this genus and determining species are summarized in Table 3.

Principal Component Analysis (PCA) of *Rheum* specimens (Figure 4) confirmed the quality of the sample and showed the differences and similarities of all samples of the studied species. Significant isolation of specimens of the section *Ribesiformia* (*R. cordatum* and *R. maximowiczii*) along coordinate 1 from other individuals was revealed. The samples of *R. altaicum* and *R. compactum* individuals were distributed diffusely in one group, confirming the close relationship between these species and belonging to the same section of *Rheum.*

Principal Component Analysis (PCA) by species difference (Figure 5) showed similarities and differences in populations within each species. A clear isolation of *R. cordatum* and *R. maximowiczii* populations from other species was revealed. *R. altaicum* and *R. compactum* populations do not have elliptical intersections, which is an important feature in separating these species. PCA shows that *R. nanum* and *R. compactum* have an elliptical intersection; *R. altaicum* and *R nanum* also have intersections.

Analysis of ranking by external similarity, presented in the cluster dendrogram (Figure 6), graphically showed significant patterns in the structural arrangement of the studied species. South Kazakhstan species from the *Ribesiformia section* (*R. cordatum* and *R. maximowiczii*) are isolated and form a separate cluster 1. East Kazakhstan species (*R. altaicum, R. compactum,* and *R. nanum*) form a separate cluster 3.

Correlation analysis of the dependence of the metric characteristics of seeds on the environmental conditions (Figure 7) showed a low, stable direct correlation between the weight of 1,000 seeds and temperature, which is explained by the full maturity of the seeds at high temperatures. A weak inverse correlation was established between seed thickness and illumination. Perhaps the limiting effect of light is more evident for mountain species, for which excessive lighting is harmful and leads to poor seed quality.

ANOVA analysis of variance (Table 4) revealed a significant influence of some environmental factors on the morphometric characteristics of seeds of the genus *Rheum*. Environmental factors were significantly influenced by temperature and reactions to the length, width, and weight of 1,000 seeds. All environmental factors significantly affect the seed length, except light and humidity.

Table 2. Linear and weight characteristics of seeds of *Rheum* populations (Pop) from different habitats

Pop	Length, mm			Width, mm			Thickness, mm			Weight of 1,000 seeds (g)
	M±m Min-Max*	C%	P%	M±m Min-Max	C%	P%	M±m Min-Max	C%	P%	
Rheum altaicum Losinsk.										
Pop 1	8.105±0.289 7.0-8.9	7.632	1.707	6.645±0.188 6.3-7.3	6.049	1.353	1.895±0.317 0.9-3.0	35.810	8.007	7.85
Pop 2	8.330±0.259 7.3-9.5	6.645	1.486	7.020±0.187 6.0-7.8	5.691	1.272	1.970±0.217 1.2-2.4	23.528	5.261	7.91
