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Physiological and Morphological Criteria for the Selection of Common Bean (Phaseolus Vulgaris L.) Genotypes in Breeding for High Productivity in Kazakhstan

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PHYSIOLOGICAL AND MORPHOLOGICAL CRITERIA FOR THE SELECTION OF COMMON BEAN (PHASEOLUS VULGARIS L.) GENOTYPES IN BREEDING FOR HIGH PRODUCTIVITY IN KAZAKHSTAN

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Abstract. This study presents a comprehensive evaluation of the morphological and quality traits of over 100 accessions of common beans (Phaseolus vulgaris L.). The aim of this study is to assess the phenotypic diversity and breeding potential of these accessions. The analysis included measurements of seed width, longitudinal section shape, seed coat color, and protein content. The accessions were categorized into three groups based on seed size: small (<6 mm), medium (6–10 mm), and large (>10 mm). Additionally, nine seed coat color types were identified within the collection: white, beige, bordeaux, black, purple, green, gray, brown, and variegated. Four morphological seed shape categories were also distinguished: round, intermediate (from round to elliptical), elliptical, and kidney-shaped. The observed diversity indicates a broad genetic base, providing valuable material for hybridization and the development of new varieties adapted to the agroclimatic conditions of the Almaty region.

The protein content of the accessions ranged from 15.5 to 30.0%, allowing for the identification of low-, medium-, and high-protein groups, as well as promising donor accessions with elevated protein content. These results provide a scientific basis for further breeding selection of bean varieties with high nutritional value, improved marketability, and enhanced adaptation to the conditions of southern Kazakhstan.

Keywords: *common bean (Phaseolus vulgaris L.), germplasm collection, seed morphology, protein content, seed traits*

Introduction. Phaseolus spp. L are the oldest and most common grain legume crops and play a key role in human nutrition and agricultural systems. Based on ancient botanical evidence and modern botanical research, beans have been domesticated for thousands of years and the different species are rapidly evolving and adapting to different climatic and edaphic conditions (Azevedo et al. 2025). Phaseolus contains about 50 species, of which common bean (P. vulgaris L.), runner bean (P. coccineus L.), and lima bean (P. lunatus L.) are of greatest economic importance. Among them, common bean (P. vulgaris L.) is the most widely cultivated and consumed species and is thus the subject of the present study. These species have many morphological characteristics - plant structure, growth habit, stem height, and seed size and color are all the most diverse and their biochemical composition is one of those factors that determines their nutritional value and breeding ability. This diversity is the reason why they are a good basis for the production of high-quality, nutritional, and high-protein plants with good chemical composition (Frascarelli et al. 2025). Bean seeds are a great source of macro- and microelements. Their energy is largely determined by carbohydrates (50-60%), dietary fiber (10-25%), and proteins (20-28% protein), which will vary from one genotype to the other depending on the types of beans and growing conditions. Bean protein is rich in lysine, an essential amino acid that is often deficient in cereals (Kudaibergenov et al. 2024). Both biological characteristics are associated with the processes of assimilate accumulation and redistribution in plant growth and thus the seed quality (at least in common bean genotypes) is key. Seed shape and color are also important for breeding. There is high diversity in seed shape, size, and color in bean collections. Elliptical seeds and kidney-shaped, round, and intermediate seeds dominate the bean collections, but other types are also studied. Seed size is small to large, and this differs for industrial use and breeding value, and coloration ranges from white and cream to red, black, and mottled. These morphological and biochemical features are integrated to create a holistic picture of breeding value and technological suitability (Saikenova et al. 2021).

These qualities are physiologically related to source-sink relationships where assimilates produced in leaves are transported and stored in seeds. Beans also play an important agroecological role as they can fix atmospheric nitrogen by symbiosis with Rhizobium bacteria, which improves plant nitrogen nutrition and soil fertility, which, in turn, reduces the need for mineral fertilizers and can help sustain agroecosystems (Sarsenbekovich et al. 2025).

However, in common bean, the biological nitrogen fixation process is quite low and very variable, resulting in nitrogen metabolism as the main biological factor for low productivity and seed generation. Nitrogen availability directly affects basic physiological processes such as chlorophyll synthesis, leaf area growth, and photosynthesis. The adequate amount of nitrogen production allows the development of a well-developed leaf surface and thus enhances light interception and determines the plant's overall performance in photosynthesis. Here, leaf area is a structural basis for productivity, since its expansion increases the plant's ability to capture solar radiation and synthesize assimilates. As the leaf area increases, the production of assimilates increases in higher quality and hence more raw biomass is accumulated, which is indicative of the efficiency of growth and resource usage in general.

