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Research Article

Optimizing Lentil Breeding Models for South-East Kazakhstan: Yield, Adaptability, and Protein Enhancement

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Abstract: This study presents the development of a model for optimizing lentil breeding in the agroclimatic conditions of southeastern Kazakhstan. By evaluating 31 lentil varieties and hybrid populations (F1, F2, and F3), key economically valuable traits such as yield, protein content, drought resistance, and adaptability to mechanized harvesting were identified. A systematic selection process enabled the creation of lentil variety models suited for both rainfed and irrigated farming, with emphasis on plant height, lower pod attachment, seed productivity, and biochemical composition. The developed models demonstrated improved yield potential, with a notable increase in crude protein content and adaptation to local soil and climatic conditions. These findings contribute to enhancing sustainable lentil production in Kazakhstan, ensuring food security and economic efficiency in agriculture.

Keywords: Lentils, Variety Sample, Yield, Protein, Variety Model

Introduction.

Lentils (*Lens culinaris* L.) are legumes and are one of the most important traditional food components. This crop has a long history of cultivation, exceeding 10 thousand years. According to the Food and Agriculture Organization of the United Nations (FAO), world production of lentils in 2008 was about 2.83 million metric tons. The main producers were Canada (36.9%) and India (28.7%), followed by Nepal, China and Turkiye (Rajendran *et al.*, 2021; Kudaibergenov, 2005).

Lentils are valued for their high content of proteins, vitamins, minerals and fiber, which makes them especially useful for people following vegetarian and vegan diets. In addition, they serve as an important source of plant protein, which is especially important in regions with limited reserves of animal protein (Dospekhov, 2012; Vishnyakova *et al.*, 2010).

From an agronomic point of view, lentils play a significant role in improving soil structure through nitrogen fixation, reducing the need for chemical fertilizers, and promoting sustainable agriculture. Their adaptability to dry and moderately hot climates, along with their drought resistance, makes them a key crop in regions with limited water resources. These qualities are particularly important in the context of climate change, where the demand for resilient crops is increasing (Saikenova *et al.*, 2021; 2019).

One of the priority tasks of breeding work with lentils is the development of new varieties with a set of features aimed at increasing yield, improving mechanized harvesting and improving grain quality. In particular, it is important to develop tall varieties that are resistant to lodging, with an optimal arrangement of lower beans, characterized by high attachment and resistance to shedding upon reaching maturity. Another important factor is ensuring uniform ripening, which helps improve conditions for mechanized harvesting and increase the quality of the crop (Singh, 2018; Varlakhov, 1996).

In addition, special attention should be paid to the creation of large-seeded, tall forms with stable yields in various climatic conditions. An important aspect is the increase in the protein content in the grain, which affects the nutritional value of the product and its competitiveness in the market (Marakaeva *et al.*, 2019). In addition, breeding research should be aimed at improving resistance to herbicides, which will ensure the possibility of using modern plant protection methods and increase the efficiency of using agrotechnical measures in the process of growing lentils (Smith & Williamson, 2020).

Research on lentil models is being conducted by scientists in various countries, who are striving to improve the agronomic, genetic and physiological characteristics of the crop. In Canada, J. Smith and T. B. Williamson are working on lentil breeding and

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developing adaptive models within the framework of the Agriculture and Food Research Organization of Canada (CSIRO) to improve crop yields and resistance (Smith & Williamson, 2020). In India, significant contributions to this research have been made by scientists such as Amin R., Laskar R. A. and Khan S. from the Indian Council of Agricultural Research (ICAR), who have been developing high-yielding varieties and improving agronomic practices to optimize lentil cultivation. The Biras Institute of Agricultural Sciences is also actively researching the genetic characteristics of lentils (Amin *et al.*, 2015). In European countries such as Spain, Italy, France, Poland, Romania and Bulgaria, scientists are also actively working on the creation and optimization of agronomic models to improve lentil yields and quality, including the work of M. Ruiz (Spain), F. Papadopoulos (Greece) and I. Nistor (Romania), focused on crop resistance to diseases and the impact of climate change. The work of these scientists covers a wide range of approaches, including genetic studies, mathematical modeling of plant growth and biotechnology development, which contributes to improving lentil agricultural production at the global level (Smith & Williamson, 2020).

Research and development in the field of lentil breeding and agronomy are of particular importance for Kazakhstan, given the importance of this crop for the country's agricultural sector. Lentils are one of the leading legumes that are actively grown in Kazakhstan, especially in the northern and central regions, where they play a significant role in ensuring food security, improving crop rotation and increasing agricultural profitability. Given the country's climatic conditions, which are characterized by temperature variability and aridity, it is extremely important to develop lentil varieties that are highly resistant to extreme climatic conditions, diseases and pests, and provide stable yields.