Pop 3	7.745±0.169 7.0-8.0	4.674	1.045	5.730±0.196 5.0-6.6	7.319	1.637	3.470±0.256 2.4-4.4	15.815	3.536	8.78
Pop 4	7.910±0.252 7.1-9.0	6.825	1.526	6.115±0.253 4.9-6.6	8.851	1.979	3.720±0.310 3.0-5.6	17.823	3.985	8.6
Pop 5	7.255±0.205 6.4-8.2	6.041	1.351	5.510±0.263 4.7-6.4	10.214	2.284	3.570±0.259 2.4-4.2	15.559	3.479	8.81
Pop 6	6.895±0.162 6.2-7.4	5.035	1.128	4.870±0.195 4.0-5.5	8.560	1.914	3.630±0.165 3.0-4.3	9.713	2.172	8.76
Pop 7	7.420±0.166 7.0-8.0	4.782	1.069	5.005±0.254 4.0-6.7	10.856	2.428	3.815±0.221 2.9-4.7	12.391	2.771	8.72
Pop 8	7.245±0.296 6.6-8.9	8.735	1.953	5.510±0.337 4.7-7.7	13.073	2.923	1.935±0.186 1.3-2.5	20.554	4.596	7.91
Pop 9	7.505±0.151 6.9-8.0	4.312	0.964	6.435±0.221 5.8-7.0	7.363	1.646	2.200+0.128 1.5-2.6	12.426	2.779	7.82
Pop 10	8.000±0.287 6.4-8.9	0.614	1.716	6.130±0.268 5.0-7.4	9.365	2.094	3.390±0.360 2.4-5.8	22.727	5.082	8.6
Pop 11	7.675±0.208 6.8-9.6	5.809	1.299	5.985±0.224 5.0-6.8	7.917	1.770	3.240±0.209 2.8-4.7	13.781	3.082	7.75
Rheum compactum L.										
Pop 1	7.310±0.349 6.5-9.4	10.236	2.290	5.835±0.361 5.0-8.0	13.232	2.959	1.190±0.098 0.9-1.7	17.648	3.946	12.91
Pop 2	7.320±0.180 6.4-8.0	5.256	1.175	5.535±0.154 4.8-6.0	5.973	1.336	0.965±0.079 0.7-1.4	17.559	3.926	11.98
Pop 3	8.070±0.313 7.3-10.0	8.309	1.858	6.270±0.272 5.4-7.8	9.258	2.070	3.870±0.287 2.8-5.0	15.842	3.542	12.96
Pop 4	6.790±0.124 6.4-7.4	3.908	0.874	5.490±0.148 5.0-6.1	5.784	1.294	1.780±0.166 1.3-2.5	19.934	4.457	11.93
Pop 5	8.900±0.295 8.0-10.2	7.097	1.587	6.895±0.336 6.0-8.1	10.421	2.330	4.110±0.243 3.4-5.2	12.702	2.840	12.34
Rheum wittrockii Lundstr.										
Pop 1	8.395±0.258 7.0-9.0	6.564	1.468	7.250±0.269 6.2-8.0	7.949	1.777	2.425±0.186 1.8-3.1	16.379	3.662	18.66
Pop 2	8.825±0.565 8.2-10.2	13.701	3.064	8.780±0.344 7.8-10.0	8.391	1.876	1.065±0.172 0.7-2.1	34.503	7.715	16.25
Pop 3	9.320±0.236 8.7-10.2	5.411	1.209	7.270±0.337 6.0-8.5	9.909	2.216	2.300±0.290 1.2-3.6	27.024	6.043	19.54
Pop 4	8.625±0.308 7.0-9.8	7.634	1.707	7.415±0.277 5.7-8.3	7.988	1.786	0.975±0.030 0.8-1.0	6.550	1.465	17.78
Pop 5	9.065±0.286 8.0-10.0	6.756	1.511	8.010±0.450 7.2-10.3	12.035	2.691	6.330±0.437 5.0-7.8	14.776	3.304	18.42
Pop 6	10.595±0.422 9.3-13.0	8.527	1.907	9.160±0.413 8.3-12.0	9.644	2.157	7.595±0.280 6.4-8.5	7.882	1.763	19.65
Pop 7	9.480±0.257 8.7-11.0	5.804	1.298	8.080±0.381 7.0-10.2	10.091	2.256	3.641±0.491 3.0-5.3	28.876	6.457	17.87
Pop 8	11.400±0.260 10.6-12.0	4.879	1.091	10.030±0.375 8.3-11.1	7.996	1.788	8.000±0.348 7.0-9.2	9.319	2.084	18.68
Pop 9	9.295±0.265 8.2-10.1	6.091	1.362	8.015±0.386 7.2-9.8	10.307	2.305	6.790±0.312 6.1-7.8	9.826	2.197	18.32
Pop 10	9.630±0.274 8.4-11.1	6.084	1.360	8.200±0.339 7.5-9.6	8.838	1.976	5.995±0.318 4.4-7.0	11.358	2.540	17.98
Pop 11	8.965±0.283 8.2-10.5	6.764	1.512	6.910±0.317 5.8-8.7	9.803	2.192	5.865±0.364 5.0-8.0	13.268	2.967	18.04
Pop 12	8.950±0.242 8.0-10.2	5.783	1.293	7.490±0.257 7.0-8.7	7.337	1.641	6.785±0.292 5.5-7.7	9.201	2.057	18.32