For instance, Sarsenbekovich et al. (2026) have shown that nitrogen fertilization significantly increases pod number, seed number per plant, and grain yield in common bean through better physiological performance. This relationship between leaf area and biomass is further explained by photosynthetic potential, which is the amount of leaf area in the growing process. So, photosynthetic potential is not only the size of the assimilating surface but also the function of the assimilating surface over time. Higher photosynthetic potential ensures a longer and stable supply of assimilates, which is essential for sustaining plant growth and supporting reproductive development.

Photosynthesis is a crucial component of nitrogen metabolism as it is at flowering and pod formation time when the demand for assimilates is highest . In this case, it is critical for assimilate partitioning to be efficient, because assimilates must be redistributed effectively from vegetative organs to developing seeds. Tobiasz-Salach, et al. (2022) reported large genotypic variation in nitrogen-use efficiency and assimilate redistribution and showed that efficient transport of nitrogen and carbon compounds to developing seeds is a critical factor for yield and protein content.

The environment also plays a role in this interconnected physiological system. In drought or at high temperature, light interception is inhibited under low leaf area and hence biomass accumulation and photosynthesis are inhibited. These changes undermine assimilate production and transport, and lead to a decrease in nitrogen assimilation and seed development. Zhumabaevna et al. (2025) showed that nitrogen metabolism is closely related to stress response mechanisms including antioxidant activity and osmotic adjustment to maintain physiological stability under adverse conditions.

Thus, seed formation in beans represents the outcome of a tightly integrated physiological system that includes nitrogen assimilation, photosynthesis, leaf area expansion, biomass accumulation, and assimilate redistribution. At the seed filling stage, carbon and nitrogen metabolism is associated with seed size, 1000-seed weight, and protein accumulation and therefore physiological efficiency is associated with agronomically important traits. Beans are the top producers of grain legumes globally and in terms of cultivated area and production volume. Most producers are in Latin America, Africa, and Asia (FAO, 2024). Beans have a global production of 45 million tons and consumption of beans is 8-10 kg per capita per year in some areas and beans are considered very important in food security (Abildaeva et al. 2025). This drives breeding programs to increase productivity and quality of seed.

Most recent breeding efforts are focused on providing high-yielding stress-resistant plants with favorable agronomic traits such as compact plant architecture and the optimal height of lower pod attachment for mechanized harvesting. Selection parameters for seed quality are very important as they directly affect yield and market value (Kudaibergenov et al. 2024) and these are closely related to physiological traits such as nitrogen-use efficiency, photosynthetic capacity, and partitioning efficiency.

A lot of recent research is focused on protein quality as well. Genetic variation allows for the selection of genotypes with better protein characteristics, and molecular techniques have helped to accelerate breeding progress (Martineau-Côté et al. 2024). Oladzad (2020) described excellent bioavailability of bean proteins and the need to integrate biochemical and physiological methods in breeding. Bean protein concentrates are up to 79.8% protein with high protein content of essential amino acids which are competitive with other plant protein sources. Punia et al. (2020) also pointed out the presence of bioactive compounds and antioxidant properties in legumes. These are closely related to efficient nitrogen assimilation and redistribution in the plant. The wide range of protein content (12-38%) among bean genotypes is indicative of differences in physiological efficiency, especially nitrogen metabolism and accumulation in the plant (Saikenova et al. 2019).

This variability is especially important for breeding programs. In Kazakhstan, particularly in the Almaty region, beans are in high demand because of their nutritional value and adaptability. The crop is a promising source of plant protein with the potential for use in the home and export market (Kudaibergenov et al. 2024). To achieve this potential we need to understand not only morphological and biochemical traits but also the physiological mechanisms that drive productivity as well. The objective of this study is to identify the morphological and quality traits (shape, size, color) of bean seeds from physiological and biochemical factors.

Materials and Methods. The study was conducted in agroecological conditions of the Almaty region in 2023-2024. The previous crops were winter and spring cereals. The soils were mainly light chestnut loamy, with some sandy loam. The field experiments were carried out on 1 m² plots with two replications, and the seeds were planted at a depth of 5-6 cm.

