RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
58 (4) 1773-1783, 2026
http://doi.org/10.54910/sabrao2026.58.4.28
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

LENTIL (*LENS CULINARIS* L.) PRODUCTIVITY MANAGEMENT WITH SOWING METHODS

B.R. SAIKENOV[1], A.N. ZHAMANGARAYEVA[1], A.ZH. SAIKENOVA[2], and G.S. SAKEN[2*]

[1]NJSC Kazakh National Agrarian Research University, Almaty, Kazakhstan
[2]Kazakh Research Institute of Agriculture and Plant Growing, Almaty Region, Kazakhstan
Corresponding author's email: gaukharsaken@mail.ru
Email addresses of co-authors: saikenov.bakytzhan@kaznaru.edu.kz, aigul.zhamangarayeva@kaznaru.edu.kz, alma.arai@mail.ru

SUMMARY

This study aimed to evaluate the effects of row spacing (15 and 30 cm) and biological seed treatments with biofertilizers (phosphobacillin and nitragin) on the yield formation of three lentil (*Lens culinaris* L.) cultivars. These were on large-seeded cultivars Shyraily and Sakura and small-seeded Krapinka, with the experiment held during 2024–2025 under irrigated conditions of southeast Kazakhstan. The results revealed the highest grain yield emerged in the lentil cultivar Shyraily with a 30-cm row spacing and phosphobacillin in 2024 (1.68 t/ha) and with nitragin in 2025 (1.74 t/ha), exceeding the control by 0.52–0.55 t/ha. However, the narrow-row spacing (15 cm) showed reduced productivity in all lentil cultivars during both crop seasons. The results demonstrated the optimized row spacing combined with biological treatments enhanced the lentil yield formation.

Keywords: Lentil (*L. culinaris* L.) cultivars, row spacing, biofertilizers, nitragin, phosphobacillin, productivity, dryland farming

Key findings: The large-seeded lentil (*L. culinaris* L.) cultivar Shyraily achieved the highest grain yield at a 30-cm row spacing with phosphobacillin in 2024 (1.68 t/ha) and with nitragin in 2025 (1.74 t/ha), exceeding the control by 0.52–0.55 t/ha.

Communicating Editor: Dr. Anita Restu Puji Raharjeng

Manuscript received: February 17, 2026; Accepted: May 27, 2026.

Citation: Saikenov BR, Zhamangarayeva AN, Saikenova AZH, Saken GS (2026). Lentil (*Lens culinaris* L.) productivity management with sowing methods. *SABRAO J. Breed. Genet. 58 (4) 1773-1783. http://doi.org/10.54910/sabrao2026.58.4.28*.

INTRODUCTION

Dryland farming's primary aim is to achieve stable and high yields through the efficient use of limited natural moisture reserves in Southeastern Kazakhstan (Zhumabaevna *et al*., 2025). However, this requires conserving snow and rainwater in the soil and cultivating drought-resistant crops such as spring wheat, barley, millet, and legumes. It also necessitates protecting soil from erosion and dry winds, applying fertilizers efficiently, and employing efficient crop rotations to improve soil moisture and nutrient regimes (Sarsenbekovich *et al*., 2025).

Rising costs of production have enhanced the breeder's attention to focus on resource-saving and economically efficient technologies. Modern field equipment, such as moisture-conserving tillage tools (flat-cutters, chisels, and disc harrows), minimum and zero tillage systems, global positioning system (GPS)-controlled precision seeders, and combined seeding complexes (Amazone, John Deere, and Seed Hawk), are widely used techniques to improve productivity and reduce resource use.

Despite numerous studies on lentil cultivation technologies, previous research has mainly focused either on sowing methods or on the application of biofertilizers separately, with limited attention given to their combined effects under dryland conditions. Furthermore, information regarding the interaction between sowing techniques and biofertilizer treatments for lentil production in specific agroecological conditions of Southeastern Kazakhstan remains insufficient. Therefore, the novelty of the presented study lies in the integrated evaluation of different sowing methods and biofertilizer treatments and their combined influence on lentil growth, productivity, and resource-use efficiency under dryland farming conditions. The obtained results will contribute to the development of sustainable and economically efficient lentil cultivation technologies adapted to arid and semi-arid environments.