Rheum nanum Siev.										
Pop 1	8.008±0.241 7.1-8.6	5.186	1.438	6.346±0.405 5.0-7.1	11.023	3.057	2.661±0.269 1.7-3.3	17.458	4.842	8.11
Pop 2	9.290±0.477 8.5-12.8	10.982	2.456	6.165±0.468 5.3-10.0	16.240	3.613	1.350±0.267 0.7-2.6	42.279	6.454	8.65
Pop 3	9.860±0.246 9.0-11.0	5.330	1.192	6.395±0.341 5.5-8.0	11.395	2.548	5.590±0.281 4.5-7.1	10.748	2.403	8.92
Pop 4	10.270±0.232 9.4-11.5	4.834	1.081	10.480±0.300 9.4-11.8	6.134	1.372	2.385±0.170 2.0-3.3	15.286	3.418	10.23
Rheum tataricum L. fil.										
Pop 1	7.515±0.236 7.1-8.7	6.720	1.503	5.630±0.264 5.0-6.4	10.016	2.239	1.345±0.173 0.8-2.0	27.554	6.161	16.93
Pop 2	8.865±0.393 7.0-10.3	9.475	2.119	6.760±0.287 5.8-7.8	9.086	2.032	2.105±0.244 1.2-1.2	24.828	5.552	18.25
Pop 3	10.749±0.583 8.3-12.5	11.599	2.594	9.315±0.674 6.4-11.0	15.483	3.462	1.925±0.210 1.2-2.6	23.407	5.233	20.54
Pop 4	11.500±0.210 10.7-12.2	3.909	0.874	7.980±0.349 7.2-9.1	9.356	2.092	3.350±0.138 2.8-3.8	8.797	1.967	21.04
Pop 5	8.190±0.384 6.8-9.6	10.029	2.243	5.520±0.240 4.9-6.6	9.286	2.076	3.540±0.317 2.6-5.1	19.168	4.286	22.13
Pop 6	9.175±0.256 8.1-10.0	5.979	1.337	6.645±0.324 6.3-7.6	10.420	2.330	5.055±0.271 3.6-6.0	11.489	2.569	21.66
Pop 7	10.430±0.358 9.0-11.4	7.349	1.643	7.360±0.325 6.0-9.0	9.459	2.115	6.050±0.317 5.0-7.7	13.097	2.929	20.32
Pop 8	9.870±0.286 8.7-11.3	6.194	1.385	6.495±0.271 5.5-7.2	8.928	1.996	5.720±0.225 5.3-7.0	8.405	1.879	19.89
Pop 9	10.235±0.514 9.0-12.7	10.737	2.401	7.485±0.317 6.0-8.0	9.074	2.029	6.265±0.397 3.9-7.0	13.557	3.031	20.43
Pop 10	11.020±0.218 10.2-11.7	4.242	1.949	7.225±0.241 6.3-8.1	7.141	1.597	6.055±0.191 5.4-6.7	6.745	1.508	20.41
Pop 11	9.865±0.286 9.0-10.6	6.199	1.386	7.110±0.233 6.2-8.0	7.024	1.570	4.905±0.326 4.0-6.0	14.209	3.177	21.22
Pop 12	10.875±0.432 9.8-12.6	8.501	1.901	7.450±0.356 6.5-9.0	10.227	2.287	5.650±0.349 4.0-6.2	13.226	2.957	22.36
Pop 13	11.800±0.478 10.0-12.7	8.669	1.938	8.050±0.345 7.0-9.5	9.168	2.050	6.380±0.290 5.8-7.4	9.710	2.171	21.16
Rheum cordatum Losinsk.										
Pop 1	12.045±0.713 10.2-14.6	12.664	2.832	9.435±0.601 7.4-12.0	13.631	3.048	2.605±0.298 1.3-3.6	24.485	5.475	25.18
Pop 2	10.795±0.298 9.7-12.0	5.901	1.319	8.250±0.468 7.3-9.3	12.149	2.717	4.165±0.406 2.4-5.3	20.848	4.662	24.65
Pop 3	13.995±0.389 12.6-15.6	5.962	1.333	10.050±0.483 8.6-12.6	10.293	2.301	8.945±0.276 8.0-10.0	6.614	1.479	28.87
Pop 4	11.275±0.416 10.2-13.0	7.901	1.767	10.290±0.537 8.5-12.5	11.160	2.496	8.560±0.317 7.4-10.0	7.936	1.775	25.65
Pop 5	13.020±0.387 12.0-14.6	6.366	1.423	9.880±0.554 8.4-13.0	12.010	2.686	8.500±0.257 8.0-10.0	6.477	1.448	29.44
Pop 6	12.775±0.430 11.4-14.6	7.201	1.610	9.125±0.309 8.0-10.0	7.259	1.623	2.995±0.432 2.0-4.3	30.897	6.909	26.56
Rheum maximowiczii Losinsk.										
Pop 1	16.013±0.701 13.8-18.8	8.193	2.115	14.087±0.890 11.2-15.5	11.714	3.024	4.953±0.497 4.1-7.0	18.579	4.797	32.64
Pop 2	12.060±0.542 9.5-14.0	9.611	2.149	10.260±0.597 8.0-12.8	12.443	2.782	1.790±0.277 1.2-3.2	33.120	7.406	27.14
Pop 3	15.295±0.494 14.0-16.7	6.905	1.544	14.265±0.706 12.8-17.0	10.588	2.368	2.045±0.493 1.8-5.3	34.632	7.744	30.27
Pop 4	15.770±0.466 14.0-16.9	6.331	1.416	13.785±0.487 11.0-15.1	7.569	1.695	4.245±0.358 2.8-6.0	18.061	4.039	31.74
Pop 5	14.215±0.463 12.6-16.9	6.965	1.557	11.235±0.441 10.0-13.6	8.391	1.876	3.730±0.447 2.0-5.2	25.628	5.731	28.25
Pop 6	17.060±0.804 13.0-19.2	10.080	2.254	14.185±0.706 12.0-16.7	10.643	2.379	4.590±0.307 3.5-5.8	14.328	3.204	34.84
Pop 7	13.725±0.463 12.5-15.1	7.215	1.614	10.464±0.248 9.5-11.5	5.068	1.133	9.475±0.222 8.3-10.0	5.019	1.122	29.06

