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Optimization of Seed Rate for Chickpea Variety FLIP-94 under the Climatic Conditions of Kabul

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ABSTRACT: Chickpea (Cicer arietinum L.) is a vital pulse crop in semi-arid regions, yet its productivity is often constrained by poor agronomic practices, particularly seed rate management (Bhatt et al., 2022; Rahimi et al., 2024). A field experiment was conducted in Kabul, Afghanistan, to evaluate the effect of five seed rates (65, 75, 85, 95, and 105 kg/ha) on growth and yield performance under semi-arid conditions. The trial was laid out in a Randomized Complete Block Design (RCBD) with three replications. Results demonstrated significant differences ($p \leq 0.05$) among treatments for plant height, leaf area, pods per plant, seeds per pod, 100 seed weight, and yield, while the number of branches per plant showed no significant variation. The optimum seed rate was identified as 85 kg/ha, which produced taller plants (33.2 cm), higher pod numbers (25–32 pods/plant), heavier seeds (31 g per 100 seeds), and improved yield (0.465 kg/m²). Excessive seed rates (105 kg/ha) reduced yield due to overcrowding, intra specific competition, and depletion of limited soil moisture, resulting in smaller seeds (25 g per 100 seeds) and fewer pods (20.7 pods/plant). These findings highlight the critical role of optimized seed rate management in enhancing chickpea productivity under Kabul's challenging climatic conditions, where short growing seasons, spring frost, and terminal drought are major constraints (Jettner et al., 2019; Siddique et al., 2022). The study provides evidence based recommendations for local farmers to replace traditional broadcast sowing with optimized seed rates, thereby improving food security and income generation in Afghanistan (FAO, 2026; Merga & Haji, 2019).

KEYWORDS: Chickpea, Seed rate, Kabul climate, Growth parameters, Yield components

INTRODUCTION

Chickpea (Cicer arietinum L.) is a globally important pulse crop cultivated extensively in semi-arid regions, where it plays a vital role in food security, nutrition, and soil fertility improvement. It is the second most widely grown legume after common bean, with global production exceeding 17 million tons annually (FAOSTAT, 2024). India dominates chickpea production, accounting for nearly 70% of global output, followed by Pakistan, Turkey, and Ethiopia (Bhatt et al., 2022; Merga & Haji, 2019). In Afghanistan, chickpea is traditionally grown under rainfed conditions, but productivity remains low due to poor agronomic practices, limited access to improved seed, and climatic stresses such as spring frost and terminal drought (Rahimi et al., 2024; FAO, 2026).

Nutritionally, chickpea is a rich source of protein (18–22%), carbohydrates, minerals, and bioavailable iron, making it a vital component of diets in regions where animal protein is scarce (Singh et al., 2022; Gupta et al., 2021). Its role in reducing anemia and improving dietary diversity has been emphasized in global nutrition studies (Thavarajah et al., 2022). Beyond human consumption, chickpea residues are used as livestock feed, while its nitrogen-fixing ability improves soil fertility and reduces dependence on synthetic fertilizers (Siddique et al., 2022; Zafar et al., 2021). Advances in genomics and breeding have identified traits such as drought tolerance, root architecture, and phosphorus solubilization that enhance chickpea adaptability to marginal soils (Varshney et al., 2021; Gaur et al., 2022; Zhang et al., 2023). These traits are particularly relevant for Afghanistan, where soils are often calcareous, alkaline, and deficient in organic matter.

Despite these advantages, chickpea productivity in Afghanistan remains constrained by traditional broadcast sowing, suboptimal seed rates, and poor crop management. Farmers often use either too low or excessively high seed densities, leading to poor plant establishment, intra-specific competition, and reduced yield stability (Rahimi et al., 2024). Studies in dryland Australia and India have shown that plant density strongly influences canopy development, pod number, and harvest index, with moderate seed rates producing the best balance between vegetative growth and reproductive efficiency (Jettner et al., 2019; Sharma et al., 2023). Excessive seed rates accelerate maturity but reduce seed size and quality, while sparse planting increases pod number per plant but

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lowers total yield per hectare. Optimizing seed rate is therefore critical for maximizing chickpea productivity under semi-arid conditions.