The experimental material included 100 bean accessions from various regions with different origins, taken from the germplasm collections of major N.I. Vavilov All-Russian Institute of Plant Genetic Resources (VIR), the All-Russian Research Institute of Legumes and Groat Crops, the All-Russian Research Institute of Lupin Breeding, the Institute of Field and Vegetable Crops, and the Scientific and Practical Center of the National Academy of Sciences of Belarus for Arable Farming. Seed morphology (shape, size and color) was measured according to standard descriptors for grain legumes (AOAC International).

Seed protein content was measured using the Kjeldahl method (GOST10846-91) and near-infrared spectroscopy (Pacific Scientific 4250) based on calibrated equations. Statistical analysis was carried out in R environment and Microsoft Excel (R Core Team, 2024), and analysis of variance (ANOVA) was carried out in IBM SPSS Statistics 25 to ensure the validity of our results.

The production of plants from plants in different phenological stages and their growth and development were quantified by looking at photosynthesis activity of pea agrocenoses, such as fresh and dry biomass, leaf area and photosynthesis potential (Carbas et al. 2020). Fresh and dry biomass were determined using the gravimetric method. Leaf surface area was estimated using the punch (disc) method, whereby leaf surface density was calculated as:

$$P_{л} = \frac{\sum Ml}{Nl * Sl}$$

Results. In this study, we have measured morphological and quality characteristics of more than 100 common bean (Phaseolus vulgaris L.) accessions. Specifically, we have paid great attention to the shape of their longitudinal section, seed width, seed coat color, and protein content. This integrated approach has enabled us to accurately characterize the diversity of the phenotypic characteristics in the common bean species, identify the most common and rare morphological types, and determine which ones can breed best and have the best nutritional value. We have obtained this information and have provided the basis for the selection of more high productivity and high technology species that are suitable for the agroecological conditions in southern Kazakhstan. Seed width is a very important morphological trait in common bean and also has a direct effect on seed weight, yield, and market quality. It also reflects the genetic variation of the collection and should be used to identify the lines that are suitable for breeding and for industrial applications.

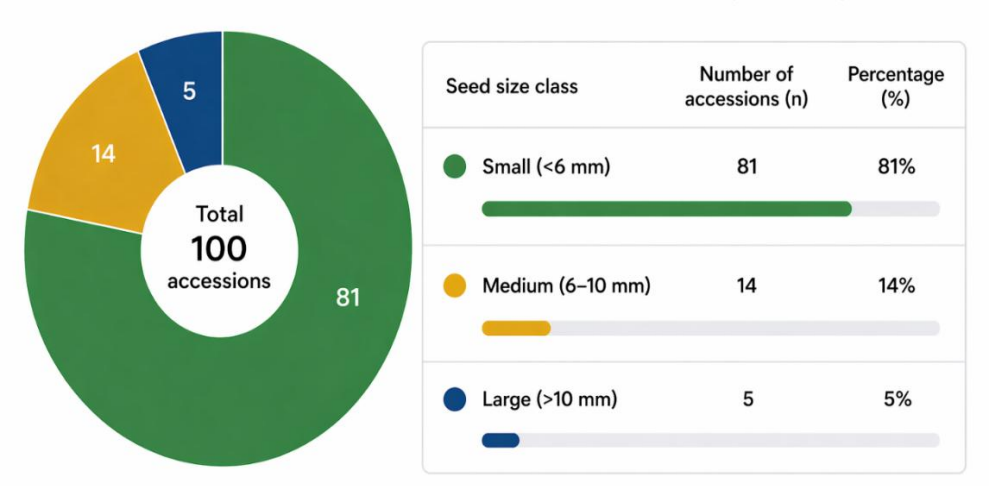


Fig. 1 Seed width of bean accessions in the collection nursery

As a result of seed width, all the bean accessions studied were classified into three categories: small-seeded (<6 mm), medium-seeded (6-10 mm) and large-seeded (>10 mm).

The small-seeded category comprised 81 accessions with seed width of 3 to 5 mm and the following genotypes: 152, 153, 154, 158, 164, 168, 170, 171, 172, 173, 176, 179, 182, 183, 185, 188, 189, 190, 191, 194, 196, 197, 208, 209, 210, 211, 213, 215, 216, 217, 220, 222, 223, 230, 231, 232, 233, 235, 236, 247, 250, 1071, 1088, 1106, 1202, 1214, 1279, 1280, 2145, 8400, 10709, 11633, 11758, 11789, 12170, 12700, 15134, 15189, 15190, 15245, Empress, Brilliant, Cabretta, Elita, Judia, Shokoladnitsa, Nina-Megazin, 08-543, Strela, Zolotaya Shpaga, Zagadka, Belko, BR (Boranzha), 2-vad, and Superstar. The small-seeded group represents compact seed forms in most modern bean cultivars and is a consequence of breeding trends towards high productivity, compact plant types (fig.1).