Note: *M: The average value of the metric feature, m: Allowable limits, min-max: Minimum and maximum feature values, C%: Coefficient of variation of a feature, P%: The relative error of the sample mean (accuracy of the experiment)

Table 3. Indicators of morphological traits of *Rheum* seeds in Kazakhstan

Morphological features of seeds	Species name						
	R. altaicum	***R. compactum***	***R. wittrockii***	***R. nanum***	***R. tataricum***	***R. cordatum***	***R. maximowiczii***
Size, shape	Medium (*mediocre**), trihedral (*triangulare*), straight (*rectum*)	Medium (*mediocre*), trihedral (*triangulare*), flattened in one plane (*planum*), straight (*rectum*)	Medium (*mediocre*), trihedral (*triangulare*), straight (*rectum*)	Medium (*mediocre*), trihedral (*triangulare*), straight (*rectum*)	Medium (*mediocre*), trihedral (*triangulare*), straight (*rectum*)	Large (*magnum*), trihedral (*triangulare*), straight (*rectum*)	Large (*magnum*), trihedral (*triangulare*), straight (*rectum*)
Length, mm	7.6±0.2	8.5±0.2	9.5±0.2	9.5±0.2	9.8±0.2	12.5±0.2	15.2±0.2
Width, mm	5.7±0.2	6.2±0.2	8.0±0.2	7.0±0.2	7.3±0.2	9.5±0.2	12.2±0.2
Thickness, mm	2.5±0.1	3.0±0.1	5.5±0.2	2.9±0.1	4.8±0.2	7.6±0.2	4.5±0.2
Average weight of 1000 seeds, g.	7.9	12.2	18.1	8.5	21.0	25.5	31.3
Seed colors (*color seminis*)	Brown color (*brunneum*), yellowish brown wings (*lateolo-brunneum*), glossy (*nitidum*)	Brown color (*brunneum*), yellowish brown wings (*lateolo-brunneum*), glossy (*nitidum*)	Brown color (*brunneum*), plain yellow wings (*luteum*), glossy (*nitidum*)	dark brown color (*atrobrunneum*), reddish brown wings (*rubeolo-brunneum*), matte (*opacum*)	light brown color (*dilute brunneum*), yellowish brown wings (*lateolo-brunneum*), matte (*opacum*)	reddish brown color (*rubeolo-brunneum*), orange-brown wings (*aurantiaco-brunneum*), matte (*opacum*)	Brown color (*brunneum*), orange-brown wings (*aurantiaco-brunneum*), glossy (*nitidum*)
Seed shape	trihedral (*triangulare*), ovoid shape (*ovoideum*), with narrow curved wings	trihedral (*triangulare*), ellipsoidal shape (*ellipsoideum*), with strongly curved wings	trihedral (*triangulare*), ovoid (*ovoideum*), with well-developed wings	trihedral (*triangulare*), oblong-ovoid shape (*oblongo-ovoideum*), with curved wings	trihedral (*triangulare*), ovoid (*ovoideum*), with curved wings	trihedral (*triangulare*), heart shape (*medullare*), with curved wings	trihedral (*triangulare*), heart shape (*medullare*), with curved wings
The surface of the seed (*spermoderma*)	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), rough (*scabrum*), without pubescence (*glabrum*). Wings are smooth (*leve*), with longitudinal vein	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), transversely wrinkled (*transverse-rugosum*). Wings are smooth (*leve*), membranous (*paleaceum*) with longitudinal vein	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), transversely wrinkled (*transverse-rugosum*). Wings are smooth (*leve*), membranous (*paleaceum*), with dark longitudinal vein	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), longitudinally striated (*longitudinaliter-sulcatum*). Wings are smooth (*leve*), membranous (*paleaceum*)	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), longitudinally wrinkled (*longitudinaliter-rugosum*). Wings are smooth (*leve*), membranous (*paleaceum*)	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), longitudinally wrinkled (*longitudinaliter-rugosum*). Wings are smooth (*leve*), longitudinally striated (*longitudinaliter-sulcatum*)	Thin (*tenue*), dry (*siccum*), leathery (*coriaceum*), longitudinally wrinkled (*longitudinaliter-rugosum*). Wings are smooth (*leve*), membranous (*paleaceum*)
Micropyle condition (*micropyle*)	overgrown (*obductum*), faintly distinguishable (*parum discernendum*), depressed (*impressum*), round shape (*orbiculare*).	overgrown (*obductum*), well distinguishable (*bene discernendum*), protrusive (*exsertum*), round shape (*orbiculare*)	overgrown (*obductum*), well distinguishable (*bene discernendum*), protrusive (*exsertum*), oblong shape (*oblongum*), much darker than testa	overgrown (*obductum*), faintly distinguishable (*parum discernendum*), depressed (*impressum*), round shape (*orbiculare*)	overgrown (*obductum*), faintly distinguishable (*parum discernendum*), a little protrusive (*exsertum*), point shape (*punctatum*)	overgrown (*obductum*), faintly distinguishable (*parum discernendum*), a little protrusive (*exsertum*), point shape (*punctatum*)	overgrown (*obductum*), faintly distinguishable (*parum discernendum*), a little protrusive (*exsertum*), round shape (*orbiculare*)
Features of the chalazal end	slightly thickened (*margine incrassatum*), smooth (*leve*)	Noticeably thickened (*margine incrassatum*), wrinkly (*rugosum*)	slightly thickened (*margine incrassatum*), smooth (*leve*)	Noticeably thickened (*margine incrassatum*), wrinkly (*rugosum*)	slightly thickened (*margine incrassatum*), wrinkly (*rugosum*)	sharply tapering (*angustatum*), wrinkly (*rugosum*)	slightly thickened (*margine incrassatum*), wrinkly (*rugosum*)
Type and shape of the seed scar (*hilum*)	Small (*parvum*), protrusive (*exsertum*), round shape (*orbiculare*), basal (*basales*)	Small (*parvum*), depressed (*impressum*), triangular (*triangulare*), basal (*basales*)	Point (*punctatum*), depressed (*impressum*), basal (*basales*)	Small (*parvum*), protrusive (*exsertum*), round shape (*orbiculare*), basal (*basales*)	Small (*parvum*), rimmed (*valliculo cinctum*), round shape (*orbiculare*), basal (*basales*)	Small (*parvum*), в protrusive (*exsertum*), round shape (*orbiculare*), basal (*basales*)	Small (*parvum*), protrusive (*exsertum*), triangular (*triangulare*), basal (*basales*)

Note: *Terms in brackets are in Latin

Table 4. Results of analysis of variance ANOVA

Factor/Trait	L	T	M	R	N	S	Species
Length	ns	***	ns	***	**	*	***
Width	ns	**	ns	***	*	ns	***
thickness	*	ns	ns	ns	ns	ns	*
Weight of 1000 seeds	ns	**	ns	***	**	*	***