In grain crop production, cost management ensures profitability and sustainability. Developing productive legume agrocenoses is the key direction in adaptive-landscape farming, by utilizing regional bioclimatic resources, supplying plant protein, and addressing ecological challenges (Zafar *et al*., 2012). With rising energy prices and limited resources, farming prioritizes energy-efficient crops and technologies; appropriate tillage and chemical treatments support high-protein legume production while maintaining soil fertility (Balashov and Balashov, 2013; Fedyushkin and Pasko*,* 2021).

Different seed-sowing methods considerably affect plant density, nutrition area, plant vigor, 1000-seed weight, and grain yield (Gataulina and Belyshkina, 2017; Eliseeva *et al*., 2017; Voshedskiy *et al.,* 2020). When crop rows have correct spacing, with plant-to-plant distance naturally adjusted by seed rate and germination, the crop forms a balanced canopy that uses light, water, and nutrients more efficiently. The common recommendation for sowing lentil types is in continuous rows with a 15-cm row spacing (Saikenova *et al*., 2019; Eliseeva *et al*., 2020).

Research and development in the field of lentil (*Lens culinaris* L.) breeding and agronomy are particularly vital for Kazakhstan, as the said crop has greater importance in the country's agricultural sector. Lentils are one of the leading legumes that reach active cultivation in Kazakhstan, especially in the Northern and Central regions, and they play a vital role in ensuring food security, improving crop rotation, and increasing agricultural profitability. The country's existing climatic conditions, characterized by temperature variability and aridity, extremely require developing lentil cultivars highly resistant to extreme climatic conditions, diseases, and pests, as well as providing the highest and most stable yields (Saikenova *et al*., 2021).

Therefore, the development and implementation of resource-saving technologies for cultivating promising high-protein cultivars under dryland farming conditions of Southeastern Kazakhstan are greatly essential. The novel study aimed to evaluate the effects of row spacing (15 and 30 cm) and biological seed treatments with biofertilizers (phosphobacillin and nitragin) on the yield formation of three lentil *(L. culinaris*

L.) cultivars. These are Shyraily and Sakura (large-seeded) and Krapinka (small-seeded), with the research conducted during the 2024–2025 cropping season under irrigated conditions of Southeast Kazakhstan. Nitragin, containing symbiotic nitrogen-fixing bacteria, enhances biological nitrogen fixation and improves plant nitrogen nutrition, while phosphobacillin promotes the mobilization and availability of soil phosphorus, stimulating root development and overall plant growth. Together, these biological treatments contribute to improved nutrient uptake, plant productivity, and yield formation in lentil crops.

MATERIALS AND METHODS

Experimental site and procedure

The concerned study on lentil (*L. culinaris* L.) commenced during the growing seasons of 2024–2025 at the Agro-University Educational and Experimental Station, Kazakh National Agrarian Research University, Almaty Region, Kazakhstan. The experimental site represents the dryland farming conditions of Southeastern Kazakhstan.

The experimental field sits on meadow-brown soils of the clayey foothill zone with a heavy mechanical composition. These soils are typical of lowland relief areas, intermountain valleys, and river terraces, characterized by shallow groundwater occurrence at 1.5–2.0 m depths. Before sowing, the collected soil samples underwent analysis, showing the following average values: humus content (6.15%), nitrate nitrogen (24.5 mg/kg), available phosphorus (50.8 mg/kg), available potassium (699.7 mg/kg), and available sulfur (17.8 mg/kg). Soil reaction was neutral (pH 7.5).

The experiment began as a field trial using a randomized complete block design with three replications. The experimental factors included sowing method and lentil cultivar. Two sowing methods tested comprised a narrow-row sowing with a row spacing of 15 cm and a wide-row sowing with a row spacing of 30 cm. The study objects were domestic lentil (*L. culinaris* L.) cultivars—the large-seeded cultivars Sakura and Shyraily and the small-seeded cultivar Krapinka. Cereals served as the preceding crop.

