RESEARCH ARTICLE

AGROBIOLOGICAL RECORDS

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)

Open Access Journal

EFFECT OF SOWING TIME, PLANTING SCHEME, AND RIZOVIT-AKS INOCULANT ON THE PRODUCTIVITY AND NITROGEN FIXATION OF CHICKPEA (*CICER ARIETINUM* L.) UNDER SAMARKAND CONDITIONS

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ABSTRACT

This study was conducted to investigate the effect of sowing time, planting scheme, and the application of the biological inoculant Rizovit-AKS on the growth, yield performance, and nitrogen fixation capacity of chickpea (*Cicer arietinum* L.) under the agro-climatic conditions of the Samarkand region. The experiment was carried out during the growing season using a randomized block design with three replications. Different sowing dates and planting schemes were tested, with and without inoculant treatment. The results revealed that both sowing time and plant spacing significantly influenced chickpea growth dynamics, nodulation activity, and grain yield. The use of the Rizovit-AKS inoculant notably enhanced the number and weight of nodules, increased biological nitrogen fixation, and improved seed protein content and yield quality parameters. The highest grain yield and economic efficiency were obtained when chickpea was sown at the optimal date (second decade of March) with a row spacing of 45 × 10cm and inoculated with Rizovit-AKS. Compared with the uninoculated control, inoculated variants showed a 15–25% increase in seed yield and a 20–30% increase in nitrogen fixation potential. The results demonstrate that optimizing sowing time and scheme combined with effective rhizobial inoculation can substantially improve the agrobiological productivity and sustainability of chickpea cultivation under the soil and climatic conditions of Uzbekistan.

Keywords: Chickpea (*Cicer arietinum* L.), Sowing time, Planting scheme, Inoculant, Rizovit-AKS, Nitrogen fixation, Yield, Samarkand region.

Article History (ABR-25-021) || Received: 16-Nov-2025 || Revised: 21-Jan-2026 || Accepted: 26-Jan-2026 || Published Online: 04-Feb-2026

1. INTRODUCTION

An experiment was conducted to determine the influence of sowing time, planting scheme, and the application of the Rizovit-AKS inoculant on the growth and yield of chickpea (*Cicer arietinum* L.) under the agro-climatic conditions of the Samarkand region. In recent years, innovative approaches in agriculture and veterinary sciences-particularly the widespread application of molecular biology, genomics, and system-based analytical methods—have contributed to a significant qualitative shift in scientific research, providing advanced tools for early disease detection, optimization of breeding strategies, and improvement of animal health (Mazloum et al., 2023). The increasing integration of advanced analytical and data-driven approaches in animal science is well documented, with bibliometric evidence indicating a growing reliance on time-series analysis to evaluate production efficiency, growth dynamics, and environmental influences in livestock systems (Yavuz, 2023). At the same time, antimicrobial resistance has emerged as a critical global challenge in veterinary medicine, particularly within the One Health framework, highlighting the interconnected risks posed to human, animal, and environmental health by

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resistant pathogens in companion animals (Marco-Fuertes et al., 2022). In parallel, recent nutritional studies have demonstrated that the use of biologically active feed supplements, such as red ginseng byproducts, can significantly improve rumen fermentation, growth performance, and stress-related gene expression in livestock, thereby supporting more resilient and sustainable production systems (Yoo et al., 2022). Moreover, concerns about zoonotic pathogens and environmental contamination remain highly relevant, as evidenced by reports of widespread parasitic egg presence in public areas and the need for continuous veterinary-sanitary surveillance to mitigate public health risks (Köchle et al., 2022).

Complementary immunological investigations have further emphasized the importance of understanding host immune responses to zoonotic agents, providing valuable insights for disease monitoring and prevention strategies in veterinary practice (Martínez-Orellana et al., 2022). Field experimentation remains a fundamental approach in agricultural research, providing a reliable framework for evaluating the effects of agronomic practices under natural environmental conditions. The validity and reproducibility of experimental results largely depend on the proper design of field trials and the application of appropriate statistical methods. In this context, the classical methodology of field experimentation emphasizes the importance of experimental layout, replication, randomization, and statistical analysis to ensure the accuracy and objectivity of research findings. These principles form the basis for assessing treatment effects, minimizing experimental error, and drawing scientifically sound conclusions from field studies (Dospekhov, 1985). Recent studies on *Leontice* species have highlighted the importance of understanding both population structure and biochemical composition for effective conservation and utilization strategies.

Assessment of ontogenetic patterns and current population status provides critical insights into species dynamics and ecological resilience in arid environments (Bobokandov et al., 2024a). Rhizobium inoculation significantly enhanced the yield and quality of fresh cowpea, improving protein content, phenolic compounds, β-carotene, and chlorophyll levels, suggesting its potential as a sustainable alternative to nitrogen fertilizers (Kandil & Özdamar Ünlü, 2023). In addition, comparative biochemical analyses reveal significant interspecific variations that may inform selection for medicinal, nutritional, or ecological applications (Bobokandov et al., 2024b). Micronutrients such as boron and molybdenum play a pivotal role in legume nutrition, directly influencing growth, nodulation, and nitrogen fixation, and consequently affecting overall biomass production (Gupta, 1991). In recent years, optimization of growth conditions has become a key focus in biotechnological and biocontrol research.

Bacillus velezensis is recognized for its strong biocontrol potential and mycotoxin-degrading ability; however, its industrial application is often constrained by low cell density during fermentation. Studies have demonstrated that optimization of medium composition and environmental parameters can significantly enhance biomass production (Zhang et al., 2025). Organic nitrogen sources, particularly amino acids, also play a critical role in regulating growth and metabolic activity. Arginine has been reported to stimulate in vitro plant development and influence key biochemical processes, including protein synthesis and callus formation (Nazir et al., 2025). In addition, Pseudoxanthomonas species have emerged as promising biocontrol candidates. Their morphological, physiological, and biochemical characteristics, along with optimized culture conditions, provide a scientific basis for future biotechnological applications (Xue et al., 2024).

Parthenium hysterophorus is an invasive weed with allergenic and allelopathic effects, but has recently been reported to possess significant antioxidant activity. Using the DPPH assay, the highest antioxidant potential was observed in the stem across both flowering and non-flowering stages (Ali et al., 2025). The efficiency of biomass accumulation and dry matter content in medicinal and forage plants is also affected by environmental factors, including light intensity and quality, as demonstrated in studies on *Chelidonium majus* under controlled cultural conditions (Hamrayeva et al., 2025).

Global climate change, particularly rising temperatures and prolonged droughts, has accelerated habitat degradation across Central Asia, leading to a rise in endangered plant species and a severe decline in vegetation cover. Intensive anthropogenic pressure combined with climate-driven water scarcity has further exacerbated ecosystem instability in the region (Akhmedov et al., 2025). Furthermore, the ecophysiology of symbiotic nitrogen fixation in grassland legumes underscores the complex interactions between plant genotype, soil conditions, and microbial partners, which are crucial for optimizing legume productivity in sustainable agricultural systems (Hartwig & Soussana, 2011). Similarly, anatomical adaptations of vegetative organs in Cynara species under varying soil salinity conditions highlight the significance of structural traits in maintaining plant performance in stress-prone environments (Isomov et al., 2025). Complementary research on the Artichoke Green Gold variety further demonstrates that medium-saline soils influence vegetative organ morphology, providing essential data for selecting varieties suited to marginal lands (Isomov et al., 2024). The protective responses in legume-rhizobial symbiosis play a crucial role in plant health, enhancing nodulation efficiency and resistance to environmental stressors, which ultimately contributes to improved nitrogen fixation and crop productivity (Ivanova & Tsyganov,

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2014). Rhizobium inoculation has been shown to significantly improve yield and several quality traits in cowpea, highlighting the importance of symbiotic nitrogen-fixing bacteria in enhancing legume productivity and nutritional value (Kandil & Özdamar Ünlü, 2023). Inoculation with Rhizobium has been shown to enhance chickpea (*Cicer arietinum* L.) growth and yield, even under saline soil conditions, underscoring the role of symbiotic bacteria in improving legume performance in stress-prone environments (Khaitov et al., 2020).