Note: ns: not significant, *: P<0.05, **: P<0.01, ***: P<0.001

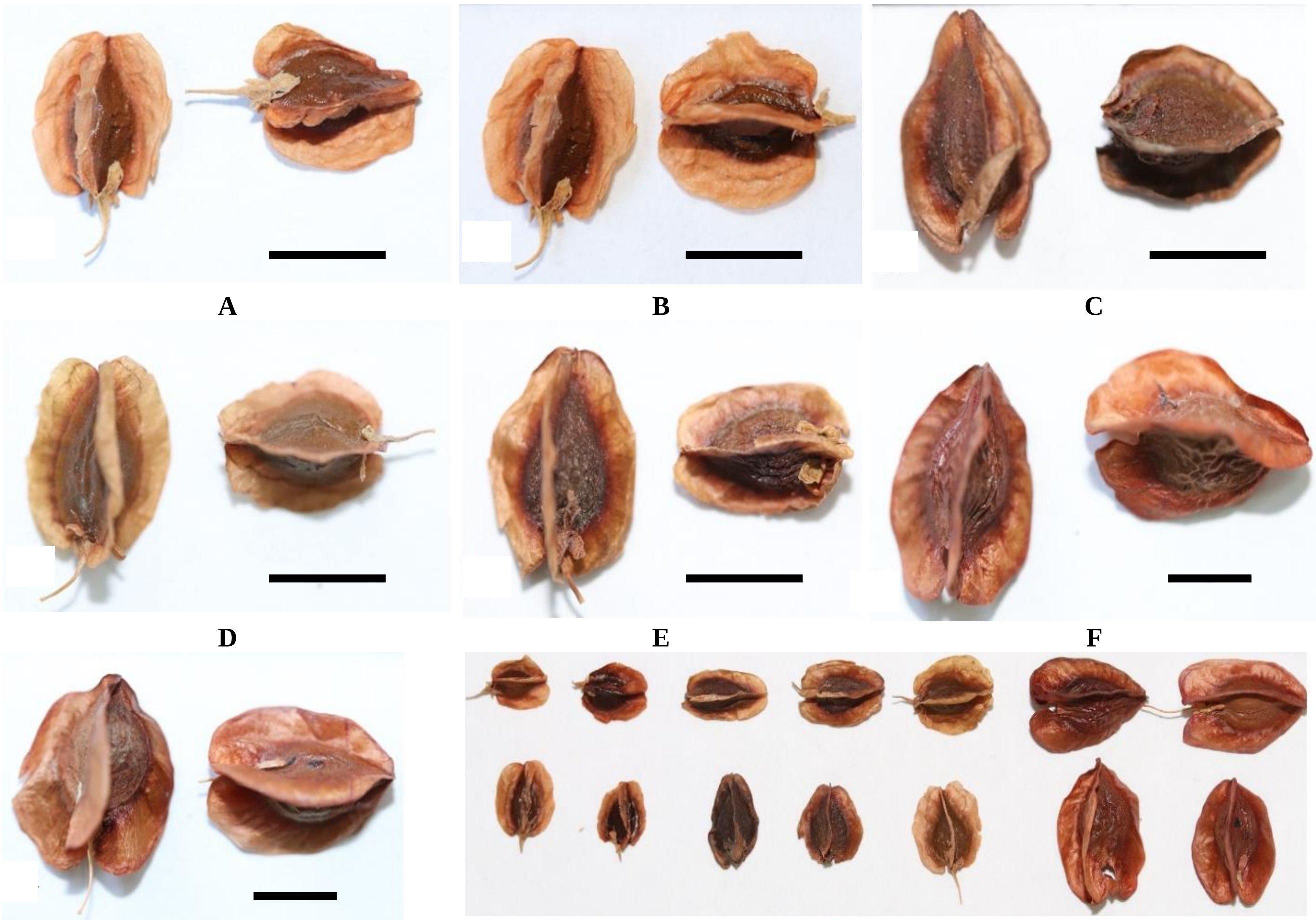

Figure 3. Morphology of seeds of the genus *Rheum* L. from Kazakhstan. A. *R. altaicum*, B. *R. compactum*, C. *R. nanum*, D. *R. wittrockii*, E. *R. tataricum*, F. *R. cordatum*, G. *R. Maximowiczii*. Bar = 5 mm