Medium-seeded accessions have seed width of between 6-10 mm and include 14 accessions. Models of medium seed are sparse in our data and thus can potentially be used as breeding material in breeding programs to increase seed size and market quality (fig.1).

The least represented group comprises large-seeded accessions, including genotypes 1986, 15185, 15483, 15529, and SZh (Slavonskiy Zheltozeleniy). Despite being sparsely produced, these accessions are of high breeding and economic value. The large seed size is one of the most important characteristics related to consumer appeal and market value of beans, so these genotypes make them attractive to breed high-quality competitive bean cultivars (fig.1).

The longitudinal seed section is a feature in the data that reflects the structure of the seed and the differences between accessions as well as genetics. It is thus widely used in the morphological characterization of germplasm collections and breeding practice.

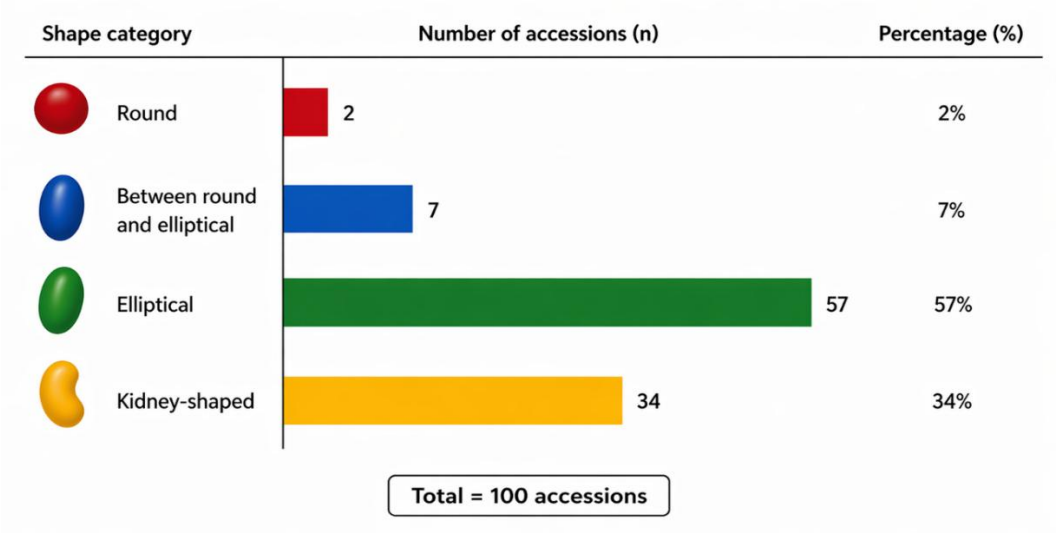


Fig. 2 Shape of the longitudinal section of bean seeds

According to this trait, there were many morphological types in the studied collection. The most common ones were the elliptical shape of the longitudinal seed section obtained in 57 accessions (152, 153, 154, 158, 160, 164, 173, 176, 182, 183, 185, 191, 194, 196, 197, 210, 215, 226, 230, 231, 232, 233, 247, 250, 268, 1071, 1088, 1202, 1214, 1279, 1280, 2145, 8400, 10709, 11633, 11758, 11789, 12170, 15185, 15189, 15190, 15245, 15260, 15366, 15378, 15480, 15571, Empress, Brilliant, Cabretta, Judia, Shokoladnitsa, Nina-Megazin, Strela, Zagadka, BR (Boranzha), and SZh (Slavonskiy Zh)) (fig.2).

Besides the predominant type, a large portion of the collection consisted of accessions with a kidney-shaped longitudinal section obtained in 34 accessions (165, 167, 168, 170, 171, 179, 189, 190, 208, 209, 211, 213, 216, 217, 222, 223, 228, 235, 236, 1986, 1106, 12700, 15134, 15452, 15483, 15522, 15529, and the cultivars Fabilio na/balong, Elita, 08-543, 2-vad and Superstar) (fig.2).

In contrast to the previous two cases, the intermediate shape of the longitudinal section (round to elliptical) was much less often found and was only found in 7 accessions (172, 178, 214, 220, 224, 225, Belko). The round shape was the least common type and was only found in 2 accessions (188, Zolotaya Shpaga) (fig.2).