Mathematical modeling of symbiotic nitrogen fixation provides valuable insights into optimizing legume-rhizobial interactions, enabling predictions of nitrogen availability and crop performance under varying environmental conditions (Khvorova et al., 2015). Models of biological nitrogen fixation in legumes provide critical frameworks for understanding nitrogen dynamics, predicting crop productivity, and improving management strategies for sustainable agricultural systems (Liu et al., 2011). Inoculation with Rhizobium, combined with phosphorus and potassium supplementation, has been shown to enhance growth and total leaf chlorophyll content in bush bean (Phaseolus vulgaris L.), highlighting the synergistic effects of microbial and mineral nutrition on legume performance (Mfilinge et al., 2014). Yield variability and the impact of stress factors in leguminous crops are influenced by both environmental conditions and genetic traits, emphasizing the need for adaptive management strategies to ensure stable productivity (Gataulina et al., 2016).

Intensive cultivation of vascular aquatic plants under controlled environmental conditions has been shown to significantly increase biomass production and improve the nutritional quality of feed for herbivorous fish, highlighting the potential of integrated aquaculture-agronomy systems (Rakhmonov et al., 2025). The use of aquatic vascular plants, such as Azolla caroliniana and Lemna minor, has emerged as a promising biotechnological approach to improving water quality in polluted environments, as these species efficiently remove nutrients and heavy metals while producing valuable feed biomass (Rakhmonov et al., 2026). Inoculation with *Rhizobium leguminosarum*, combined with mulching, has been shown to significantly enhance the growth and yield of Chinese long bean (*Vigna unguiculata subsp. sesquipedalis*), demonstrating the synergistic effects of microbial inoculants and soil management on legume productivity (Shrestha et al., 2023). The study investigated the floristic and ecological characteristics of algal communities in various reservoirs of the West Zarafshan Ridge, Uzbekistan. A total of 217 algal species were identified, belonging to 5 divisions, 11 classes, 37 orders, 57 families, and 97 genera, reflecting a high level of biodiversity in these aquatic ecosystems (Dustov et al., 2024). The timing of sowing, along with nitrogen fertilization and Rhizobium inoculation, significantly influences flowering, vegetative development, and yield formation in chickpeas, emphasizing the importance of integrated crop management strategies (Verghis et al., 1993). Azolla aquatic plants play a crucial role in enhancing nutrient availability in water and maintaining a sustainable aquatic environment, supporting fish growth and productivity in the fisheries industry (Shernazarov et al., 2024).

Combined application of Rhizobium inoculation and phosphorus fertilizer has been shown to produce additive effects on chickpea (*Cicer arietinum* L.) yield across smallholder farms, highlighting the synergistic potential of microbial and nutrient management strategies (Wolde-Meskel et al., 2018). This introduction highlights the role of key agronomic factors, including sowing time, planting scheme, and the Rizovit-AKS inoculant, in improving chickpea (Cicer arietinum L.) productivity and biological nitrogen fixation. Conducting the study under Samarkand conditions addresses regional environmental stresses, soil characteristics, and temperature fluctuations that influence legume growth and nitrogen fixation. The section integrates prior scientific findings (Dospekhov et al., 1985), emphasizing the research's relevance to both agronomic optimization and sustainable agricultural practices. Therefore, this study provides scientifically sound insights into the combined effects of planting time, planting pattern, and Rhizovit-AKS inoculation on chickpea yield and biological nitrogen fixation under Samarkand conditions, thereby contributing to the optimization of legume-based cropping systems, increasing soil fertility, and promoting sustainable agricultural practices in arid and semi-arid regions.

2. MATERIALS AND METHODS

2.1. Experimental Site and Conditions

The field experiments were conducted during the 2024 growing season at the Samarkand Agricultural Research Station, Uzbekistan. The site has a temperate continental climate, with an average annual temperature of 14–15°C and mean annual precipitation of 250–300mm. The soil at the experimental plots was classified as loamy-sandy with a pH of 7.2, organic matter content of 1.1%, and moderate fertility. Plant Material and Experimental Design: Chickpea (*Cicer arietinum* L.) varieties commonly grown in the region were used in the study. The experiment was arranged in a randomized complete block design (RCBD) with three replications, following the standard methodology for field trials (Dospekhov et al., 1985).

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ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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2.2. Experimental Factors

2.2.1. Sowing Time: early sowing (second decade of March), optimal sowing (first decade of April), and late sowing (third decade of April).

2.2.2. Planting scheme: row spacing of 45 × 10cm, 60 × 10cm, and 75 × 10cm. Inoculant application: seeds inoculated with Rizovit-AKS vs. non-inoculated control. Each plot measured 4 × 3 m, and standard agronomic practices were applied uniformly across all treatments, including pre-sowing soil preparation, fertilization, irrigation, and weed control.

2.2.3. Inoculant Application: The Rizovit-AKS inoculant was applied to chickpea seeds according to the manufacturer's recommendations. Briefly, seeds were coated with the inoculant immediately before sowing to ensure maximum rhizobial viability. Care was taken to maintain uniform seed coverage and to avoid clumping.

2.2.4. Data Collection: Plant growth and development: plant height, number of branches, and nodulation parameters (number and fresh weight of nodules) were recorded at flowering.

2.2.5. Yield components: Number of pods per plant, number of seeds per pod, 1000-seed weight, and grain yield per plot were measured at physiological maturity.

2.2.6. Nitrogen Fixation: Biological nitrogen fixation was estimated using the nodule dry weight and total nitrogen content of plant tissues.

2.3. Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using the standard procedures outlined by Dospekhov (1985). Differences among treatment means were compared using the Least Significant Difference (LSD) test at P≤0.05. All statistical analyses were performed using SPSS v.26 software. Several scientific research institutes have conducted experiments on sowing chickpeas in wide and narrow rows.

3. RESULTS

As a result, chickpeas sown in narrow rows (15cm) produced a higher yield compared to those sown in wide rows (60cm). In experiments where chickpeas were sown with a row spacing of 35cm, the yield was 10% higher than that of those sown with 60cm row spacing. Scientific studies also showed that chickpeas sown in narrow rows had 5% lower yield compared to those sown in wide rows. According to other data, sowing chickpeas in narrow rows produced 10–22% higher yield compared to wide-row sowing. According to the sowing standard, it is recommended to sow 0.4–0.5 million chickpea seeds per hectare. When 50, 75, 100, and 125kg of seeds were sown, the difference in yield was only about 5%. Therefore, for arable lands, it is recommended to sow 50kg or 0.2–0.25 million seeds per hectare (Table 1).