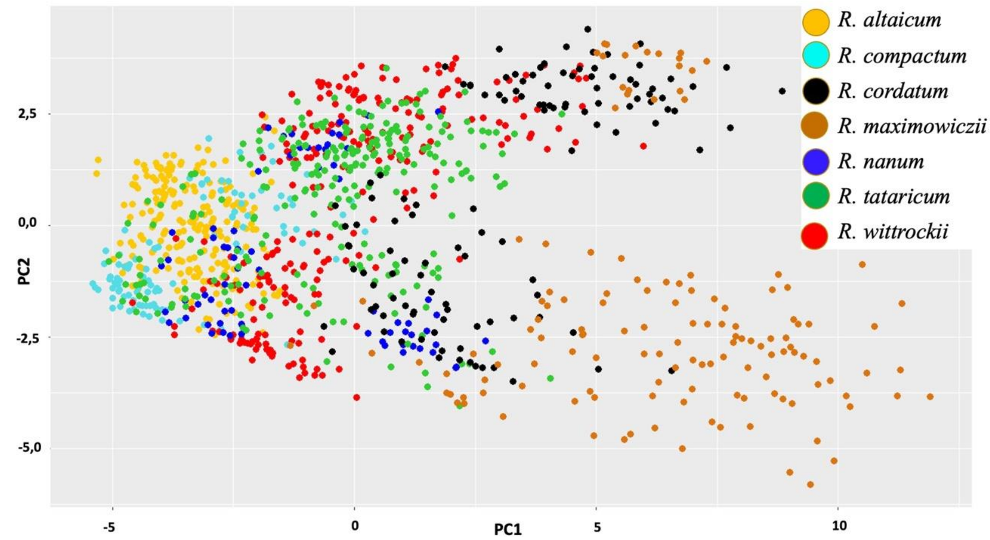

Figure 4. Principal Component Analysis (PCA) of individuals of the genus *Rheum* L. from Kazakhstan

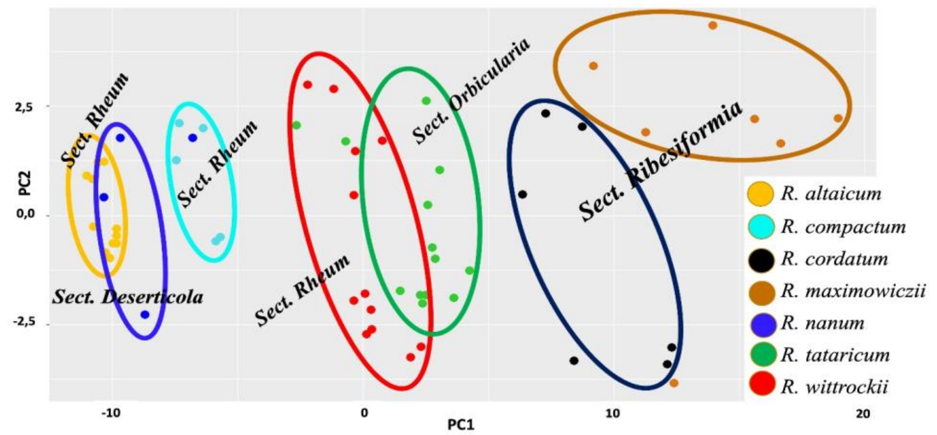

Figure 5. Principal Component Analysis (PCA) for populations of *Rheum* species from Kazakhstan

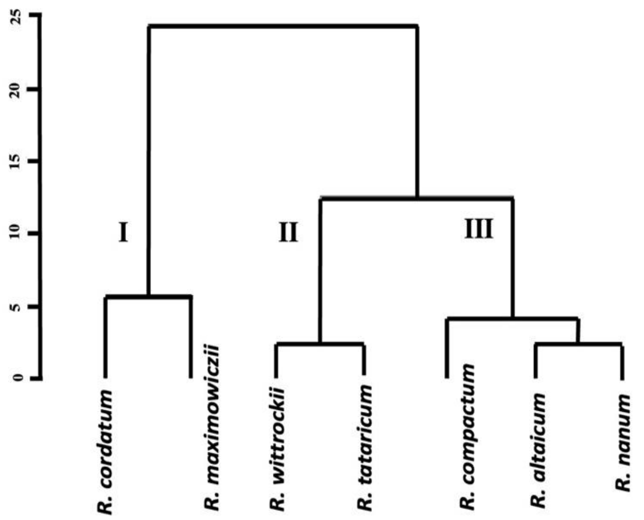

Figure 6. Cluster analysis of the similarity of species of the genus *Rheum* L. according to external morphometric features

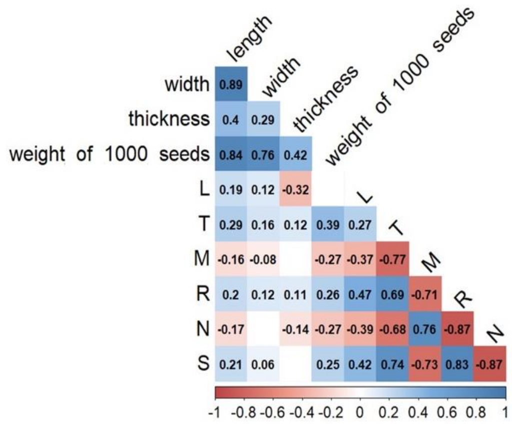

Figure 7. Correlation between the morphometric characteristics of seeds of the genus *Rheum* and the conditions of the external ecological environment. Correlations with the significance of $P<0.05$ are highlighted in color. The red color corresponds to a negative correlation, and the blue color corresponds to a positive correlation. The colors' intensity demonstrates the correlation's strength on a given scale