The sowing of lentil cultivars proceeded in the second 10-day period (20 days) of April in 2024 and in the third 10-day period (30 days) of April in 2025. The lentil cultivars entailed sowing at an approximate seeding rate of 2.0 million viable seeds ha^{-1}, equivalent to 90–110 kg ha^{-1}, depending on seed size and cultivar characteristics. The area of each experimental plot was 120 m² (4 m × 30 m). Field observations and measurements occurred during both growing seasons according to standard agronomic methods for lentil. The main recorded traits consisted of field germination (%) (calculated as the ratio of emerged seedlings to the number of sown seeds) and the duration of phenological stages (days from sowing to emergence, branching, budding, flowering, and full maturity). Other recorded traits were plant height (cm), measured from the soil surface to the top of the main stem at flowering, and green biomass (g per plant), determined by weighing the fresh aboveground mass of sampled plants.

Yield components also received assessment, including the number of pods per plant, seed weight per m² (g/m²), and 1000-seed weight (g). Weed infestation evaluation ensued by counting weed plants per m² at the seedling stage and before harvest. Grain yield determination comprised the harvested accounting area of each plot, adjusted to standard moisture content, and expressed in t/ha.

Performing biometric measurements continued on 10 randomly selected representative plants from each plot, excluding border rows to minimize edge effects. The obtained data sustained statistical processing using standard biometric methods appropriate for a randomized complete block design. Mean values' calculation transpired separately for each treatment and year. Treatment effects' evaluation was at a significance level of $P \leq 0.05$ to determine the influence of row spacing, cultivar, and seed treatment on growth, yield components, and productivity.

RESULTS AND DISCUSSION

During the initial plant growth after seedling emergence, the enhancement in plant height depends on varietal characteristics, weather conditions, and especially, the temperature. The agrobiological features and elements of lentil cultivation technology had a considerable effect on plant growth dynamics. Under dryland farming conditions, and depending on soil moisture availability, plant height assessment can be according to the average daily growth. Modern lentil studies continue to describe emergence-branching-flowering-pod set-maturity as discrete phases that respond predictably to agro-climatic conditions. Alba *et al*. (2020) reported the duration of phenological phases and the timing of developmental transitions play a decisive role in crop adaptation and yield formation. The optimal synchronization between environmental conditions and critical growth stages enhances plant resilience and improves yield stability.

The promising research showed the comparison of the phenological stages (sowing, emergence, branching, bud formation, flowering, and maturation) of three lentil cultivars (Shyraily, Sakura, and Krapinka). Phenological observations conducted during 2024–2025 disclosed significant year-to-year differences in growth and development stages among the lentil cultivars. According to phenological observations in 2024, the cultivar seeds sown on April 9 began to sprout after seven days, whereas in 2025, the said period reduced to five days. According to environmental data obtained from the Esik Meteorological Station, precipitation was only 0.98 mm in April 2024, while in April 2025, it significantly increased to 53.2 mm. However, the long-term average precipitation for this month was 56.5 mm. Kumar *et al*. (2020) reported that water and temperature constraints at the time of flowering and pod set considerably affect developmental timing and grain yield. These findings were consistent with our observations of a shorter vegetative period in the more favorable crop season.

Based on the data recorded during both crop seasons of 2024 and 2025, significant differences were evident among the lentil cultivars for seed germination dynamics, phenological development, and the duration of the vegetative period. These largely received influences from contrasting weather conditions between these growing seasons. In 2024, insufficient soil moisture during the early growth stages negatively affected seed germination, delaying seedling emergence. In contrast, in 2025, precipitation levels were close to the long-term average, which improved soil moisture availability, facilitated faster seed germination, and promoted the earlier emergence of seedlings. Improved moisture conditions in 2025 also accelerated the progression of phenological stages across all studied lentil cultivars.

The application of Tetramethylthiuram disulfide (TMTD) and seed inoculation with biofertilizers (nitragin and phosphobacillin) positively altered plant development, resulting in a shortening of key vegetative stages compared with the untreated control. In particular, the onset of branching and bud formation occurred 1–2 days earlier in treated variants, while flowering and full seed maturation advanced by approximately 2–3 days. The results revealed pre-sowing seed treatment enhanced early physiological activity and promoted rapid plant growth and development. Inoculation with rhizobia and compatible plant growth-promoting rhizobacteria (PGPR) can accelerate early growth by enhancing nodulation, nutrient acquisition, and stress resilience. In their study, Johnson *et al*. (2021) reported significant growth and yield benefits with rhizobial inoculation strategies in lentil crops.