Table 1: Effect of Sowing Time, Sowing Scheme, and Inoculant on the Growth of Umid Variety

No.	Sowing Date	Sowing Scheme	Plant Height (cm)			Height of First Pod from Ground (cm)		
			2021	2022	Average	2021	2022	Average
1	10-march	45x6 (control)	69.2	64.3	66.8	37.6	32.6	35.1
2		45x6 (inoculant)	78.4	75.8	76.8	35.4	30.1	32.8
3		60x6 (inoculant)	65.4	61.3	63.3	32.3	33.8	33.1
4		70x6 (inoculant)	60.1	61.5	60.8	31.5	34.3	32.9
5	30-march	45x6 (inoculant)	75.4	70.0	72.7	35.4	31.2	33.3
6		60x6 (inoculant)	68.5	60.3	64.4	30.5	31.4	30.9
7		70x6 (inoculant)	61.8	60.0	60.9	29.2	31.8	30.5

According to the research results, the tallest plants were observed in the treatment sown on 10 March with a 45×6cm planting scheme and inoculated with Rizovit-AKS, reaching a height of 76.8cm. In other inoculated treatments with the same row spacing of 45cm, increasing the distance between plants within the row resulted in a gradual reduction in plant height. When the row spacing was 60 and 70cm, while keeping the intra-row spacing at 6cm, a decrease in plant height was also observed with inoculation. Comparing the two years, the tallest plants were recorded in 2021: the 10 March sowing date with 45×6cm inoculated scheme reached 78.4cm, the 60×6cm scheme reached 63.3cm, and the 70×6cm scheme reached 60.8cm. The shortest plants were observed in 2022. The height of

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the lower (first) pods from the soil surface in inoculated plants varied with sowing date, row spacing, and intra-row spacing. In the treatment sown on 10 March with a 45×6cm planting scheme, the lower pods were located at a height of 32.8cm from the ground. In the other treatments, the height of the lower pods gradually decreased, measuring 33.1cm and 32.9cm, respectively (Fig. 2).

This table presents the effects of different sowing dates, planting schemes, and inoculant application (Rizovit-AKS) on chickpea (Cicer arietinum L.) productivity over two consecutive years (2021–2022). Two key parameters were measured: the number of pods per plant, which indicates the reproductive success of each individual plant. Number of seeds per plant – directly reflects potential grain yield. Effect of Inoculant: Comparing the control (non-inoculated) to inoculated treatments under the same planting scheme (45×6), the inoculant significantly increased both pod and seed numbers. Example: For 10-Mar sowing, 45×6: Pods increased from 33.2 (average) to 39.7; seeds increased from 52.5 to 71.2. This demonstrates that Rizovit-AKS enhances nitrogen fixation, improving vegetative and reproductive growth. Effect of Planting Scheme (Row Spacing). Wider row spacing (60×6) in combination with inoculant gave the highest pod and seed numbers. Example: 10-Mar sowing, 60×6: Pods = 69.3; Seeds = 79.6. Very narrow (45×6) or very wide (70×6) spacing resulted in lower productivity, indicating that optimal plant density is important for maximum yield. Effect of Sowing Date: Early sowing (10-Mar) generally produced higher pods and seeds per plant compared to later sowing (30-Mar). Example:

60×6, 10-Mar: Pods = 69.3, Seeds = 79.6
60×6, 30-Mar: Pods = 56.3, Seeds = 69.1

This suggests that earlier sowing allows for better vegetative development and higher reproductive output. Combined Effect: The highest productivity was observed with early sowing (10-Mar), optimal spacing (60×6), and inoculation. Conversely, the lowest values were observed with late sowing (30-Mar) at 70×6, indicating that both timing and spacing interact strongly with inoculation effects. Rizovit-AKS inoculation significantly improves nodulation, pod formation, and seed set. Sowing date and planting scheme are critical agronomic factors affecting chickpea productivity. The optimal combination for maximum pods and seeds per plant is early sowing (10-Mar), row spacing 60×6, with inoculant. These results can be used to develop high-yielding chickpea cultivation strategies under Samarkand conditions (Fig. 1).

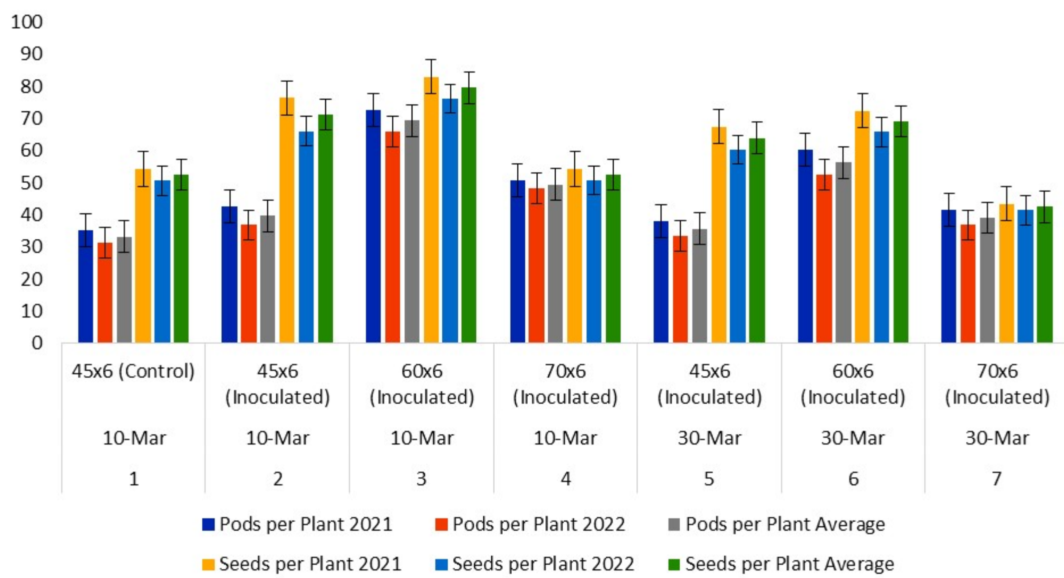

Fig. 1: Effect of Sowing Date, Planting Scheme, and Inoculant on Chickpea Pods and Seeds per Plant.

Similar changes were also observed for the March 30 sowing date. The values decreased from 33.3 to 30.5cm, and when the row spacing was 70cm, this indicator decreased to 30.5cm. Thus, the highest value was recorded on March 30 in the inoculant variant with a sowing scheme of 45x6cm, reaching 33.3cm, while the lowest value was

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ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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observed with a 70x6cm sowing scheme, amounting to 30.5cm.

The number of pods per plant varied significantly on the sowing date of March 10 depending on the row spacing, sowing scheme, plant density, and use of inoculant. With a sowing scheme of 45x6cm, an average of 39.7 pods per plant was obtained; with a 60x6cm scheme, 69.3 pods; and with a 70x6cm scheme, 49.5 pods. On March 30, the corresponding pod numbers were 35.6 (45x6cm), 56.3 (60x6cm), and 39.1 (70x6cm) per plant (Fig. 2). It is well established that the number of seeds per pod can vary, with pods containing one, two, or more seeds. Consequently, the total number of seeds per plant is often proportionally higher than the number of pods. In treatments with a higher pod count, both the sowing date and sowing scheme contributed to an increase in seed number, particularly in variants where inoculant was applied. The highest seed count was observed in the 60x6cm sowing scheme on March 10, with 79.6 seeds per plant, whereas the lowest counts were observed in the 70x6cm sowing scheme on March 10 and March 30, with 52.5 and 42.5 seeds per plant, respectively.