Scientific research in the field of lentil breeding at the KazRIAPG Institute contributes to the creation of varieties that are optimally adapted to various conditions in Kazakhstan. This includes both genetic improvements and agrotechnical methods aimed at increasing resistance to drought, high temperatures, as well as increasing the protein content in grain, which is important for the production of high-quality feed and food products. Forecasting yields, studying physiological processes such as photosynthesis and water absorption, as well as developing innovative methods of disease protection, make it possible to create resistant and highly productive lentil varieties that are able to adapt to changing climatic conditions and maintain high yields.

In addition, Kazakhstan is actively developing the legume production sector, including lentils, to meet domestic demand and increase export potential. The development of sustainability models and yield forecasting helps optimize cultivation methods, which in turn increases the economic efficiency of production and reduces plant protection costs (Kudaibergenov *et al.*, 2024).

Thus, research and development of models for improving lentil varieties are of great importance for the agricultural sector of Kazakhstan, contributing to increased food security, agricultural resilience to climate risks and improved product quality, which ultimately contributes to the country's economic growth and development.

Materials and Methods

For the experimental material, 31 lentil variety samples of diverse eco-geographical origins were used (Table 1). These samples were obtained from the International Center for Agricultural Research in the Dry Areas (ICARDA), the N.I. Vavilov All-Russian Institute of Plant Genetic Resources (VIR), and Kazakhstan. They differed from one another in terms of key economically valuable traits and biological properties, including components of major quantitative traits, the duration of the growing season, drought resistance, and other characteristics.

Table 1: Origin of the lentil collection

No.	Variety	Country
1	K-6	Russia
2	39227	Russia
3	39126	Russia
4	23209	Russia
5	K-184	Russia
6	23208	Russia
7	23202	Russia
8	4605	Russia
9	K-2849	Russia
10	39119	Russia
11	23108	Russia
12	31215	Russia
13	39229	Russia
14	39113	Russia
15	39203	Russia
16	LC04600017L	Syria
17	LC046000246L	Syria
18	LC04600068L	Syria
19	LC046000150L	Syria
20	LC04600023L	Syria
21	LC046000202L	Syria
22	LC04600010L	Syria
23	LC046000103L	Syria
24	LC046000156L	Syria
25	LC046000170L	Syria
26	LC046000270L	Syria
27	LC046000213L	Syria
28	LC046000223L	Syria
29	K-2017	Canada
30	K-1975	Canada
31	Vekhovskaya ST	Russia, 2011, registered and approved for cultivation in the North Kazakhstan region

Hybrid populations were developed across different generations F1 (D-12 - ♀39227x♂23108), F2 (K-20 - ♀ 23208x ♂ 39203; K-5 - ♀ 23208x ♂ K-6, K-15/1 -♀23208xK-184) and F3 (P-2/1 -♀4605x♂To-2017; P-3/5 - ♀ 4605x ♂ K-1975), along with older hybrid generations. Parental pairs were selected based on differences in key productivity traits, vegetation period duration, and other agronomic characteristics, while also taking into account the geographical origin of the accessions.

The research was conducted under conditions of semi-irrigated dryland and irrigated agriculture on experimental plots at the station of the Kazakh Research Institute of Agriculture and Plant Growing. Experimental work was organized in accordance with the methodological guidelines for establishing collection and hybrid nurseries, ensuring the implementation of all necessary agronomic practices aimed at providing optimal conditions for the growth and development of field crops (Dospekhov, 2012).

The plots for studying the collection were 10 square meters in size, with a sowing rate of 2.5 million seeds/ha and a sowing depth of 3-4 cm. The seeding is randomized three times, and every 10th number is seeded with a standard. The Vekhovskaya variety, which is zoned in Kazakhstan, was used as the standard in two zones.

Phenological observations included the recording of major stages in the plant ontogenesis: sowing, emergence, flowering, and ripening. Visual assessments of economically useful traits and phenotyping of productivity elements such as plant length, height of lower pod attachment, number of branches, plant mass, number of pods, number of seeds, seed mass, 1000-seed mass, and number of seeds per pod were conducted according to the methodological guidelines for studying legume crop collections (Vishnyakova *et al.*, 2010).

In irrigated agriculture, irrigation was carried out during the flowering and pod-filling stages. Each irrigation required 1000 m³ of water. Soil moisture at a depth of 25 cm was maintained at 80%. Moisture was measured using a moisture meter.

A biochemical analysis of protein content in lentil grains was conducted at the Quality Control Laboratory of the Kazakh Scientific Research Institute of Agriculture and Plant Growing, using the Kjeldahl method. The analysis was carried out following the "Methodology for State Variety Testing of Agricultural Crops and Technological Assessment of Cereal, Grain Legume, and Pulse Crops." The results of the study allowed for the evaluation of the quality characteristics of the grain, depending on the genotypic features of the germplasm samples and the growing conditions.

The protein content in the grain and the content of protein fractions (Osborne) were determined using the Kjeldahl method (GOST 10846-91), which is based on the combustion of organic components of the sample in a Kjeldahl flask in the presence of sulfuric acid. The released nitrogen was determined by titration, and its quantity was used to calculate the protein content. Additionally, infrared spectroscopy (FOSS DS 2500) was employed for analysis.