Based on our results, the distribution of accessions according to shape of longitudinal seed section indicates a pronounced morphological diversity in our collection. The presence of multiple morphotypes expands the potential for using this germplasm for breeding programs which aim to improve economically valuable traits such as seed shape and size as well as their aesthetic and market appeal.

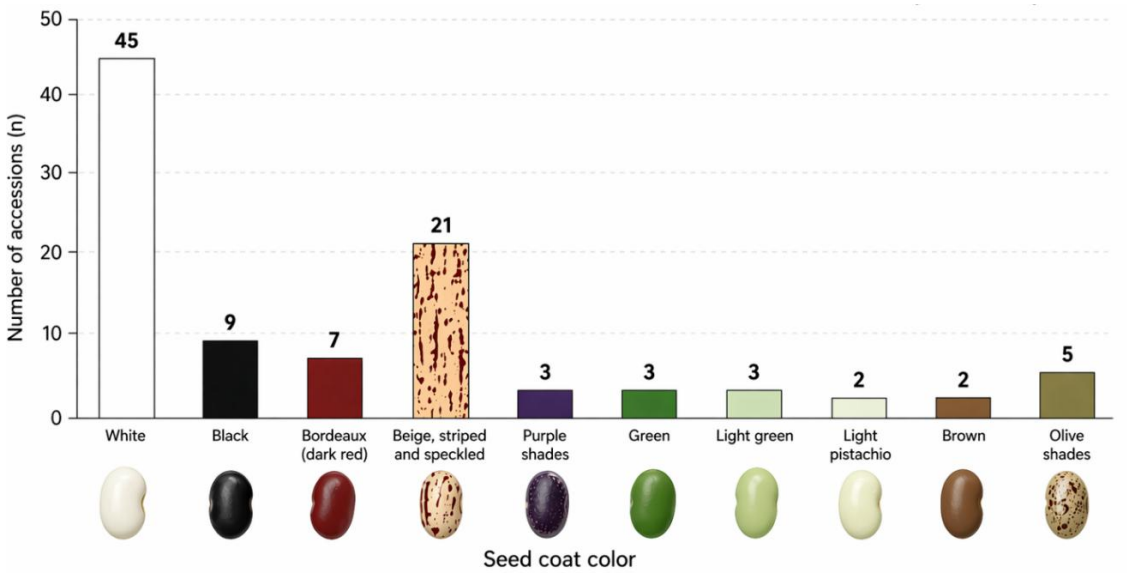


Fig.3 Seed coat color of bean accessions in the collection nursery

The distribution of bean accessions according to seed coat color revealed a pronounced predominance of light-colored forms. The largest proportion of the collection was represented by white-seeded accessions (fig.4a), including milky, light milky, and white ribbed types, which comprised 45 accessions, indicating their dominant position within the studied germplasm.

A substantial share of the collection was formed by accessions with beige, striped and speckled seed coats (fig.4b-c), accounting for 21 accessions. This group reflects a high degree of phenotypic variability and represents transitional forms between uniform and variegated coloration patterns.

Among the darker seed coat categories, black coloration (fig.4e) was identified in 9 accessions, while bordeaux (dark red) shades (fig.4d) were recorded in 7 accessions. Additionally, olive-colored accessions constituted a minor group comprising 5 accessions, contributing to the diversity of darker pigmentation types within the collection.

Rare color classes were represented by a limited number of accessions. Purple shades were observed in 3 accessions, whereas green and light green seed coat colors were each identified in 3 accessions. Furthermore, light pistachio and brown colorations were the least represented, each comprising 2 accessions. The occurrence of these low-frequency color groups highlights the presence of unique phenotypic variants and underscores the overall diversity of seed coat pigmentation within the studied collection.



a b c d e f

Fig.4 (a-f) Phenotypic diversity of seed coat color in bean accessions from the KazRIAPG collection

Thus, the analysis of seed coat coloration demonstrates a high level of phenotypic variability within the collection, with white coloration predominating, while uniform chestnut, yellow-brown, and beige forms are the least represented.

The identified diversity highlights the considerable potential of the studied material for breeding selection and its utilization in genetic and breeding programs aimed at improving decorative, commercial, and agronomically valuable traits of seeds.