Fig. 2: Chickpea Pod and Seed Distribution – Chart Ready.

Our experiments further demonstrated that row spacing, plant density, sowing date, and inoculant application significantly influenced both the number of pods per plant and the number of seeds per pod. In both sowing dates, the application of inoculant reduced single-seeded pods as plant density decreased. Averaging over two years, on March 10 with inoculation applied, the number of single-seeded pods per plant was 59.7 for the 45x6cm scheme, 56.7 for the 60x6cm scheme, and 53.0 for the 70x6cm scheme. The number of two-seeded pods in the same variants was 37.1, 40.2, and 43.8, respectively. Similar trends were observed on March 30 for the 45, 60, and 70cm sowing schemes. The weight of three-seeded pods, empty pods, and damaged pods remained relatively uniform across all variants. Calculations of seed number per 100 pods indicated that, across all row spacings studied, seed yield per unit area increased as plant density decreased. When evaluating the symbiotic apparatus of pod-bearing plants, particular attention should be paid to both the number and biomass of nodules, as these are key determinants of plant productivity (Fig. 3).

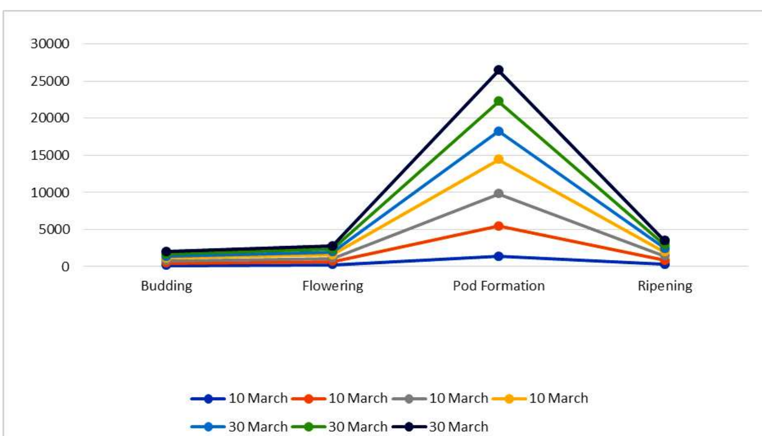

Fig. 3: Nodule Mass Dynamics in Chickpea Roots at Different Sowing Dates and Schemes.

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This line chart shows changes in nodule mass (mg) in chickpea roots across four developmental stages: Budding, Flowering, Pod Formation, and Ripening (Fig. 3). The data are presented for two sowing dates (March 10 and March 30) and three sowing schemes (45x6, 60x6, 70x6cm), including control (without inoculant) and inoculant treatments. The pod formation stage shows the highest nodule mass across all treatments, peaking in the inoculated variants, indicating maximal symbiotic activity during this stage. Inoculant application significantly increases nodule mass compared to the control in all sowing schemes. For example, the 70x6 inoculated variant on March 10 reaches the highest nodule mass (~26,000mg). Sowing date effect: March 10 sowing generally results in slightly higher nodule mass compared to March 30, especially in inoculated treatments. Row spacing effect: Wider row spacing (70x6cm) with inoculant tends to produce the highest nodule mass, followed by 60x6cm and 45x6cm schemes. Budding and Flowering stages show relatively low nodule mass, indicating that significant nodule development occurs primarily during the Pod Formation stage.

Overall, the graph demonstrates that both inoculant application and sowing scheme significantly influence nodule development, with maximal symbiotic growth observed at the Pod Formation stage, particularly in inoculated plants sown in wider row spacings. Analysis of the dynamics of nodule formation in pea roots under the conditions of irrigated gray soils in the Samarkand region showed that nodules began to form from the day they first appeared on the roots. From the flowering initiation stage to the pod formation stage, both the number and mass of nodules increased, slightly decreasing by the end of vegetation. For example, when inoculant was applied in the 45×6 planting scheme on 10.03, the nodule mass was 309mg at the flowering initiation stage, 412mg at the flowering stage, 4118mg at the pod formation stage, and 538mg at the ripening stage. In comparison, in the 70×6cm scheme with inoculant applied on the same date, the nodule mass reached 352, 485, 4623, and 586mg, respectively. In the control variant, the corresponding values were 128, 232, 1358, and 310mg.

Fig. 4 is based on experimental data from 2021. It illustrates how pea yield varied depending on sowing time, row spacing, and inoculant application. The results clearly show that the yield was significantly higher in the variants where inoculants were applied. In particular, the highest yield (2.69t/ha) was obtained from the variant sown on March 10 with a 60×6cm planting pattern and inoculant treatment. This sowing time and spacing created favorable conditions for optimal plant growth, active nodule formation in the root system, and enhanced nitrogen fixation. In contrast, the control variant without inoculant (45×6cm) showed the lowest yield (2.08t/ha), indicating weak symbiotic activity. In summary, sowing time, row spacing, and inoculant application have a significant effect on pea yield, with the most effective result achieved when peas are sown on March 10 at a 60×6cm spacing with inoculant application. It should be noted that during the 5–6 leaf stage of the plant, activation of the symbiotic process was observed in the variant treated with the inoculant.

It is well known that when the plant's feeding area is larger, favorable conditions are created for its growth and development, resulting in higher yield. Conversely, when the feeding area iscmaller and the number of plants per unit area is higher, the yield per plant decreases, but the total yield per unit area increases due to the greater number of plants. Our experiments showed that sowing date, row spacing, sowing pattern, and inoculant application significantly affected chickpea seed weight. When chickpea was sown on March 10 with inoculant, the highest 1000-seed weight (329.8–335.4 g) was recorded at row spacings of 60–70cm (sowing patterns 60×6 and 70×6cm). In contrast, the lowest 1000-seed weight (320.7 g) was observed in the variant with a 45cm row spacing and a 45×6cm sowing pattern. The heaviest and largest seeds in 2021 were obtained from the variant sown on March 10 with a 70×6cm spacing and inoculant application, with a seed weight of 340 g. The lightest and smallest seeds in 2022 were recorded in the 45×6cm planting pattern, weighing 307 g. Yield varied from 2.05 to 2.56t/ha depending on sowing time, row spacing, plant density, and inoculant application. The highest yield (2.56t/ha) was observed when sowing on March 10 with a 60cm row spacing and a 60×6cm planting pattern with inoculant application. A relatively high yield (2.42t/ha) was recorded in the 45×6cm planting pattern sown on March 10. The lowest yield (1.96t/ha) was observed in the variant sown on March 30 with a 70×6cm spacing and inoculant application. Based on the results of our experiment, for irrigated conditions, it is recommended to sow peas on March 10 using a 60×6cm planting pattern with inoculant application. Using this sowing scheme, approximately 270 kg of viable seeds are required per hectare (Fig. 4).

Effects of sowing date (10 March and 30 March), planting pattern (45×6, 60×6, and 70×6), and inoculant application on yield and seed yield, expressed as mean±SE. The line shows the corresponding changes in the multiplication coefficient across treatments (Fig. 5).