Results and Discussion

The development of models of varieties for each agroclimatic cultivation zone seems to be extremely important, since in selection there is often a difficulty in combining high productivity potential and ecological plasticity of varieties in one genotype. The use of valuable varieties obtained in other agroclimatic zones does not always guarantee success, since varieties isolated in one zone and demonstrating high productivity there often turn out to be unsuitable for other conditions (Saikenova *et al.*, 2021; 2019). In this regard, each agroclimatic zone should have its own varietal composition, adapted to local soil and climatic conditions and resistant to the main harmful diseases.

It is also necessary to take into account such parameters as temperature and humidity, as well as their distribution by the phases of plant development. During our study of the collection material, we managed to identify a number of variety samples that were recommended as sources. These samples exceeded the standard or corresponded to it in the main parameters listed in the key parameters of lentils. In hybrid populations F2-F3, an assessment was made of the inheritance of traits from parental forms to their hybrids, which made it possible to identify the donor properties of variety samples.

The parameters of the model of lentil varieties for rainfed and irrigated agriculture in southeastern Kazakhstan were developed taking into account the specific agroclimatic conditions of this region. The model includes criteria such as high productivity, resistance to major pests and diseases, and adaptability to changing climatic conditions.

In addition, emphasis is placed on such agronomic characteristics as the vegetation period, the number of seeds per plant and the weight of 1000 seeds. These parameters contribute to the formation of varieties capable of providing stable yields under various cultivation conditions (Figures 1-2). The development of this model is an important step towards improving the efficiency of agriculture in southeastern Kazakhstan and increasing food security in the region.

Under rainfed conditions (Figure 1), the 'New variety model' achieved a crude protein content of 37.5%, significantly higher than the 31.2% recorded for the 'Vekhovskaya' variety. This increase in protein content is likely due to the 'New variety model's' enhanced genetic capacity for nitrogen fixation and efficient nutrient utilization, which are critical traits for rainfed agriculture. Additionally, the 'New variety model'

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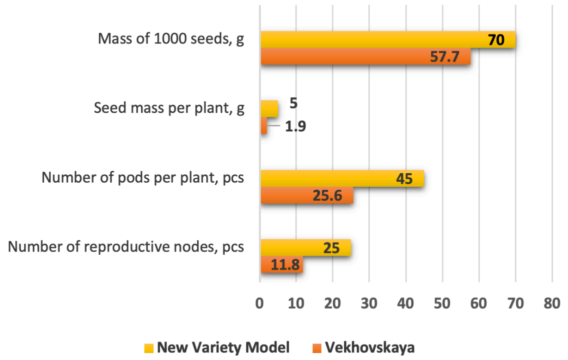
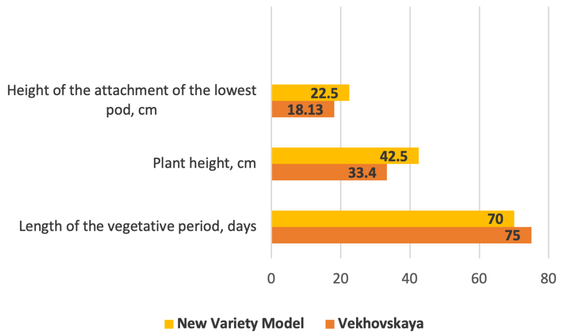
exhibited a potential grain yield of 14 c/ha, compared to only 4 c/ha for the 'Vekhovskaya' variety. This substantial yield gap can be attributed to the 'New variety model's' improved drought resistance and higher number of productive nodes, which enable it to maximize resource use under water-limited conditions.

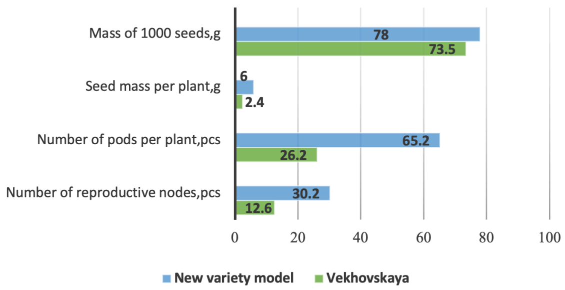


(a) Structural Analysis Indicators

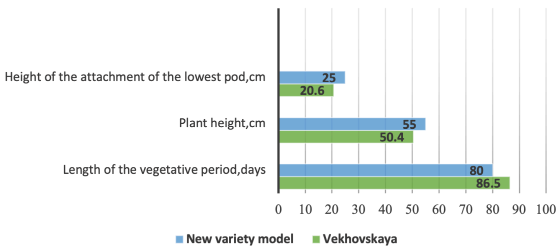


(b) Biological Characteristics

Fig. 1: Yield and Protein Content Trends in Lentil Varieties under Rainfed Farming Conditions



(a) Structural Analysis Indicators



(b) Biological Characteristics

Fig. 2: Parameters of the lentil variety model for irrigated agriculture

Under irrigated conditions (Figure 2), the 'New variety model' continued to outperform the 'Vekhovskaya' variety, with a potential yield of 18 c/ha compared to 5.33 c/ha. The 'New variety model's' ability to maintain high yields under irrigation is linked to its optimal plant height (50-55 cm) and lower pod attachment height (22-25 cm), which reduce seed losses during mechanized harvesting. Furthermore, the 'New variety model' demonstrated a protein content of 35%, compared to 31% for the 'Vekhovskaya' variety, highlighting its superior nutritional quality.