Row spacing significantly influenced the duration and intensity of plant growth processes. The results enunciated the lentil plots with a 30-cm row spacing; the phenological stages seemed slightly prolonged, whereas plants grown with a 15-cm row spacing exhibited better intensive growth and a shorter overall development period. This is because the growth rate and length of the vegetative period seemed to be critical factors in determining crop adaptation to specific agro-climatic conditions. The duration of the vegetative cycle remains a limiting parameter for lentil cultivation in certain regions. Recent field studies revealed row spacing plays a crucial role in managing canopy architecture, optimizing resource capture, and enhancing yield components in lentils. In their research, Layek (2022) reported that a row spacing of 30 cm promoted yield attributes and eventually grain yield, compared with narrower row spacings.

The improved yield formation observed under the 30-cm row spacing may have an association with reduced intra-specific competition between plants for light, soil moisture, and nutrients. Wider spacing likely promoted better canopy aeration and more uniform light penetration into the crop stand, which enhanced photosynthetic activity and supported more efficient assimilate accumulation during reproductive development. Additionally, reduced plant competition under wider rows could have contributed to improved root growth and nutrient uptake efficiency, particularly under dryland conditions where soil moisture availability is a limiting factor. These conditions favored better pod formation, seed filling, and ultimately higher grain productivity. Although narrower row spacing (15 cm) promoted greater biomass accumulation due to denser plant stands, excessive competition among plants may have limited the effective utilization of environmental resources and reduced individual plant productivity.

In lacking moisture availability during the crop season of 2024, the vegetative period of lentil cultivars—from sowing to full seed maturation—ranged from 98 to 103 days. In 2025, with more favorable moisture and temperature conditions, this period considerably shortened to 88–90 days. Overall, the initiation and duration of the phenological stages occurred earlier in 2025 compared to 2024, reflecting the decisive role of soil moisture and weather conditions in regulating lentil growth and development. Improving crop competitiveness through plant density management reduces weed biomass and protects the grain yield in lentils. Balech *et al*. (2023) reported that increased seeding rate and mechanical tactics reduced the weed biomass and increased lentil yield. Al-Noor *et al*. (2024) reported the crop arrangement affects weed infestation under organic systems, supports weed reduction under denser stands, and improves crop vigor in the presented study.

Field germination assessments showed the first seedlings emerged after 5–7 days of sowing. The pre-sowing lentil seed treatment with TMTD + nitragin and TMTD + phosphobacillin significantly improved field germination and early plant establishment. Across the 2024–2025 growing seasons, the treated variants exhibited an average increase in field germination (3.8%) compared with the control. In untreated plots, field germination ranged from 85% to 95%, whereas seed treatment increased this range to 88%–97%. Recent lentil biofertilizer research reported the consistent gains in plant growth traits by applying nutrient-mobilizing microbes. Balech *et al*. (2024) documented improved nutrient economy and performance in lentils with solubilizing microbes. Gebremedhin *et al*. (2024) observed improved growth responses under bacterial consortia, matching the biometric improvements measured in this latest study.

Among the lentil cultivars, Shyraily consistently demonstrated the highest field germination and plant density across all treatments, reaching 96%–97%. The cultivar Sakura showed the highest germination rates (95%–96%) when treating seeds with TMTD + nitragin and TMTD + phosphobacillin. The lentil cultivar Krapinka had a characteristic of considerable stability in field germination, achieving a maximum of 97.3% in 2025 under the phosphobacillin treatment. The results confirmed pre-sowing seed treatment with biofertilizers, in combination with optimal row spacing, proved effective in agronomic practice for improving field germination, accelerating early growth and development, and ensuring uniform crop establishment in lentil cultivars under diverse climatic conditions.

Regarding weed infestation in lentil fields, both perennial and annual weeds were visible in lentil plots. Perennial weeds included couch grass, wild mustard, and prostrate oats, while annual weeds included buckwheat, foxtail millet, white mustard, and amaranth species.