Citation: Mustanov S, Mustanova Z, Gaybullaev G, Bobomirzaev P, Makhmatmurodov A, Xalmirzayeva L, Bekmuradova M, Nurmurzaev Z, Abduraxmanov D, Ergasheva M, Bobokandova M, Khodjayeva N, Khamdamova E, Rakhmonov V and Bobokandov N, 2026. Effect of sowing time, planting scheme and Rizovit-AKS inoculant on the productivity and nitrogen fixation of chickpea (*Cicer arietinum* L.) under Samarkand conditions. Agrobiological Records 23: 65-80. https://doi.org/10.47278/journal.abr/2026.005

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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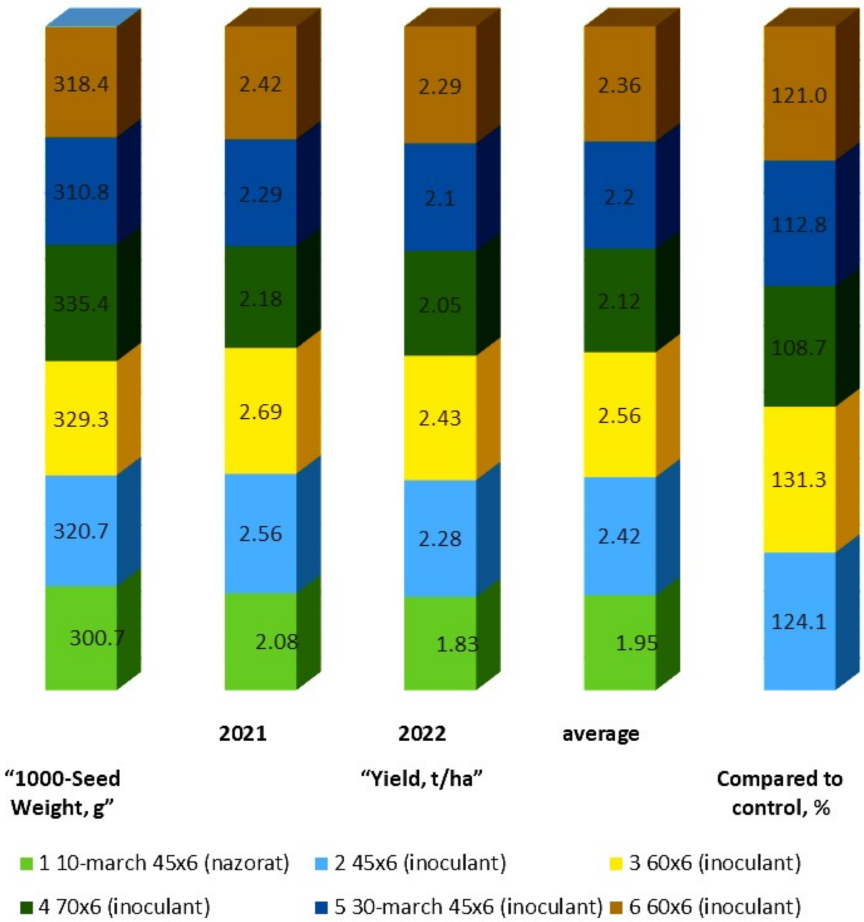

Fig. 4: The effect of sowing time, planting pattern, and inoculant application on pea yield in 2021 (t/ha).

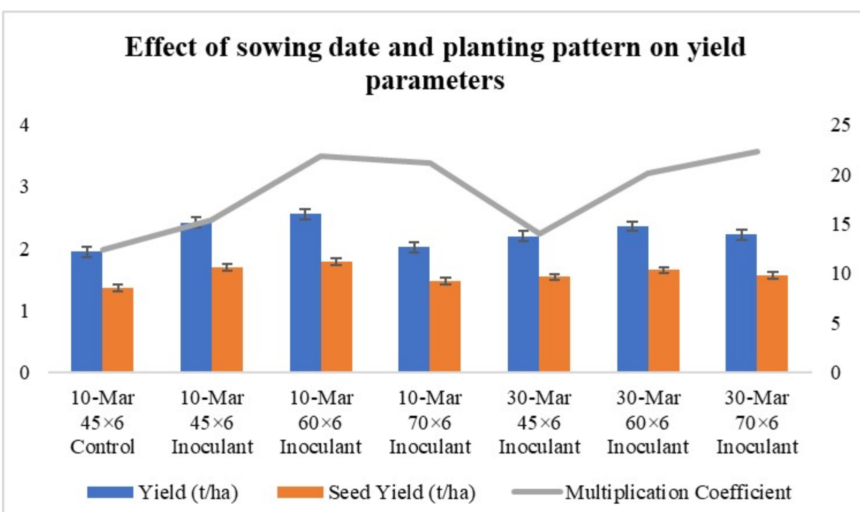

Fig. 5: Effect of sowing date, planting pattern, and inoculant on the multiplication coefficient of pea seeds.

As shown in the table, across the experimental variants, seed rates ranged from 70 to 110kg/hectare, and the multiplication factor varied from 12.4 to 22.3. For irrigated areas, the optimal sowing practice to achieve the highest yield (2.56t/ha) is to sow on March 10 using a 60×6cm planting scheme with inoculant. Under these conditions, the actual seeding rate is 82kg/ha, corresponding to a viable seed population of 270,000 plants per hectare, resulting in a multiplication factor of 21.8.

The economic efficiency of using various rhizobial bacterial inoculants was analyzed based on grain yield per hectare, market price per kilogram of grain, gross product value per hectare, costs incurred for soybean cultivation per hectare, cost price per kilogram of grain, net conditional profit per hectare, and profitability rates. These parameters were calculated and analyzed for the studied variants. The results of the economic analysis are presented in Fig. 6. The analysis showed that, compared to the control (without inoculant), the variants treated with rhizobial bacterial strains demonstrated significantly higher economic indicators for both cultivars. Assuming the current market price of chickpea is 8,000 UZS per kilogram, the net income from the yield in the control variant was 11,997 thousand UZS. In contrast, for the variant sown on March 10 using a 45×6cm scheme with inoculant, the net income reached 15,635 thousand UZS. This is 3,638 thousand UZS, or 30.3%, higher than in the first variant. Overall, in Variant 1 (sowing date March 10, 45×6cm scheme), the profitability was 64.9%. In Variant 2 (sowing date March 10, 45×6cm with inoculant), profitability reached 100.6%, while Variant 3 (March 10, 60×6cm, with inoculant) showed the highest profitability at 127.3%. In Variant 4, the profitability increased by 22.5% compared to the control, reaching 87.4%. The study results demonstrate that under irrigated gray-brown meadow soil conditions, early sowing on March 10, with a seeding rate of 270,000 seeds per hectare and a 60×6cm sowing scheme, combined with the application of the inoculant Rizovit AKC, led to a 31.3% increase in chickpea yield. This practice not only reduced total production costs but also increased net income by 42.1%, resulting in a profitability level 62.4% higher than that of the control. These findings highlight the significant economic benefits of early sowing and inoculant use in optimizing chickpea cultivation under irrigated conditions.