These results obtained under rainfed and irrigated farming conditions indicate the high potential of the "New variety model" for adaptation under two farming conditions, making it a promising choice for agricultural production. Moreover, the results underscore the importance of selecting for traits such as plant height, pod attachment, and drought resistance in lentil breeding programs aimed at improving both yield and quality."

Vegetation Period

When selecting for maximum seed productivity, the task of optimizing the duration of the growing season is actualized, which, on the one hand, allows varieties to make maximum use of environmental resources for harvest accumulation due to long vegetation, and on the other hand, ensures ripening in conditions favorable from the point of view of hydrothermal factors (Saikenova *et al.*, 2019). In this regard, early-ripening and mid-ripening samples are of particular interest, which for dryland farming have a vegetation period of 65-70 days, and for irrigated farming - 77-80 days.

The results of our studies have demonstrated that the vegetation period under irrigation conditions for large-seeded varieties exceeds that of small-seeded varieties by 8-10 days, amounting to 85.8±1.9 days and 77.7±2.7 days, respectively. It should be noted that the absence of irrigation leads to a reduction in the vegetation period in the large-seeded group by an average of 11 days, while for small-seeded samples this period is reduced by only 3 days, amounting to 75.3±2.5 days. A study of the duration of individual development phases under both rainfed and irrigated farming conditions revealed the presence of accessions for which irrigation significantly affected the duration of the growing season, while for other accessions this parameter remained stable regardless of growing conditions, including such accessions as LC04600068L, LC046000223L, 39119, K-1975, 23108, K-2017, 39229, 39113 and 39203.

Plant Height

Plant height is an important morphological trait that plays a critical role in the resistance of agrocenoses to lodging, which is due to the fact that stem length is defined as a quantitative trait that affects the mechanical properties of plants. According to scientists, varieties with an erectoid habitus and medium height are characterized by increased resistance to lodging and better adaptation to mechanized harvesting (Saikenova *et al.*, 2019). Interest in plant height remains among both geneticists and breeders, since the stem performs many functions and determines key plant properties, including resistance to lodging, efficiency of nutrient transport, and photosynthetic activity.

The recommended height parameters for varieties intended for rainfed farming are 40.0-42.5 cm, while for irrigated farming these parameters increase to 52.2-55.0 cm. According to Singh (2018), a highly productive technological variety of lentils should be at least 40 cm high, and Varlakhov (1996) confirms that the stem length should be close to 50 cm. Our studies have established that the optimal height at which the best yield is achieved in the conditions of the Almaty region is in the range of 45-55 cm, since low-growing varieties are often characterized by low bean attachment, and tall varieties are prone to lodging, which in both cases can lead to yield losses during combining. In the conditions of rainfed farming, such samples as LC046000246L, 39119 and K-1975 stood out.

Under irrigated conditions, we identified the following varieties by height: K-2849 (53.6 cm), LC046000213L (53.3 cm), K-1975 (52.7 cm), LC04600023L (52.1 cm), 39119 (51.9 cm), 23209 (51.7 cm), 4605 (51.0 cm), K-6 (50.7 cm), LC046000270L (50.7 cm), 39203 (50.5 cm), and LC04600010L (50.3 cm).

Height of Attachment of the Lower Bean

For successful cultivation of lentils on an industrial scale, it is necessary to take into account not only the high productivity of samples, but also the early maturity and technological qualities of the crop. When selecting varieties suitable for mechanical harvesting, producers prefer varieties with a lower bean attachment height exceeding 20 cm (Saikenova *et al.*, 2021). However, our data indicate that further increasing the lower bean attachment height is inappropriate, as this may negatively affect the yield potential of varieties.

This phenomenon can be explained by the fact that the increase in the height of the lower bean is achieved by increasing the node of the first flower, which in turn leads to their later appearance. Experimental data by Marakaeva (2019) confirms that with an increase in the height of the plant, the height of the lower beans also increases, which in turn helps to reduce seed losses during mechanized harvesting; similar results were obtained in our studies.

It is interesting to note that the variability of the plant height trait is characterized by a wider range than the variability of the lower bean attachment height trait, which can be observed in percentage terms (Figure 3).

This fact indicates that plant height is subject to greater variations, which, in turn, can have a significant impact on the selection process and the adaptation of varieties to different agro-ecological conditions.

Thus, the results of the study highlight the need for a more detailed analysis of the factors influencing plant height, which will allow optimizing breeding programs and increasing crop yields.