However, weed populations attained significant influences from row spacing and pre-sowing seed treatment with TMTD + nitragin and TMTD + phosphobacillin. According to results, the number of weeds in the fields of lentil cultivars varied depending on the experimental treatments and seed inoculation with biofertilizers. Lentil seeds treated with biofertilizers (TMTD + nitragin and TMTD + phosphobacillin) displayed a substantial reduction in weed population compared with the control. In the cultivar Shyraily in 2024, the number of weeds at the seedling stage was 30.2 plants/m² in the control, 29.3 plants/m² with TMTD + nitragin, and 27.9 plants/m² with TMTD + phosphobacillin. The findings disclosed that these biofertilizers inhibit weed growth.

In lentil plots with a row spacing of 15 cm, the number of weeds was generally lower than in plots with the 30-cm row spacing, and the denser lentil plant population creates a certain barrier to weed growth and development. Although the number of weeds increased before harvest in all cultivars, in variants with microfertilizer-treated seeds, weed growth was slower, and the final number of weeds before harvesting was also lower than the control. For instance, in the cultivar Sakura during 2025, before harvest, plots treated with TMTD + nitragin at a 15-cm row spacing had 70.2 weeds/m², compared with the control (71.4 weeds/m²). Toleikiene (2025) reported that optimal row spacing (30 cm) remarkably improved lentil growth and seed yield under semi-arid conditions by balancing plant competition and resource utilization. These findings were greatly analogous to the row spacing effects observed in the concerned study.

The lentil cultivar Krapinka had a slightly lesser infestation of weeds in some variants than the other two cultivars, which may be in association with its specific growth characteristics. In conclusion, the seed inoculation of TMTD + nitragin and TMTD + phosphobacillin reduced weed infestation in lentil fields. Pre-sowing treatment with biofertilizers considerably suppressed weed growth and eventually developed favorable conditions for crop growth and development. The number of weeds had influences coming from row spacing and pre-sowing seed treatment with TMTD + nitragin and TMTD + phosphobacillin (Figures 1, 2, and 3). Past studies revealed weed infestation can cause yield losses of 20%–80% in lentils, as weeds compete with the crop for moisture and nutrients due to the lentil's weak early vigor and slow canopy development (Chang *et al*., 2025). These findings further support the presented observations that weed pressure significantly influenced the lentil crop performance under differing treatments.

Variations in the biometric indicators of lentil cultivars showed the growth indicators (plant height, green biomass accumulation) and yield formation of lentil cultivars Shyraily, Sakura, and Krapinka gained notable effects in 2024 and 2025. These were dependent on row spacing and the seed inoculation of TMTD + nitragin and TMTD + phosphobacillin. In all cultivars, the use of biofertilizers increased plant height. The cultivar Shyraily treated with TMTD + phosphobacillin provided a plant height of 6%–10% higher than the control. The cultivar Sakura increased by approximately 5%–8%, and the cultivar Krapinka in 2025 displayed a plant height of 0.7–1.1 cm higher in the treated variants than the control. Similar findings have emerged in reports of previous studies on lentils and other leguminous crops. Sharma *et al*. (2021) reported that seed inoculation with plant growth-promoting rhizobacteria significantly enhanced plant height and biomass accumulation due to improved nutrient availability and biological nitrogen fixation.

Regarding green biomass accumulation, variants TMTD + phosphobacillin and TMTD + nitragin considerably enhanced biomass growth. For instance, in the cultivar Shyraily at a 15-cm row spacing, biomass reached 83.5–71.2 g, about 20% higher than the control. The cultivar Sakura at a 30-cm row spacing achieved the highest biomass with the treatment of TMTD + phosphobacillin (84.5–83.5 g). Although the biomass of the cultivar Krapinka decreased in 2025, the treated variants still exceeded the control.