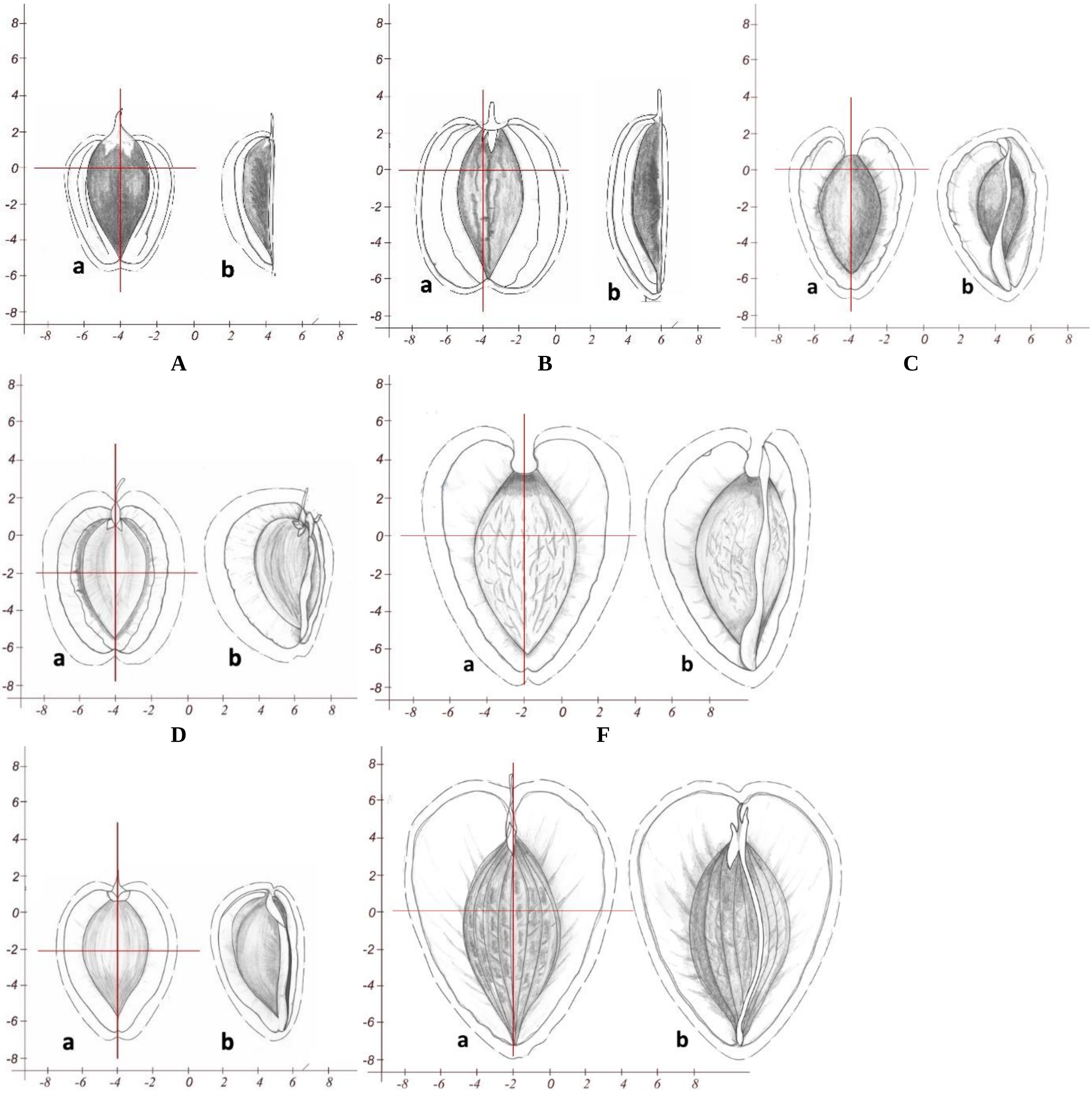

Figure 8. Schemes of seed structure based on average metric indicators of traits (mm): A. *R. altaicum*, B. *R. compactum*, C. *R. nanum*, D. *R. wittrockii*, E. *R. tataricum*, G. *R. cordatum*, F. *R. Maximowiczii*. a. Front view, b. Side view, a broken line indicates maximum dimensions

As a result of the data obtained, schemes of the standard external structure of seeds of *Rheum* species from Kazakhstan were compiled (Figure 8).

Discussion

Distinctive morphometric characteristics of seeds can serve as additional qualitative features in determining the species. Comparison of traits in a population and identification of groups of similar populations makes it possible to more accurately determine the boundaries and rank in complex taxonomic groups of plants.

Morphological studies of the genus *Rheum* are actively carried out in neighboring countries. Previously, Paul and Chowdhury (2020) have already conducted a study on pollen morphometry of 28 species from the family Polygonaceae from India. Yang et al. (2001) studied the pollen morphology of 40 rhubarb species from China. Xu-Mei Wang et al. (2014) performed leaf section morphometry for 5 species of the genus *Rheum.* Hu et al. (2022) studied the morphology of the structure and leaf surface of *Rheum tanguticum* in China. Song et al. (2013) studied the morphology of multifunctional bracts in *Rheum* *nobile*. Zhao et al. (2008) studied flower morphometry for *Rheum rhaponticum.*

The development and morphology of seeds in *Rheum* are of particular interest (Song et al. 2013a). Kong et al. (2018) examined seed morphology in 45 taxa of the family Polygonaceae in Korea. Sharma and Sharma (2017) studied the longevity and germination of rhubarb seeds in India. When studying 58 populations of 7 species of the genus *Rheum* from Kazakhstan, we analyzed the morphometric characteristics of seeds using 4 metric characters. The collection of material from the country's entire territory and in all typical habitats ensures the quality of the sample specimens. Thus, the results of this study harmoniously complement the fundamental study on the morphology of *Rheum* species throughout the genus distribution range.