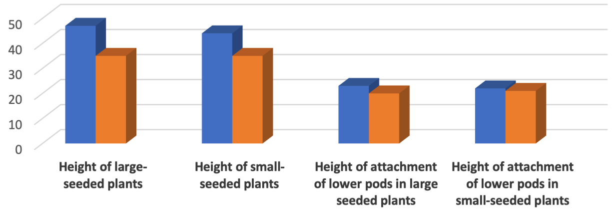


Fig. 3: Variability in Plant Height and Lower Pod Attachment Height under Different Irrigation Conditions

Plant height exhibits greater variability than lower pod attachment height across irrigation regimes, suggesting that stem length is more responsive to environmental conditions, which could complicate breeding for consistent mechanized harvesting traits. In rainfed conditions, compact varieties with high pod attachment (e.g., 22.6 cm in 39229) thrive, while irrigation boosts attachment heights (e.g., 25.5 cm in LC046000270L), indicating water's role in enhancing structural adaptability and reducing seed loss (Figure 3).

Under dryland farming conditions, varieties characterized by a compact habit and high attachment of lower beans were isolated. Thus, the highest attachment height values were recorded for the following samples: 39229 (22.6 cm), LC046000223L (22.3 cm), 23202 (22.2 cm), LC046000170L (22.2 cm), LC04600010L (22.2 cm), K-2849 (22.0 cm) and others, the general trend of which indicates the high adaptability of these varieties in conditions of limited resources. Under irrigation conditions, other variety samples stood out according to the attachment height of lower beans, which demonstrated significantly higher results: LC046000270L (25.5 cm), 39119 (25.2 cm), LC04600023L (25.2 cm), 4605 (25.1 cm), LC04600010L (24.9 cm) and a number of other samples, which confirms the effect of irrigation on increasing the height of attachment of the lower beans. The recommended parameters for the height of attachment of the lower beans are 20.0-22.5 cm for rainfed agriculture and 22.0-25.0 cm for irrigated agriculture, which indicates the need to select varieties depending on growing conditions in order to achieve optimal yield indicators. In Canada, research by Smith and Williamson (2020) has shown that lentil varieties with a lower bean attachment height of 18-22 cm (rainfed) are preferred for mechanized harvesting. This slightly lower range compared to our study is likely due to differences in agroclimatic conditions and farming practices. Canadian varieties are often bred for shorter growing seasons and cooler climates, which may favor slightly lower bean attachment heights to reduce lodging and seed shattering.

While the optimal height of attachment of the lower beans in Kazakhstan is slightly higher than in Canada, both studies agree that this trait is crucial for improving harvest efficiency and reducing seed losses (Smith & Williamson, 2020).

Number of Productive Nodes and Pods

The number of productive nodes and beans per plant is one of the most important breeding traits directly related to plant productivity. The potential indicator of the number of productive nodes for rainfed agriculture is 20.0-25.0 pieces, while for irrigated agriculture this indicator increases to 25.1-30.2 pieces. These data emphasize the importance of breeding activities aimed at increasing both the number of productive nodes and the total number of beans, which, in turn, can lead to an increase in the overall productivity of agricultural crops.

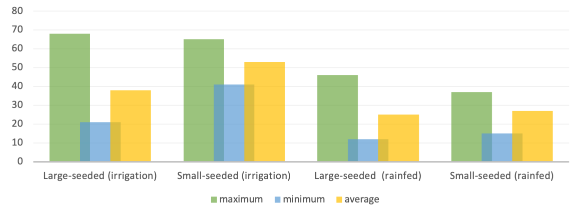


Fig. 4: Pod Production Trends in Large-Seeded and Small-Seeded Lentil Varieties under Rainfed and Irrigated Conditions

Number of Beans from One Plant

Under irrigation conditions, the number of beans per plant in small-seeded varieties was significantly higher than in large-seeded varieties, amounting to 55.2±3.7 pcs. and 38.6±2.1 pcs., respectively. When switching to dry farming conditions, a decrease in the number of beans per plant was observed in both groups, with the lack of irrigation having the greatest impact on the small-seeded group, as a result of which the number of seeds per plant in large-seeded and small-seeded varieties leveled off at 25.6±2.0 pcs. and 26.5±1.5 pcs., respectively (Figure 4).

Under rainfed conditions, the number of beans per plant varied from 12.4 to 46.0 pcs., among which the following samples stood out: LC046000223L (46.0 pcs.), 23208 (40.0 pcs.), 23108 (37.3 pcs.), LC04600068L (32.4 pcs.) and K-184 (30.4 pcs.). Under irrigated conditions, on the contrary, the number of beans per plant increased significantly compared to rainfed farming, and among the most productive varieties, the following can be distinguished: 23208 (68.5 pcs.), 39229 (65.6 pcs.), K-184 (62.8 pcs.), 39203 (62.1 pcs.), 23108 (57.7 pcs.) and others, which emphasizes the importance of irrigation for increasing yields.

The recommended parameters for the number of beans per plant are 40-45 pcs. for dry farming and 60.2-65.2 pcs. for irrigated farming, which indicates the need to optimize breeding strategies depending on cultivation conditions.