The sowing methods also revealed considerable variations in green biomass. At the 15-cm row spacing, the higher biomass

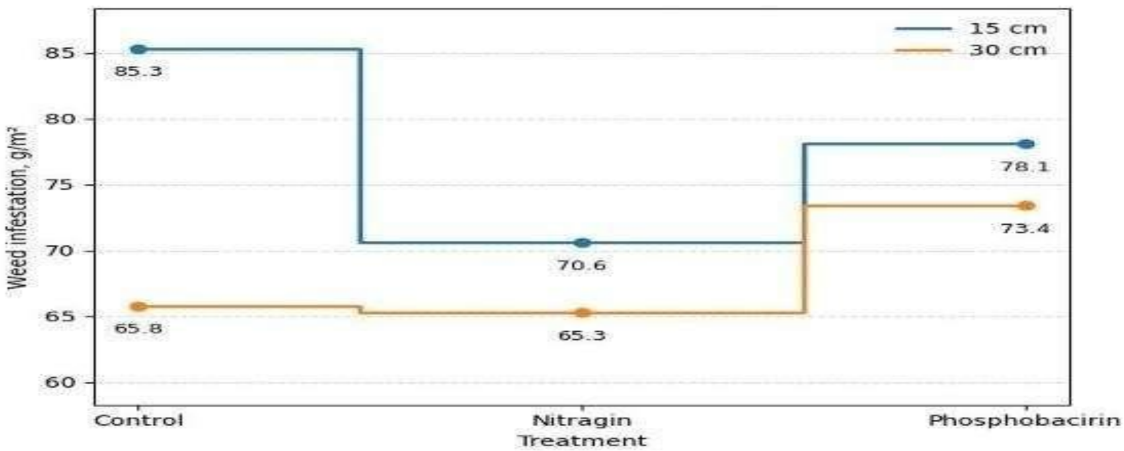

Figure 1. Weed infestation in fields of the lentil cultivar Shyraily (15 cm vs. 30 cm).

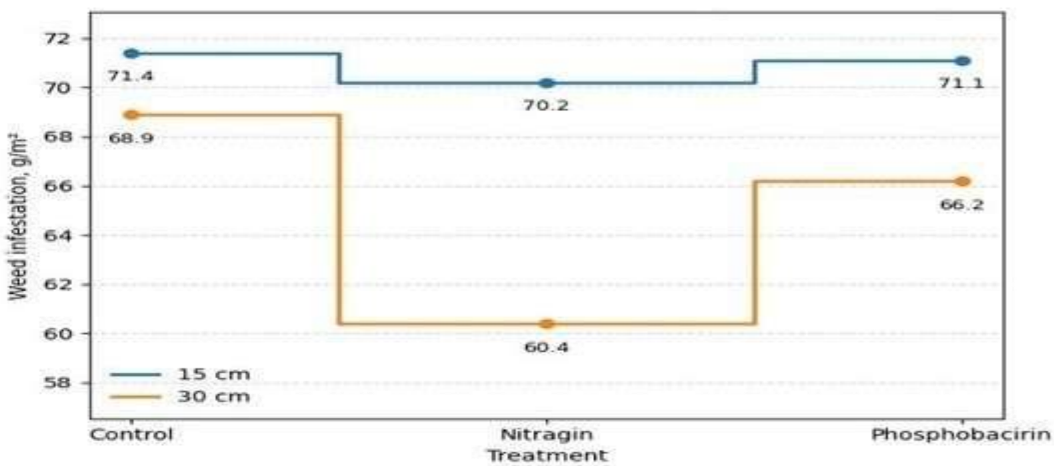

Figure 2. Weed infestation in fields of the lentil cultivar Sakura (15 cm vs. 30 cm).