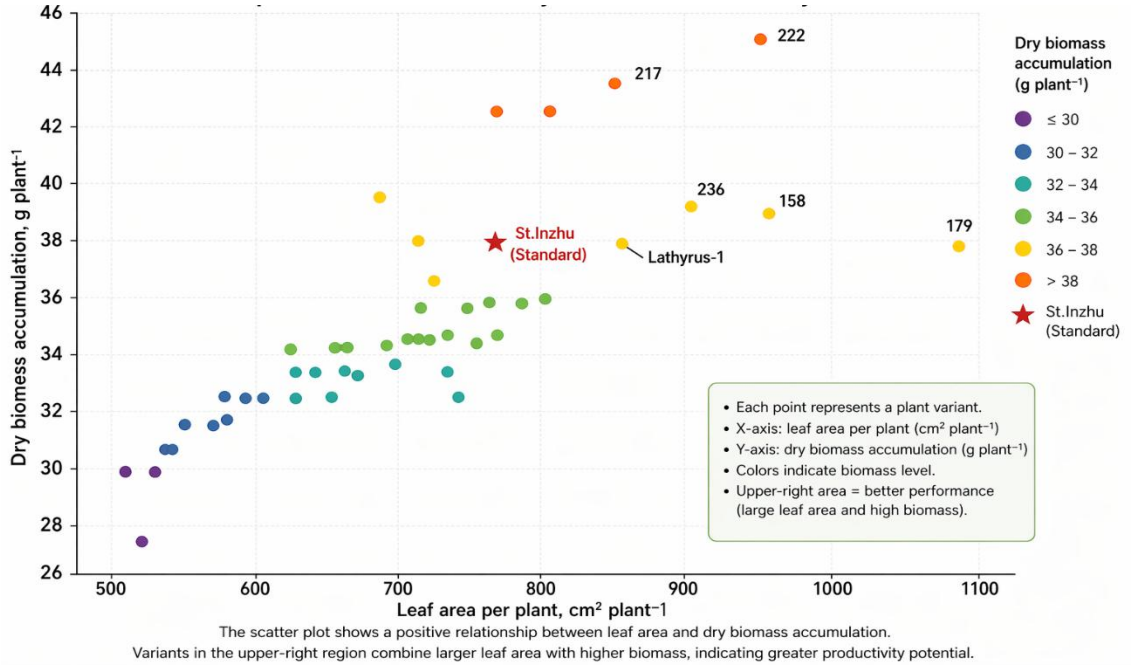


Fig.5 Relationship between leaf area, dry biomass and photosynthetic potential

According to the modern theory of photosynthetic productivity, one of the key indicators determining both biological and economic yield is the total leaf surface area of the crop canopy.

The data presented in the figure indicate that, on average over the years of study in the bean collection nursery, leaf area ranged from 511 to 1011 cm² plant⁻¹, while dry biomass accumulation varied from 27 to 45 g plant⁻¹. During the pod formation stage, the maximum values of leaf area and dry biomass accumulation (825-1011 cm² plant⁻¹ and 39-45 g plant⁻¹, respectively) were observed in accessions 236, 158, 222, and 179, which were characterized by a well-developed assimilatory apparatus.

The group with intermediate values (550–750 cm² plant⁻¹) included accessions 190, 191, 196, 208, 210, 211, 220, 167, 197, 230, 232, 233, as well as *Clendick*, *Nina Megazin*, and *Zolotaya shpaga*. Despite moderate leaf area, these accessions demonstrated relatively high dry matter accumulation (up to 43-44 g plant⁻¹).

Reduced leaf area values (511-528 cm² plant⁻¹) were recorded in accessions 15480 and 214, indicating weaker development of the leaf apparatus.

To evaluate the efficiency of each unit of leaf surface, the parameter net photosynthetic productivity (NPP) is used. NPP depends both on the physiological state of the plant and on environmental factors, primarily moisture availability and temperature.

The highest values of photosynthetic potential (15,000-20,200 cm²·day) were recorded in accessions 235, 217, *Lathyrus-1*, 236, 158, 222, and 179, significantly exceeding the remaining material. This indicates intensive development of the leaf apparatus and high potential photosynthetic activity.

Intermediate values of photosynthetic potential (13,040–14,800 cm²·day) were observed in the majority of the collection (more than 35 accessions), including 223, 231, 10709, 15452, *Fabiolo nano balong*, 191, 160, 11633, *Clendick*, 1280, 1106, 1279, 12170, 15245, 15260, *Nina Megazin*, *Zolotaya shpaga*, 215, 190, 233, 11758, 15185, 1088, 1202, 08-543, *Boranja*, 232, 15366, 230, 197, 167, 1071, 15378, 2-vad, and 250. These accessions were characterized by a balanced development of morphophysiological traits and high adaptability.