While in India, research by Amin *et al.* (2015) has demonstrated that lentil varieties producing 30-40 pods per plant under rainfed conditions and 50-60 pods per plant under irrigation are considered high-performing. These findings highlight the importance of pod production as a key determinant of yield, particularly in regions with variable water availability. The study also emphasized that pod production is influenced by factors such as plant architecture, nutrient availability, and water use efficiency, which are critical for optimizing yields in both rainfed and irrigated systems. While the pod production in Kazakh varieties under irrigation is comparable to or even exceeds the Indian benchmarks, the performance under rainfed conditions is somewhat lower, particularly for small-seeded varieties.

Weight of Seeds from One Plant

The seed weight per plant is a complex trait reflecting the final result of the implementation of genetic information, which is formed on the basis of such simple traits as grain size and the number of productive nodes. Seed productivity depends on many components, including the number of seeds per plant and the weight of 1000 seeds. As a result of studying the collection material under dryland conditions, the following samples were isolated: LC046000223L, 23208, 23108, LC04600068L and K-184. Under irrigated conditions, significant results in seed weight per plant were demonstrated by the following samples: 23208, 39229, K-184, 39203, 23108, K-1975, LC04600068L, K-2017, 39119, LC046000223L and others. The recommended parameters for seed weight per plant for dryland farming are 3.5-5.0 g, while for irrigated farming they are 4.0-6.0 g.

Research by Amin *et al.* (2015) in India has shown that lentil varieties producing 5.0-7.0 g of seeds per plant under rainfed conditions and 7.0-9.0 g under irrigation are considered high-performing. Seed weight per plant is a critical trait that reflects the overall productivity of a variety, as it combines both the number of seeds per plant and the size of individual seeds. The study emphasized that seed weight per plant is influenced by factors such as genetic potential, nutrient availability, and water use efficiency, making it a key focus for breeding programs aimed at improving lentil productivity. While the performance of Kazakh varieties under irrigation is competitive, the seed weight per plant under rainfed conditions is somewhat lower compared to the Indian benchmarks.

Weight of 1000 Seeds

The mass of 1000 seeds, which determines the grain size, plays an important role in the overall productivity of the plant and depends on both varietal characteristics and external factors. As A.V. Amelin and other scientists point out, for most leguminous crops the mass of 1000 seeds is a key factor influencing the yield during the selection process and determining their consumer qualities (Amelin *et al.*, 2013). Under irrigated conditions, the 1000-seed weight of large-seeded varieties varied from 62.4 to 70.4 g, while under dry-farming conditions this figure was from 57.6 to 60.1 g. The following varieties stood out in both zones: 31215, 4605, LC046000103L, LC046000270L. The recommended parameters for the 1000-seed weight for dry-farming are 59.0-67.0 g, and for irrigated agriculture - 75.0-78.0 g.

Research by Amin *et al.* (2015) in India has shown that lentil varieties with a 1000-seed weight of 65-75 g under rainfed conditions and 75-85 g under irrigation are considered high-performing. The 1000-seed weight is a critical trait that directly influences both yield and market value, as larger seeds are often preferred for their nutritional content and cooking quality. The study highlighted that seed size is influenced by factors such as genetic potential, nutrient availability, and water use efficiency, making it a key focus for breeding programs aimed at improving lentil productivity. While Kazakh small-seeded varieties perform well under irrigation, there is significant potential for improvement in large-seeded varieties, especially under rainfed conditions. By incorporating genetic diversity, optimizing agronomic practices, and leveraging modern breeding techniques, Kazakh breeding programs can develop lentil varieties that achieve larger seed sizes and yield stability across diverse agroclimatic conditions.

Yield and Correlation with Number of Beans

Figure 5 provides a clear visual representation of the yield differences between the studied lentil varieties under rainfed and irrigated conditions. The figure highlights the significant impact of irrigation on yield, particularly for small-seeded varieties, which showed a dramatic increase in productivity under irrigated conditions. The figure also illustrates the variability in yield among different varieties, with some accessions (e.g., K-184, 39229, and 39113) consistently performing well under both rainfed and irrigated conditions.

The yield of lentils was found to be strongly correlated with the number of beans per plant, a key determinant of productivity. Under irrigation, small-seeded varieties outperformed large-seeded varieties, achieving a yield of 14.8±1.2 c/ha compared to 7.9±1.3 c/ha for large-seeded varieties. This difference is attributed to the higher number of beans per plant in small-seeded varieties, which allows them to maximize resource utilization and produce more seeds under optimal growing conditions. However, the absence of irrigation led to an almost twofold decrease in yield for small-seeded varieties, reducing their productivity to 6.9±0.6 c/ha. In contrast, large-seeded varieties showed more stable yields under rainfed conditions, with no significant reduction in productivity, highlighting their greater adaptability to water-limited environments.