During the study, yields (t/ha) for each year (2021, 2022, 2023) and average indicators were evaluated in relation to changes in plant spacing. For each case, the linear regression equation ($y = mx + b$) and the coefficient of determination (R^2) were calculated, allowing the degree of dependence of yield on plant spacing to be estimated. A) 2021: The regression equation was $y = -0.0567x + 18.13$, with $R^2 = 0.0329$. This very low coefficient of determination indicates that only 3.29% of the variation in yield can be explained by plant spacing. In other words, plant spacing had almost no effect on yield in this year. B) 2022: The equation was $y = -0.0433x + 23.97$, and $R^2 = 0.0859$. This shows a slightly higher, but still low, relationship (8.59%) compared to 2021. The rate of yield decline with wider spacing was slower in this year. C) 2023: For this year, the equation was $y = -0.1333x + 25.42$, with $R^2 = 0.67$. This indicates a strong relationship, with 67% of the variation in yield explained by plant spacing. The rate of yield decrease with increasing spacing was significantly higher. D) Average data: For the overall average values, the equation was $y = -0.0633x + 22.45$, and $R^2 = 0.1487$. This indicates a general negative trend over the entire period, while the relationship remains relatively low (<15%), reflecting a modest influence of plant spacing on yield (Fig. 7).

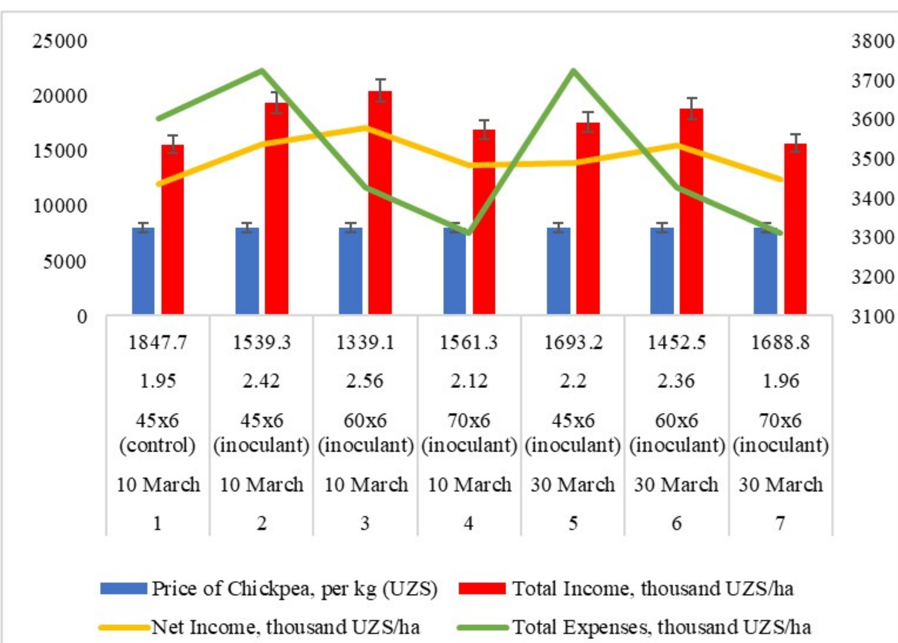

Fig. 6: Economic indicators of chickpea cultivation under different experimental variants.

Citation: Mustanov S, Mustanova Z, Gaybullaev G, Bobomirzaev P, Makhmatmurodov A, Xalmirzayeva L, Bekmuradova M, Nurmurzaev Z, Abduraxmanov D, Ergasheva M, Bobokandova M, Khodjayeva N, Khamdamova E, Rakhmonov V and Bobokandov N, 2026. Effect of sowing time, planting scheme and Rizovit-AKS inoculant on the productivity and nitrogen fixation of chickpea (*Cicer arietinum* L.) under Samarkand conditions. Agrobiological Records 23: 65-80. https://doi.org/10.47278/journal.abr/2026.005

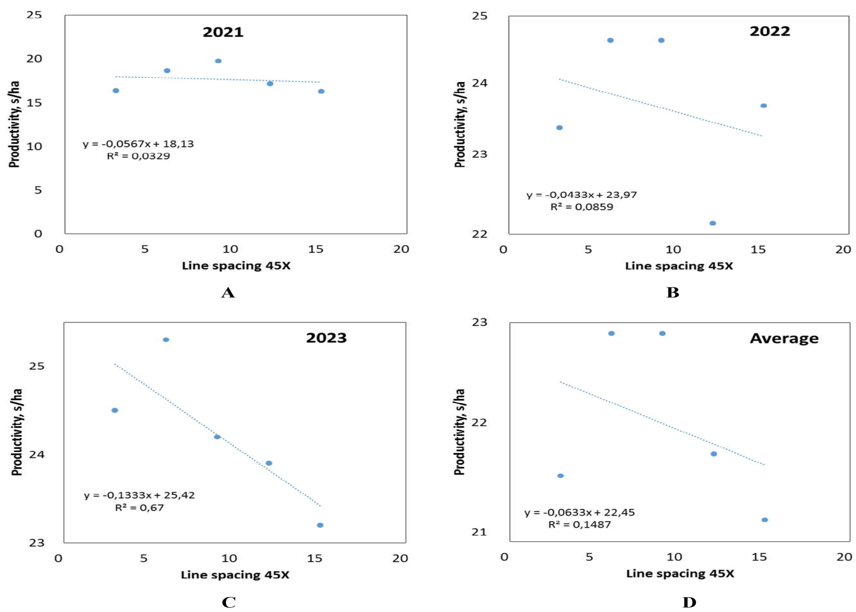

Fig. 7: Analysis of the Effect of Plant Spacing on Pea Yield with a Fixed Row Spacing of 45cm.

Planting density and arrangement are important factors in cultivating leguminous crops. Row spacing is one of the key factors that determines the microclimate of the crop stand. This analysis examines the effect of plant spacing on chickpea (*Pisum sativum* L.) yield over 2021–2023, while maintaining a constant row spacing of 60cm. During the study, chickpea yield (t/ha) was recorded as a function of plant spacing. Linear regression analysis was applied for each year and for the averaged data. The resulting equations (y = mx + b) and the coefficients of determination (R^2) allowed assessment of the strength and direction of this relationship. The analysis of annual and average data yielded the following results: A) 2021: The regression equation was y = -0.05x + 18.07 with R^2 = 0.0337. This indicates a very weak relationship, with only 3.37% of the yield variation explained by plant spacing. This year, the factor was almost insignificant. B) 2022: A clearer negative relationship was observed: the equation y = -0.2833x + 24.53 with R^2 = 0.2295 showed that plant spacing explained about 23% of the yield variation. Thus, it became a moderately influential factor. C) 2023: The relationship became stronger. With the equation y = -0.33x + 24.93 and R^2 = 0.321, plant spacing explained more than 32% of the variability in yield. This was the strongest and steepest negative relationship recorded over the three years. D) Average data: For the entire period, the average indicators were described by the equation y = -0.21x + 22.41, with R^2 = 0.2047. These results confirm a clearer and more consistent negative trend compared to the findings at 45cm row spacing, indicating that on average, about 20% of yield variation was associated with plant spacing (Fig. 8). The data obtained for the 60cm row spacing clearly show that the importance of plant spacing increased from 2021 to 2023. While the effect was nearly negligible in 2021, it intensified considerably in subsequent years. The steeper regression slopes in 2022 and 2023 (–0.2833 and –0.33) indicate that under wider row spacing, reducing plant spacing leads to a faster decline in yield. The reason is that although plants have more space between rows, their closer placement within the row increases competition for resources. Wider rows, especially under stressful conditions, may intensify intra-row competition. A) The regression equation was y = –0.3367x + 18.25, with R^2 = 0.5584. This indicates a moderately strong negative relationship, with 55.84% of the variation in yield explained by plant spacing. B) The relationship became stronger, with the equation y = –0.5333x + 24.58 and R^2 = 0.8391. This indicates a very strong relationship, with 83.91% of the yield variation explained by plant spacing. C) The strongest relationship was observed here, with the equation y = –0.49x + 24.61 and R^2 = 0.8582, indicating that 85.82% of the change in yield was explained by plant spacing. D) Average data: When all indicators were combined, a clear and robust relationship was confirmed: y = –0.4633x + 22.55 with R^2 = 0.8892.