Low photosynthetic potential values (10,230–10,560 cm²·day) were observed in accessions 15480 and 214.

Thus, it was established that an increase in leaf area is accompanied by a rise in photosynthetic potential and dry biomass accumulation, confirming the key role of the assimilatory surface in the formation of bean productivity. The most promising accessions for breeding purposes are those with high leaf area (>750 cm² plant⁻¹) and photosynthetic potential exceeding 15,000 cm²·day, ensuring maximum realization of the crop's productive potential.

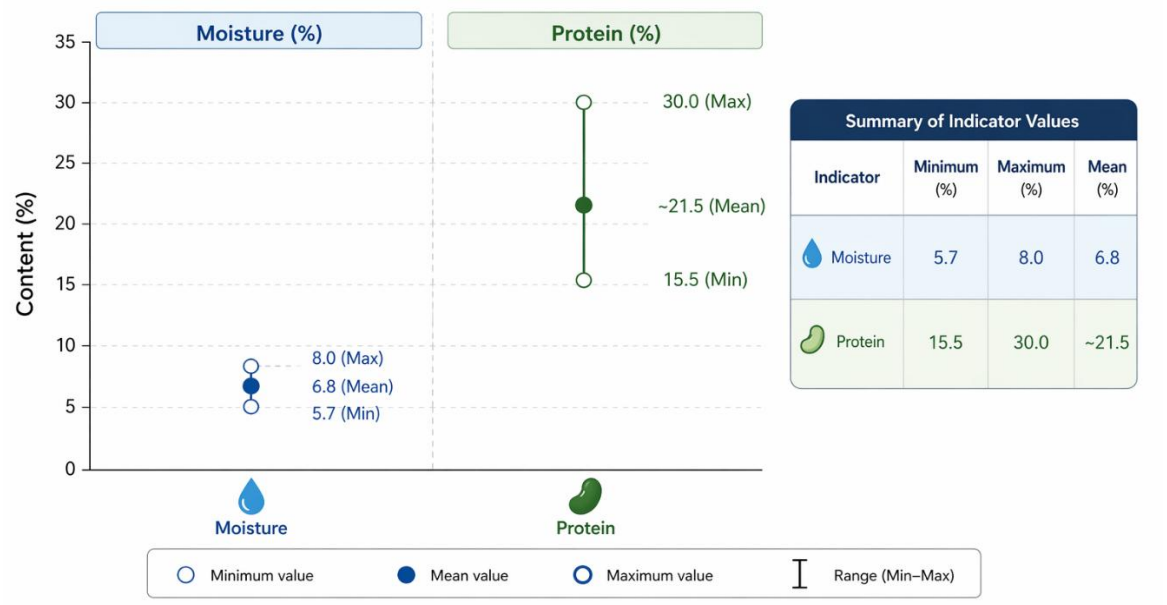


Fig.6 Variation in moisture and protein content of bean seeds

The moisture content of the studied accessions ranged from 5.7 to 8.0%, with a mean value of approximately 6.8–6.9%. The relatively narrow range of variation indicates uniform post-harvest processing of the зерна and ensures the reliability of comparative evaluation of protein content among accessions (fig.6).

In contrast, the protein content in bean seeds exhibited considerable variability, ranging from 15.5 to 30.0%, which reflects pronounced genetic differentiation within the collection.

To assess breeding value, the accessions were classified into three groups based on protein content. The median protein content in the low-protein group was approximately 19%, in the medium-protein group about 21.5%, and in the high-protein group around 26% (fig.6).

Both the range of values and the interquartile range increased with higher protein content levels, indicating greater variability within the high-protein group. The presence of outliers in the low-protein group suggests the existence of a subset of accessions with particularly low protein content, which differ markedly from the main distribution.