Under dry farming conditions, the most productive accessions were LC046000223L, which achieved a yield of 13.7 c/ha, followed by LC046000103L and 23108, both with yields of 9.5 c/ha. Other accessions, such as LC04600068L and 39229, showed yields of 9.2 c/ha and 9.3 c/ha, respectively. This variability in productivity underscores the influence of varietal characteristics and growing conditions on yield potential.

Under irrigation, the highest yield was demonstrated by variety 23108, with a yield of 18.4 c/ha. Other high-performing varieties included K-184, 39229, and 39113, which achieved yields of 16.7 c/ha. Varieties such as 39203 (16.1 c/ha), LC046000103L (13.0 c/ha), and LC046000223L (13.3 c/ha) also confirmed their productivity, though their yields were lower than the top performers. These results are visually summarized in Figure 5, which illustrates the yield indicators of the studied lentil varieties under both rainfed and irrigated conditions.

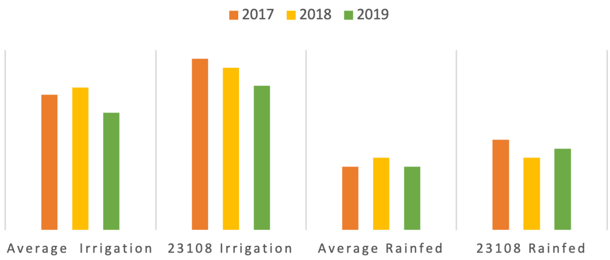


Fig. 5: Yield Trends and Correlation with Pod Production in Lentil Varieties under Rainfed and Irrigated Conditions

When growing lentils, the main goal is to achieve maximum yield with a high content of quality protein. The national economic importance of this crop is due to its diverse use and rich biochemical composition. As part of the study, a biochemical assessment of the quality of seeds of 31 lentil varieties was carried out.

The protein content of lentil seeds varied significantly between irrigated and rainfed conditions. Under irrigation, protein content ranged from 29.9 to 37.0%, while under dry farming, it ranged from 29.2 to 36.7%. Small-seeded samples consistently exhibited higher protein content than large-seeded samples under both conditions. Notable small-seeded varieties included K-2017 (37.5% under irrigation; 36.15% under dry farming), 23108 (36.74% under irrigation; 36.35% under dry farming), and 39113 (36.71% under irrigation; 36.75% under dry farming). Among large-seeded varieties, 23208 (36.65% irrigated; 36.0% dry-farmed) and LC04600068L (34.94% irrigated; 35.1% dry-farmed) stood out.

The higher protein content in small-seeded varieties is likely due to their greater metabolic efficiency and ability to allocate more resources to protein synthesis. This makes them particularly valuable for both human nutrition and animal feed, where high protein content is a key quality parameter. The recommended protein content ranges of 33-37.1% for dry farming and 32.0-37.5% for irrigated farming provide clear targets for breeders aiming to improve the nutritional quality of lentils.

The results of this study highlight the importance of selecting for traits such as the number of beans per plant, seed size, and protein content in lentil breeding programs. Small-seeded varieties, with their high yield potential under irrigation and superior protein content, are particularly promising for regions with access to reliable water resources. However, their sensitivity to drought underscores the need for further research into drought-resistant genotypes.

For rainfed conditions, large-seeded varieties offer more stable yields, though their lower protein content may limit their market value. Breeding programs should aim to combine the high protein content of small-seeded varieties with the drought tolerance and yield stability of large-seeded varieties, creating hybrids that perform well across diverse agroclimatic conditions.

Recent advancements in lentil breeding have focused not only on increasing yield but also on improving seed quality, particularly through the development of non-browning varieties. Non-browning lentils are highly valued for their aesthetic appeal, extended shelf life, and resistance to enzymatic discoloration during storage and processing. These traits are increasingly important for meeting consumer preferences and expanding export opportunities, particularly in markets where visual quality and product consistency are critical.

Recent research by Kumar *et al.* (2022) has identified key genetic markers associated with non-browning seed traits in lentils. Their study demonstrated that non-browning lentils exhibit higher levels of polyphenol oxidase (PPO) inhibitors, which prevent the enzymatic browning process. By leveraging these genetic markers, breeders can develop lentil varieties with improved seed color stability and enhanced nutritional quality, while also maintaining or even increasing yield potential.

The connection between seed quality and yield is particularly evident when considering the number of beans per plant, a key determinant of productivity. As shown in Figure 5, high-yielding varieties such as 23108 and K-184 not only produce a large number of beans per plant but also exhibit desirable seed quality traits, including resistance to browning.

Similarly, Canadian breeding programs, led by Smith and Williamson (2020), have focused on improving lentil adaptability to diverse climatic conditions through advanced genomic tools. In contrast, this study relies primarily on traditional breeding methods, which, while effective, may not achieve the same level of precision and efficiency as modern molecular techniques (Smith & Williamson, 2020).

To address this gap, a comparative analysis could be conducted to evaluate how the traits identified in this study (e.g., yield, protein content, and drought resistance) compare with those developed in other countries. For instance, the high-yielding variety 23108 identified in this study could be compared with similar varieties from India or Canada to assess its performance under different agroclimatic conditions. Additionally, the study could explore how the adoption of molecular breeding techniques, such as MAS or CRISPR/Cas9, could enhance the development of lentil varieties in Kazakhstan.