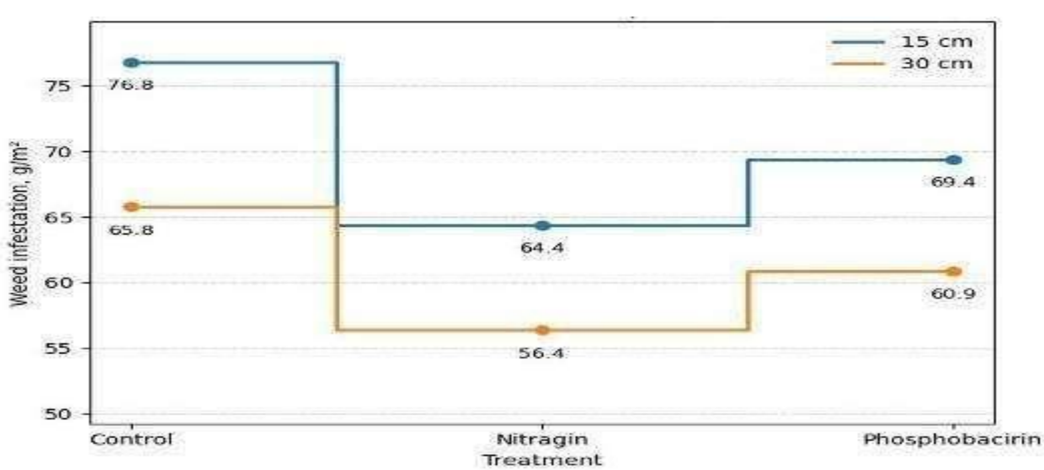

Figure 3. Weed infestation in fields of the lentil cultivar Krapinka (15 cm vs. 30 cm).

occurred due to a denser plant growth creating a favorable microclimate. However, excessive plant density under narrow-row spacing likely increased interplant competition for light, moisture, and nutrients, which reduced pod formation and seed-filling efficiency. In contrast, the 30-cm row spacing provided a more balanced canopy structure and better resource distribution, resulting in improved reproductive development and a higher grain yield. At the 30-cm row spacing, although plant height was slightly higher, green biomass was lower, likely due to an increased light and nutrient availability from sparse sowing. Singh *et al*. (2022) observed that narrower row spacings boosted total biomass per unit area due to better canopy structure and better light interception. In contrast, wider row spacings enhanced individual plant growth but did not always enhance the total biomass accumulation. These findings supported the current results that the combined application of microbial inoculants and optimized sowing methods plays a decisive role in biomass formation and yield development in lentil cultivation.

Under a 15-cm row spacing, the denser plant arrangement promoted rapid canopy closure and increased total biomass accumulation per unit area. However, the higher plant density also intensified intra-specific competition for light, soil moisture, and available nutrients, particularly during the reproductive stages of development. As a result, although vegetative growth was more intensive, the allocation of assimilates toward reproductive organs was less efficient, which may explain the lower number of pods per plant and reduced 1000-seed weight than the 30-cm row spacing. Moreover, limited light penetration within the dense canopy likely reduced photosynthetic efficiency in lower plant layers, negatively affecting seed filling and individual plant productivity. These findings indicate that excessive plant density under narrow row spacings may favor vegetative biomass production rather than optimal yield structure formation in lentil crops.

A comparative assessment of microfertilizer treatments demonstrated that the combination of TMTD + phosphobacillin produced the highest values of biometric traits across all lentil cultivars. The superior performance of this variant can refer to the activity of phosphate-mobilizing bacteria, which stimulated root system development and enhanced the nutrient uptake efficiency. Improved phosphorus availability in the rhizosphere likely contributed to intensified physiological processes and robust vegetative growth and development. Although the TMTD + nitragin treatment also positively influenced plant growth and development, its effectiveness was slightly lower than the phosphobacillin. The results suggested that under the existing soil and climatic conditions, phosphorus mobilization played a more decisive role in promoting lentil growth than nitrogen fixation alone. Kumar *et al*. (2022) also concluded that the phosphate-mobilizing bacteria significantly enhanced root system development and improved nutrient uptake efficiency in leguminous crops, ultimately leading to better growth performance and yield formation.

The seed inoculation with biofertilizers, particularly TMTD + phosphobacillin, notably enhanced plant height and green biomass accumulation. A row spacing of 15 cm promoted higher biomass production, whereas the 30-cm row spacing favored increased plant height and improved yield components. Similar effects of row spacing on canopy structure, resource utilization, and seed yield in lentils had previous reports from Yadav *et al.* (2021) and Singh *et al.* (2022).

Thus, comparing biometric indicators of studied lentil cultivars, one can conclude the observed improvements in plant height, green biomass accumulation, and root system development had the management of seed inoculation with biofertilizers (especially TMTD + phosphobacillin) and optimized row spacing. They highlight the importance of fine-tuning specific elements of varietal technology. Under mountainous steppe conditions, such targeted optimization enables the production of maximum seed yields with superior nutritional quality in lentils.