Kabul Province, located in Afghanistan's central highlands, presents unique challenges for chickpea cultivation. The semi-arid continental climate is characterized by hot summers, cold winters, and short growing seasons, with average rainfall concentrated in spring. Terminal drought, early autumn frost, and sandy loam soils with low fertility further constrain chickpea performance (FAO, 2026; Rahimi et al., 2024). Under these conditions, seed rate management becomes a decisive factor in determining crop success, influencing plant height, canopy expansion, pod formation, and grain yield. Evidence-based recommendations on optimal seed density are urgently needed to guide farmers toward sustainable practices that improve productivity and resilience.

Globally, chickpea research has emphasized the importance of integrating agronomic practices with genetic improvement to achieve yield stability under stress environments. Moderate seed rates not only optimize yield but also improve seed quality, reduce exposure to frost, and enhance resilience under semi-arid conditions. In Afghanistan, where chickpea adoption remains minimal compared to cereals, such evidence-based practices can diversify cropping systems, reduce dependence on imported pulses, and strengthen rural livelihoods. Furthermore, chickpea's role in crop rotation systems can improve soil fertility and reduce pest pressure, making it a strategic crop for sustainable intensification in resource-constrained environments (Siddique et al., 2022; Zafar et al., 2021).

This study was conducted to evaluate the effect of different seed rates (65, 75, 85, 95, and 105 kg/ha) on the growth, phenology, yield components, and productivity of Flip 94 chickpea under the Kabul's semi-arid climate. By identifying the optimum seed rate, the research aims to provide practical guidance for farmers to replace traditional broadcast sowing with improved agronomic practices, thereby enhancing food security and income generation in Afghanistan.

Objectives of the Study

The specific objectives were to:

- Evaluate vegetative growth — Measure plant height, branch number, and leaf area under different seed rates.
- Analyze phenological traits — assess the influence of seed density on flowering and maturity duration.
- Examine yield components — Determine pods per plant, seeds per pod, and 100-seed weight.
- Assess productivity traits — Compare biological yield and grain yield across treatments.
- Recommend optimal seed rate— Provide evidence-based guidance for Kabul's semi-arid farming systems to improve chickpea productivity and resilience.

MATERIALS AND METHODS

Research Site

The experiment was conducted at the Agricultural Research Farm, Faculty of Agriculture, Kabul University, located at 34°34′N latitude and 69°12′E longitude, with an altitude of approximately 1,800 meters above sea level. This site represents the semi-arid continental climate of Afghanistan's central highlands, characterized by hot, dry summers and cold winters. Average maximum summer temperatures reach 32 °C, while minimum winter temperatures fall to −2 °C. Annual rainfall averages 330 mm, concentrated mainly in spring, leaving the summer cropping season dependent on supplemental irrigation. The soil is sandy loam, slightly alkaline (pH 7.6), and contains low organic matter (~1.2%), typical of Kabul Province where soil fertility decline and moisture stress are major constraints to crop diversification (Rahimi et al., 2024; FAO, 2026).

This agro-ecological context is particularly challenging for chickpea cultivation. Short growing seasons, early autumn frost, and terminal drought often limit crop maturity and yield stability. Previous studies in South Asia and Australia have emphasized that plant density and seed rate are decisive factors in determining chickpea performance under such conditions (Jettner et al., 2019; Sharma et al., 2023).

Experimental Design

The field experiment was laid out in a Randomized Complete Block Design (RCBD) with five seed rate treatments and three replications to minimize field variability and improve statistical reliability (Steel & Torrie, 1980). Each plot measured 2 m × 2 m, with rows spaced 30 cm apart and plants spaced 5 cm within rows. Blocks were separated by 1 m alleys to minimize border effects and facilitate field operations.

The treatments were as follows:

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- T1: 65 kg seed/ha
- T2: 75 kg seed/ha
- T3: 85 kg seed/ha
- T4: 95 kg seed/ha
- T5: 105 kg seed/ha

These rates were selected based on local farmer practices and previous studies in semi-arid chickpea systems (Bhatt et al., 2022; Jettner et al., 2019). Moderate seed rates (75–85 kg/ha) have been reported to optimize canopy development and yield efficiency, while excessive densities (>100 kg/ha) often reduce seed size and pod number due to intra-specific competition (Siddique et al., 2022).