The seed width of all rhubarb species in Kazakhstan varies more than the length, which is consistent with generally accepted statements of seed morphology (Suthar and Das 1996). The linear sizes of the seeds of the studied species are characterized by insignificant and single-average variability, which indicates a moderate qualitative heterogeneity of seeds, as well as a low adaptive potential of the studied plants, which indicates a narrow ecological amplitude of *R. altaicum*, *R. compactum*, *R. wittrockii*, *R. nanum*, *R. tataricum*, *R. cordatum,* and *R. maximowiczii* in the flora of Kazakhstan.

Seeds of rhubarb species growing in Kazakhstan are of medium or large size, always triangular, ovoid, oblong-ovoid, or heart-shaped. Seeds have a thin, dry, leathery surface. Smooth membranous wings are usually significantly curved. The micropyle is always overgrown, poorly distinguishable, round, or dotted. In most species, the chalazal end is slightly thickened, smooth, or wrinkled. The seed scar is usually small, always basal.

Related species from the section *Rheum*: *R. altaicum* and *R. compactum* noticeably differ only in the weight of the seeds, which may, in part, reflect slight differences in their size. Both taxa are separate species in regional floras and distinguished by leaf shape, which is orbicular in *R. compactum* and ovate-triangular in *R. altaicum* (Flora of the USSR 1934), or by seed size, which is larger (9-12 x 7-11 mm) in *R. compactum* than *R. altaicum* (5.5-8 x 4.5-7 mm) (Bojian and Grabovskaya-Borodina 2003). However, probably due to these small differences, Tupitsyna (2012) treated these species as conspecific. More research is needed to confirm whether these are taxonomically distinct entities. An attempt to distinguish taxa at the molecular level is worth considering. Zhang et al. (2022) have identified five genes with high nucleotide diversity and potential in either species delimitation or for use as molecular markers in phylogeny.

Principal Component Analysis (PCA) for populations and individuals of Rheum species showed close similarity between populations belonging to the sections *Rheum* and *Deserticola* and between *Rheum* and *Orbicularia.* The species belonging to the section *Ribesiformia* are clearly separated and form a separate cluster, which shows the possibility of using seed morphometry in determining the species of this section.

Additional attention was paid to the relationship between ecological growing conditions and external structure as important factors in seed morphometry in the study area. Cluster analysis data (Figure 5) show the influence of geography and environmental conditions on the morphometry of the studied species. Thus, species from southern Kazakhstan and eastern Kazakhstan formed separate clusters despite belonging to different sections. The morphometric parameters of seeds within Kazakhstan, in addition to the generally accepted sectional division, may also be affected by the growing area's environmental and climatic conditions.

In addition, the correlation analysis showed a low, stable relationship between the metric parameters of seeds and some environmental conditions, such as temperature. Unusually, no significant association was found between seed size and vital conditions such as soil moisture and richness. ANOVA analysis of variance showed a significant influence of factors such as temperature and pH reaction on rhubarb seeds' linear and weight parameters. At the same time, the absence of the influence of factors such as illumination and humidity confirms the correlation analysis data.

Unfortunately, not all of the taxa studied have been sampled in phylogenetic studies, so we do not know the full picture of affinities between species (Wang et al. 2005; Sun et al. 2012; Li and Wang 2020; Zhang et al. 2022), especially section *Ribesiformia*. On the other hand, relationships between *R. altaicum* and *R. compactum* are unresolved, and *R. wittrockii* is the sister to *R. nanum* (Sun et al. 2012). All four taxa seem closely related; however, in our seed analysis, *R. wittrockii* forms clusters with distantly related *R. tataricum.* Therefore, the similarity of seeds of *Rheum* species results more from similar ecological conditions and occurrence than phylogenetic relationships, which is confirmed by the clustering of species with similar distribution ranges in Kazakhstan.

In conclusion, as a result of the work performed, the morphobiological characteristics of the seeds of 7 species of the genus *Rheum* L. from the natural flora of Kazakhstan were given, which expands the understanding of the external structure of the seeds of *R. altaicum*, *R. compactum*, *R. wittrockii*, *R. nanum*, *R. tataricum*, *R. cordatum,* and *R. maximowiczii*. A significant influence of the environmental conditions of the place of growth and the region has been established. The obtained data on the morphometry of the structure of seeds can serve as an important additional feature in the taxonomy of the genus *Rheum* L. in Kazakhstan. Species of the section *Ribesiformia* have a group of stable distinguishing features that can be used in defining the species of this section. The two species in this section, *R. cordatum* and *R. maximowiczii*, have much larger seeds and differ considerably in weight. The study of seeds of related species *R. altaicum* and *R. compactum* did not reveal characteristic stable features in morphometry, and these species differ markedly only in seed weight.

Environmental conditions have a major impact on the characteristics of the seeds, which, however, are stable within the species. However, because of this, seed similarity will not necessarily reflect phylogenetic relationships between species of the genus *Rheum*. The metric sizes of the seeds indicate a low adaptive potential to changes in environmental conditions, and, despite the vast area, they showed a narrow ecological amplitude of these species. These studies further confirm the importance of preserving the main ranges of species of the *Rheum*. Comparative morphological studies of rhubarb seeds make it possible to additionally identify a group of characters that can be used in developing identification parameters and to clarify the taxonomic affiliation of selected rhubarb species in Kazakhstan. The results can be practically applied in the ex-situ conservation of these species, particularly in botanical introduced collections.

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