According to yield-related traits and seed productivity, as row spacing increased from 15 cm to 30 cm, the number of pods also increased. The pre-sowing seed treatment with TMTD + nitragin and TMTD + phosphobacillin raised this indicator to 15–21 pods compared with the control variant (12–19 pods). Similar effects of improved pod formation through biological seed inoculation were in reports from Sarker *et al*. (2021). They noted that microbial inoculants enhanced the reproductive organ formation in legumes by improving nutrient availability and nitrogen fixation. Seed weight per one m² increased from 92.0 to 168.0 g/m², depending on the row spacing and pre-sowing inoculation. The 1000-seed weight decreased from 62.0 to 42.0 g at a 15-cm row spacing and 82.0 to 75.0 g at a 30-cm row spacing.

The positive effect of wider row spacings and biofertilizer seed treatments on lentil productivity was in close association with changes in individual yield components. Under the 30-cm row spacing, plants developed under reduced competition for moisture, nutrients, and solar radiation, which promoted better branching and reproductive organ formation, resulting in more pods per plant. Improved canopy structure and light distribution under wider spacing also likely enhanced photosynthetic efficiency during seed filling, contributing to increased seed weight per m². Furthermore, pre-sowing seed treatment with nitragin and phosphobacillin improved nutrient availability and root activity through enhanced biological nitrogen fixation and phosphorus mobilization, which positively affected assimilate accumulation and seed development. These physiological advantages contributed to an enriched 1000-seed weight, particularly in treatments combining wider row spacings with biofertilizer application. Thus, the interaction between optimized plant density and enhanced nutrient uptake efficiency played a decisive role in improving yield structure and overall grain productivity in lentils.

The highest yield of the lentil cultivar Shyraily (1.74 t/ha) resulted in plots sown at a 30-cm row spacing and seeds treated with TMTD + nitragin, whereas at the 15-cm row spacing in the control variant, the yield decreased to 1.01 t/ha. For the cultivar Sakura, the number of pods increased from 20 to 23 as row spacing rose from 15 cm to 30 cm. Seed weight per one m² ranged from 88.0 to 126.0 g at the 15-cm row spacing and 92.0 to 168.0 g at the 30-cm row spacing. The highest grain yield appeared in the cultivar Sakura plots sown at a 30-cm row spacing and the seeds treated with TMTD + nitragin or TMTD + phosphobacillin, reaching 1.68–1.51 t/ha. However, at the 15-cm row spacing, the grain yield of the cultivar Sakura decreased by 0.12 t/ha. These results were consistent with the findings by Kumar *et al*. (2022), who reported that the combination of seed treatment with biofertilizers enhanced nitrogen fixation, root growth, and yield components in leguminous crops. Likewise, Singh *et al*. (2022) concluded that optimizing plant density together with microbial inoculation increased lentil grain yield by 1.5–2 times compared with the control variant.

Overall, a 30-cm row spacing combined with seed inoculation with biofertilizers (especially TMTD + nitragin) increased the grain yield 1.5–2 times across all cultivars. The TMTD + nitragin significantly increased plant height, pod number, and grain yield, while TMTD + phosphobacillin, in some cases, enhanced seed weight.

CONCLUSIONS

The lentil cultivars responded differently to climatic conditions and pre-sowing treatments with TMTD + nitragin and TMTD + phosphobacillin. Seed inoculation shortened the sowing-germination period, improved field germination, reduced early weed infestation, and enhanced plant height and green biomass accumulation. Pre-sowing treatments significantly improved yield components, including the number of pods per plant, seeds per pod, 1000-seed weight, and overall productivity. The cultivar Shyraily demonstrated the highest yield increase (1.68–1.74 t/ha) at a 30-cm row spacing, exceeding the control by 0.52–0.55 t/ha, while the cultivar Sakura yielded 1.38 t/ha and was 0.50 t/ha above the control. Overall, optimized sowing methods combined with microfertilizer inoculation substantially improved lentil growth, yield formation, and production efficiency, warranting further agronomic evaluation of these cultivars.

ACKNOWLEDGMENTS

This research was conducted within the framework of program-targeted funding provided by the Ministry of Agriculture of the Republic of Kazakhstan for 2024–2026 under Budget Program 267, Subprogram 101 (BR22885414), «Creation of productive leguminous crop`s varieties based on methods of biology development their varietal technology and primary seed production».

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