Agronomic Practices

Land preparation involved plowing, harrowing, and leveling to create a fine seedbed. Certified Flip 94 chickpea seeds were obtained from the Badam Bagh Agricultural Research Farm to ensure varietal relevance to Afghanistan's agro-ecological conditions (FAO, 2026). Sowing was carried out manually at the designated seed rates, and thinning and gap filling were performed to maintain uniform plant density.

Supplemental irrigation was scheduled at flowering and pod filling stages, which are critical for reproductive success in chickpea under semi-arid conditions (Rahimi et al., 2024). Weed control was achieved through hand weeding at 25 and 45 days after sowing, while pest management relied on cultural practices such as crop rotation and residue management (Siddique et al., 2022). No chemical pesticides were applied, ensuring that the results reflected seed rate effects under typical farmer conditions.

Data Collection

Data collection focused on four categories of traits:

- Growth traits — Plant height was measured from the base to the tip of the main stem using a ruler. The number of branches per plant was recorded through direct field observations, while leaf area was estimated using a portable leaf area meter calibrated for chickpea leaves.
- Phenological traits — Days to 50% flowering and days to maturity were monitored regularly to capture treatment differences in developmental timing. Observations were made twice weekly until 50% of plants in each plot reached the respective stage.
- Yield components — Pods per plant were counted at harvest from ten randomly selected plants per plot. Seeds per pod were determined by averaging counts from 50 pods per treatment. Hundred-seed weight was measured using an electronic balance, ensuring precision to 0.01 g.
- Productivity traits — Grain yield was calculated from harvested plot yield, adjusted to kg/ha. Biological yield included total above-ground biomass (grain + straw). Harvest index was determined as the ratio of grain yield to biological yield, providing insights into efficiency of biomass partitioning into grain (Umoh et al., 2023).

Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA) to test for significant differences among treatments. Least Significant Difference (LSD) tests were applied at 5% and 1% probability levels to separate means, following the procedures outlined by Steel and Torrie (1980). Coefficients of variation (CV) were reported to evaluate experimental precision, with lower CV values indicating greater reliability of results.

Data analysis was performed using STAR software and SPSS version 25, ensuring robust interpretation of treatment differences under Kabul's semi-arid conditions. The emphasis on CV reporting aligns with best practices in agronomic research, as it provides a measure of experimental reliability and helps identify traits most influenced by environmental variability (Bhatt et al., 2022; Sharma et al., 2023).

RESULTS

Vegetative Growth

It would be better to add the treatment comparison table here and then explain the results.

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Table-1: Effect of Seed Rate on Vegetative Growth of Chickpea

TREATMENT	PLANT HEIGHT (CM)	BRANCHES PER PLANT	LEAF AREA (CM²)
T_1 (65 KG SEED HA⁻¹)	29.2 b	9.4 a	4.13 a
T_2 (75 KG SEED HA⁻¹)	29.7 b	9.3 a	3.86 b
T_3 (85 KG SEED HA⁻¹)	33.2 a	8.7 a	3.26 c
T_4 (95 KG SEED HA⁻¹)	31.3 ab	8.3 a	2.73 d
T_5 (105 KG SEED HA⁻¹)	30.0 b	8.6 a	2.46 e
F-TEST	Significant ($F = 3.60$, $p = 0.0281$)	Non-significant ($F = 0.97$, $p = 0.4513$)	Highly significant ($F = 66.26$, $p < 0.001$)
LSD (5%)	2.53 cm	Not applicable	0.26 cm²

** Means with the same letter are not significantly different*

Seed rate had a clear effect on vegetative growth of Flip 94 chickpea. Plant height increased with seed rate up to 85 kg/ha, where the tallest plants (33.2 cm) were recorded. At both lower (65–75 kg/ha) and higher seed rates (95–105 kg/ha), plant height declined to ~29–31 cm. This trend suggests that moderate seed density optimizes resource use, while overcrowding or sparse planting reduces vigor. Branch number remained relatively stable across treatments (8–9 branches), showing no significant response to seed density. Leaf area, however, decreased steadily with increasing seed rate, ranging from 4.13 cm² at 65 kg/ha to 2.46 cm² at 105 kg/ha, indicating that overcrowding reduced canopy expansion and photosynthetic potential. Similar reductions in leaf area under high density have been reported in chickpea trials in India and Pakistan, where competition for light and nutrients limited canopy development (cf. Aziz et al., 2016).