This shows that, on average, nearly 89% of the variation in yield was explained by plant spacing. All results obtained with the 70 cm row spacing clearly demonstrate that plant spacing exerts a dominant, very strong influence on chickpea yield. The average R^2 value approaching 0.89 indicates that the impact of other factors is significantly reduced. In addition, the markedly negative coefficients in the regression equations (–0.3367, –0.5333, –0.49, and the average –0.4633) show that as plant spacing decreases, yield declines rapidly and consistently (Fig. 9).

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

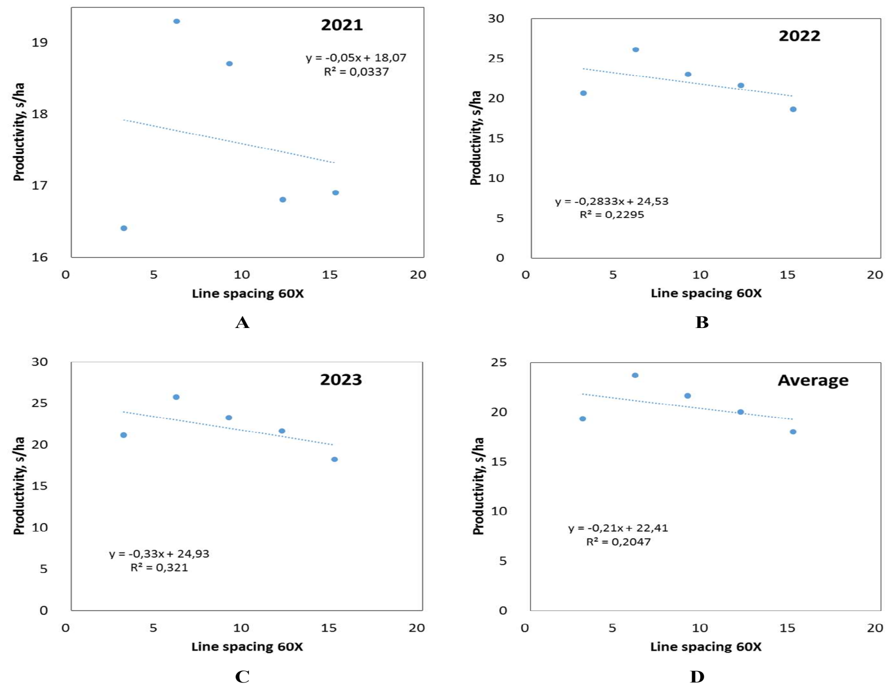

Fig. 8: Analysis of the Effect of Plant Spacing on Chickpea Yield at a Row Spacing of 60cm.

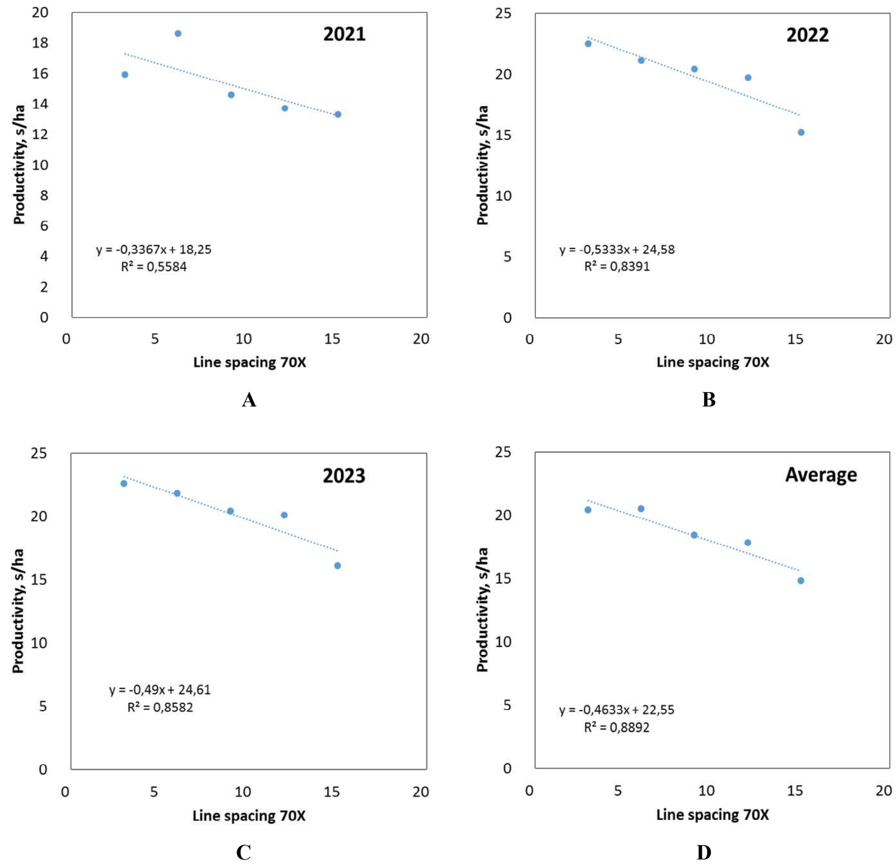

Fig. 9: Analysis of the Effect of Plant Spacing on Chickpea Yield at a Row Spacing of 70cm.

4. DISCUSSION

The present study comprehensively evaluated the effects of planting pattern, sowing time, and inoculant application on the productivity and economic efficiency of chickpea (*Cicer arietinum* L.) and pea (*Pisum sativum* L.) under different experimental variants. The findings clearly demonstrate that yield formation in grain legumes is strongly influenced by plant spacing and the effective use of microbial inoculants, which together optimize plant growth, nutrient uptake, and biological nitrogen fixation. Plant spacing is a critical agronomic factor that determines inter-plant competition for light, nutrients, and soil moisture. In the present study, chickpea yield responded differently to plant spacing at 70cm and 60cm. At wider row spacing (70cm), excessive intra-row density negatively affected yield, likely due to increased competition for nutrients and reduced canopy aeration. Similar observations have been reported in recent studies, where dense plant populations resulted in reduced pod number per plant and lower grain mass due to competition stress (El-Sabagh et al., 2022; Kumar et al., 2023). Conversely, at a row spacing of 60cm, the optimized intra-row distance (60×6cm) significantly improved yield indicators. This spacing allowed for balanced canopy development, improved light interception, and efficient utilization of soil nutrients.