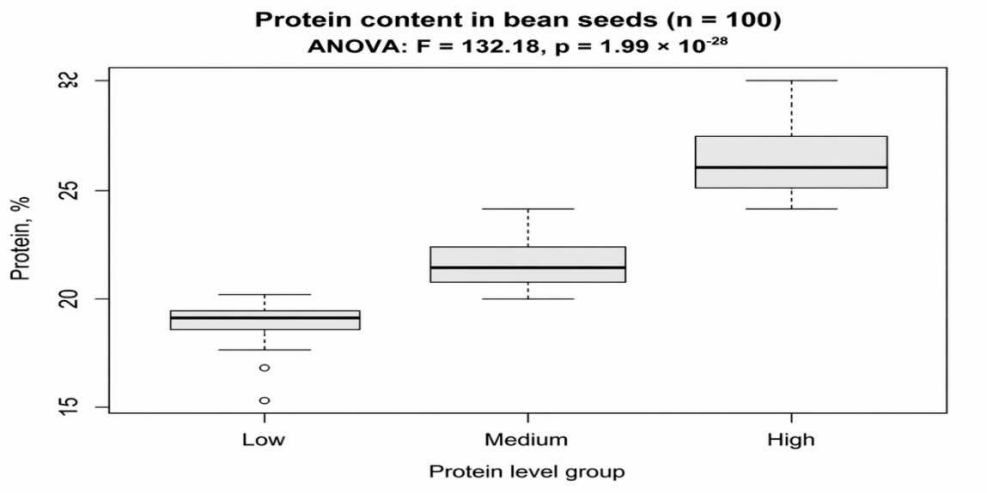


Fig.7 Comparison of protein content (%) in bean seeds among groups with different protein levels (ANOVA)

According to the results of laboratory analyses conducted using the Kjeldahl method, the total protein content in the standard variety Inzhu was 20.6%.

Based on protein content, the studied accessions were classified into three groups.

The first group, characterized by low protein content (15.5–19.9%), may be of interest primarily for breeding programs focused on other agronomically valuable traits, such as yield potential, stress tolerance, and technological qualities. This group included the following accessions: 214, 183, 1214, 15480, 171, 164, 209, 15189, 15190, 225, 8400, 176, *Cabretta*, 182, 188, 15522, 194, 196, *Shokoladnitsa*, and 213.

The second group, comprising more than half of the collection, was characterized by a moderate protein content ranging from 20.0 to 24.0%. This group included accessions such as 11789, 185, 224, *Judia*, *Zagadka*, 154, 208, 1986, SZh (*Slavonskiy Zheltozeleniy*), 15134, the standard variety *Inzhu*, 189, 210, 211, 216, 226, 12700, *Brilliant*, 2145, 15377, 15571, *Belko*, 11633, 228, 11758, *Clendick*, *Strela*, 15279, 173, 220, 10709, *Empress*, 191, *Fabilio nano balong*, 231, 15452, 232, 168, 15529, 215, 15185, *Zolotaya Shpaga*, 152, 165, 1280, 15245, 15260, 15483, *Gom*, 1279, 12170, *Nina-Megazin*, 1106, 15366, 223, BR (*Boranzha*), 08-543, 153, 15378, 1088, 1202, 197, 230, 233, 1071, 2-vad, 178, 172, 170, and 250.

The third group included accessions with protein content at or above the level of the standard variety *Inzhu*, ranging from 24.1 to 30.0%. This group comprised accessions 250, 236, *Lathyrus-1*, 190, 179, 158, 160, 235, 217, 222, and 167. The maximum protein content (30.0%) was recorded in accession 167. These accessions represent valuable genetic material and can be used as donors of high protein content in breeding programs aimed at developing bean varieties for both food and feed purposes.

Conclusion. Based on morphological traits and quality parameters obtained, we can make the following conclusions: The collection nursery contains accessions of nine seed coat color types: white, beige, bordeaux, black, purple, green, gray, brown, and variegated. For seed shape, we found round, intermediate (round to elliptical), elliptical, and kidney-shaped. This diversity suggests that genetic diversity is deep enough to be used in hybridization programs to develop new varieties suited to the agroclimatic conditions in the Almaty region. According to seed size, we found small and medium seed types, and large seed types are not noted. The small seed group contained 86 accessions with seed widths of 3 to 5 mm, and the medium seed group had 14 accessions. The moisture content of bean seeds was 5.7 to 8.0%, with an average value of approximately 6.8 to 6.9% in the case of the local environment. This low moisture content allows for more stable and transportable bean varieties. Protein content ranged from 15.5 to 30.0%, and therefore the accessions could be classified into three groups. The low protein group (15.5 to 19.9%) is more relevant for breeding programs to enhance other agronomically useful traits. The moderate-protein group (20.0-24.0%) accounts for the majority of the data and shows a stable average potential for this trait. The high-protein group (24.1-30.0%) includes accessions with protein content at or above the standard variety Inzhu, and the highest value (30.0%) was in accession 167. The high-protein accessions should be used as donors for breeding programs to develop bean varieties for food and feed with higher protein value.

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