By providing a comparative analysis, this study could better position its findings within the global context of lentil breeding, highlighting both the unique contributions of Kazakh research and the potential for integrating international advancements into local breeding programs.

Protein Content

The primary goal of lentil cultivation is to achieve maximum yield with high-quality protein content. The economic importance of this crop is due to its diverse uses and rich biochemical composition. As part of the study, a biochemical assessment of the seed quality of 31 lentil germplasm samples was conducted.

The protein content under irrigation ranged from 29.9% to 37.0%, while under rainfed conditions, the values ranged from 29.2% to 36.7%. It was found that the protein content in small-seeded varieties was higher than in large-seeded varieties in both cultivation conditions. Specifically, among the small-seeded varieties, the following stood out: K-2017 (37.5% under irrigation; 36.15% under rainfed conditions), 23108 (36.74% under irrigation; 36.35% under rainfed conditions), and 39113 (36.71% under irrigation; 36.75% under rainfed conditions). Meanwhile, among the large-seeded varieties, notable examples included: 23208 (36.65% under irrigation; 36.0% under rainfed conditions) and LC04600068L (34.94% under irrigation; 35.1% under rainfed conditions).

The maximum protein content, both under irrigation and without irrigation, was similar for both small- and large-seeded varieties, with values of 36.7–37.0% and 36.0–36.6%, respectively. The minimum protein content in the large-seeded varieties ranged from 29.2% to 29.9%, while in small-seeded varieties, it ranged from 31.6% to 32.6%. Thus, on average, the large-seeded varieties were less protein-rich than the small-seeded varieties. According to Sorokin (2009), the protein content in lentil seeds grown in arid conditions should be higher than in areas with sufficient moisture. However, in our studies, regardless of irrigation conditions, the average protein content values across the groups remained unchanged.

In their studies, Zelentsov and Moshnenko (2016) proposed models that help identify the potential mechanisms for increasing the relative protein content.

We recommend the following protein content parameters: for rainfed conditions, it should range from 33 to 37.1%, and for irrigated conditions, it should range from 32.0 to 37.5%.

Conclusion

The research conducted in this study has successfully developed optimized lentil variety models tailored for the agroclimatic conditions of southeastern Kazakhstan. By evaluating 31 lentil varieties and hybrid populations (F1, F2, and F3), key economically valuable traits such as yield, protein content, drought resistance, and adaptability to mechanized harvesting were identified. The findings demonstrate that the 'New variety model' outperforms the standard 'Vekhovskaya' variety in both yield and protein content under both rainfed and irrigated conditions, making it a promising candidate for widespread adoption in the region.

The study underscores the importance of selecting for specific agronomic traits, such as plant height, lower pod attachment, and drought resistance, to improve both yield and quality. Small-seeded varieties, with their high protein content and yield potential under irrigation, are particularly valuable for regions with reliable water resources. However, their sensitivity to drought highlights the need for further research into drought-resistant genotypes. On the other hand, large-seeded varieties offer more stable yields under rainfed conditions, though their lower protein content may limit their market value.

The integration of advanced breeding techniques, such as Marker-Assisted Selection (MAS) and CRISPR/Cas9 gene editing, could further enhance the efficiency and precision of lentil breeding programs in Kazakhstan. By leveraging genetic markers associated with key traits such as drought tolerance, disease resistance, and protein content, breeders can accelerate the development of high-performing lentil varieties that are well-adapted to local conditions.

The economic and practical implications of these findings are significant. The adoption of high-yielding, high-protein lentil varieties can enhance food security, increase farmers' incomes, and improve the competitiveness of Kazakh lentils in domestic and international markets. Furthermore, the development of drought-resistant and mechanization-friendly varieties contributes to the sustainability of lentil production in the face of climate change and resource limitations.

Practical Results: The developed models of future varieties will serve as a guideline and direct our research in the field of breeding, helping to achieve the parameters outlined in the variety models. For dry regions, these optimized lentil varieties can boost food security by providing drought-tolerant crops that perform well with limited water. Mechanization-friendly varieties can reduce labor costs and increase harvesting efficiency. High-protein lentils also enhance market competitiveness, supporting both local consumption and export.

Economic Results: The varieties created based on this model will be characterized by high yield, excellent quality, and high potential in key economically valuable traits. These varieties will have a positive impact on yield and resilience to stressful conditions, thereby ensuring economic benefits.

In conclusion, this study provides a solid foundation for the continued improvement of lentil varieties in Kazakhstan. By combining traditional breeding methods with modern genomic tools, it is possible to develop lentil varieties that meet the demands of modern agriculture, ensuring sustainable production, economic efficiency, and food security in the region. Future research should focus on integrating molecular breeding techniques and expanding the genetic diversity of lentil varieties to further enhance their resilience and productivity.

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Author’s Contributions

All authors contributed equally.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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