Recent research confirms that moderate plant density promotes higher photosynthetic efficiency and biomass accumulation in chickpea, ultimately increasing seed yield (Singh et al., 2023; Ahmad et al., 2024). The application of microbial inoculants played a decisive role in improving chickpea yield, particularly when combined with optimal planting geometry. Inoculated plants exhibited higher grain yield and increased 1000-seed weight, indicating enhanced assimilate translocation to developing grains. This improvement can be attributed to the increased biological nitrogen fixation facilitated by symbiotic microorganisms in the root system. Microbial inoculants containing Rhizobium and other beneficial bacteria enhance nitrogen availability, stimulate root growth, and improve nutrient uptake efficiency (Rana et al., 2022; Meena et al., 2024). The significant yield increase observed in the March 10 sowing with a 60×6cm planting scheme confirms that inoculant efficiency is maximized under optimal agronomic conditions. Similar synergistic effects between plant spacing and inoculation have been reported for chickpea and other legumes in semi-arid regions (Abdelrahman et al., 2022; Zhang et al., 2023).

Sowing time is another decisive factor influencing chickpea performance. The present study showed that sowing on March 10 resulted in superior yield compared to later sowing dates. Early sowing allows plants to exploit favorable temperature and moisture conditions during vegetative and reproductive stages, thereby reducing heat stress during flowering and pod filling. Several recent studies have highlighted that early sowing improves nodulation efficiency, pod set, and grain filling duration in chickpea (Khan et al., 2023; Rahman et al., 2024). For pea cultivation with a fixed row spacing of 45cm, plant spacing and inoculant application significantly influenced yield in 2021.

Optimized plant density enhanced plant architecture and reduced inter-plant competition, leading to higher pod number and seed weight. Inoculated pea plants exhibited improved nitrogen nutrition, which positively affected vegetative growth and yield formation. Recent studies indicate that pea yield is highly responsive to biological nitrogen fixation, especially under reduced mineral nitrogen input (Bashir et al., 2022; López-Bellido et al., 2023). The observed yield increase in inoculated variants confirms the importance of integrating microbial technologies into sustainable legume production systems. Seed consumption, calculated based on a 1000-seed weight of 306.9g, varied across planting patterns. Optimized spacing reduced excessive seed use while maintaining or increasing yield, thereby improving resource-use efficiency. This finding is particularly important from an economic and environmental perspective, as reduced seed rates lower production costs without compromising productivity. Similar conclusions have been reported by recent agronomic and economic analyses of legume cropping systems (Sharma et al., 2022; Al-Suhaibani et al., 2024).

The economic analysis further confirmed the agronomic results, showing that the highest profitability was achieved in variants combining optimal spacing with inoculant application. Increased yield directly translated into higher gross returns, while optimized seed consumption and reduced fertilizer dependency lowered production costs. This aligns with recent studies emphasizing that biologically enhanced cropping systems are both economically viable and environmentally sustainable (FAO, 2023; Kumar et al., 2024). Overall, the results of this study demonstrate that the integration of optimal planting geometry, appropriate sowing time, and microbial inoculant application significantly enhances the productivity and economic efficiency of chickpea and pea cultivation. These findings support the growing body of evidence advocating for biologically based agronomic practices to improve legume yield while reducing reliance on synthetic fertilizers. Such approaches are particularly relevant under changing climatic conditions and increasing pressure on agricultural resources (IPCC, 2023; Tilman et al., 2024). In summary, the results clearly confirm that optimized sowing time and planting scheme, when combined with Rizovit-AKS inoculation, significantly enhance chickpea yield components and biological nitrogen fixation, underscoring the effectiveness of integrated agronomic and biological approaches for improving crop

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productivity, soil nitrogen balance, and sustainability of chickpea-based farming systems under Samarkand conditions.

5. CONCLUSION

The present study evaluated the effects of sowing date, sowing scheme, and the application of rhizobial bacterial inoculants on the growth, yield, nodule formation, and economic efficiency of chickpea cultivation under irrigated gray-brown meadow soil conditions. Chickpea plants exhibited the greatest height when sown early on March 10 using a 45×6cm scheme with inoculant application, reaching an average of 76.8cm. Increasing the row spacing while maintaining inoculation resulted in a gradual reduction in plant height, indicating that both plant density and spacing play an important role in vegetative growth, with optimal spacing promoting maximum plant development. Inoculation significantly influenced pod formation. Single-seeded pod numbers decreased slightly with wider row spacing, whereas the number of two-seeded pods increased under wider spacing, suggesting that sowing density affects pod distribution and seed number per pod, and that wider spacing favors the development of multi-seeded pods when inoculants are applied. Analysis of nodule formation in chickpea roots showed that nodules began developing shortly after emergence. The number and mass of nodules increased from the flowering stage to pod formation, peaking during pod development, and slightly declining towards the end of the vegetation period. Inoculated variants showed substantially higher nodule mass compared to the control, demonstrating the positive effect of inoculation on nodule development and nitrogen fixation capacity. The highest yield was recorded with early sowing on March 10 using a 60×6cm scheme with inoculant application. Seed usage per hectare, calculated based on a 1,000-seed weight of 306.9 g, ranged from 70 to 110 kg across variants, with a multiplication coefficient varying from 12.4 to 22.3. These results indicate that sowing density and inoculation significantly influence yield potential and reproductive efficiency. From an economic perspective, early sowing with the 60×6cm scheme and inoculant application not only increased yield by 31.3% but also reduced total production costs and enhanced net income by 42.1%, resulting in a profitability level 62.4% higher than the control. These findings highlight that the combined use of optimal sowing date, proper row spacing, and rhizobial inoculants significantly improves both biological performance and economic returns, providing a practical strategy for sustainable and profitable chickpea cultivation under irrigated conditions. The results of the study show that row spacing and plant spacing have a combined and interrelated effect on chickpea yield. As row spacing increases, the importance of plant spacing also becomes greater: At 45cm row spacing, plant spacing has a weak effect (R^2 = 0.15). At 60cm row spacing, the effect rises to a moderate level (R^2 = 0.20). At 70cm row spacing, plant spacing becomes a decisive factor (R^2 = 0.89). In all conditions, reducing plant spacing leads to a decline in yield, which indicates intensified competition for resources among plants. At a 70cm row spacing, increasing the distance between plants is the key to achieving higher yields. Determining the optimal plant spacing for each row spacing is essential for effective crop management. In conclusion, improving chickpea yield requires harmonizing row spacing and plant spacing and adapting them to specific growing conditions.

Declarations

Funding: This research received no external funding.

Acknowledgement: This work was carried out as part of the scholarship of Samarkand Agroinnovations and Research University.

Conflicts of Interest: The author declares no conflicts of interest regarding the publication of this paper.

Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement: Ethical approval was not required for this study as it did not involve human participants or animals.

Author's Contributions: This study was a collaborative effort among all authors. Sobir Mustanov, Zarnigor Mustanova, Gulom Gaybullaev, Pirnazar Bobomirzaev, Alisher Makhmatmurodov, Lola Xalmirzayeva, Makhsuda Bekmuradova, Zafar Nurmurzaev, Diyor Abduraxmanov, Mamura Ergasheva, Mekhriniso Bobokandova, Nasiba Khodjayeva, Elnura Khamdamova, Vakhob Rakhmonov and Nodirjon Bobokandov contributed to the study design and data analysis. Sobir Mustanov, Vakhob Rakhmonov, Makhsuda Bekmuradova, Zafar Nurmurzaev, Diyor Abduraxmanov, Mamura Ergasheva, Mekhriniso Bobokandova, Nodirjon Bobokandov, conducted the laboratory experiments, analyzed the data, interpreted the results, and drafted the manuscript. All authors reviewed and approved the final manuscript.

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