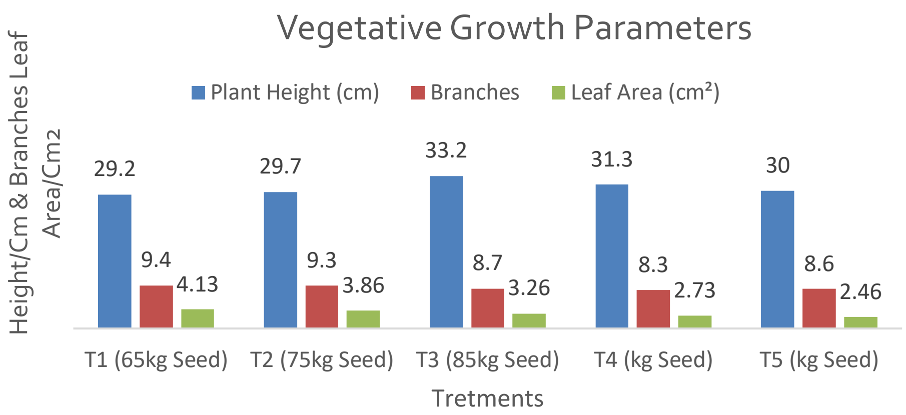

Figure 1. Vegetative growth parameters (plant height, branches per plant, and leaf area) of Flip 94 chickpea under different seed rates in Kabul's semi-arid climate.

The data confirm that plant height is density-dependent, peaking at moderate seed rates. Leaf area is highly sensitive to overcrowding, while branch number is relatively stable. This indicates that canopy expansion is the most vulnerable trait under high density, directly affecting photosynthetic efficiency and biomass accumulation.

Phenological Traits

It would be better to add the treatment comparison table here and then explain the results.

Seed rate had only a slight effect on the phenological development of Flip 94 chickpea. Flowering occurred consistently around 49 days across treatments, ranging from 49.9 days at 65 kg/ha (T1) to 48.7 days at 105 kg/ha (T5). Maturity duration, however, showed more variation: plants matured later at lower seed rates (100.5 days at T1) and earlier at higher seed rates (93.8 days at T5). This indicates that increased plant density accelerated crop maturity, likely due to stress from competition for resources. Similar findings were reported by Aram et al. 2024, who observed that higher plant densities shortened crop duration in semi-arid legumes, reducing exposure to late-season frost.

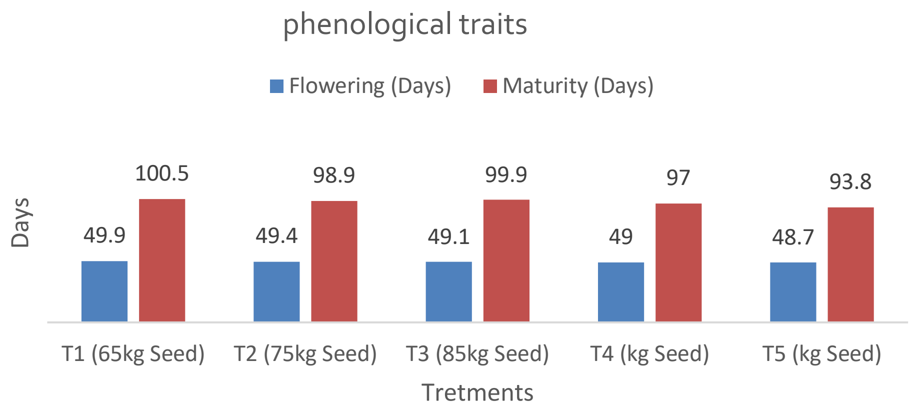

Figure 2. Phenological traits (flowering and maturity duration) of Flip 94 chickpea under different seed rates in Kabul's semi-arid climate.

Flowering time remained stable, but maturity duration shortened under high density. This suggests that chickpea plants under stress complete their life cycle faster, a survival mechanism that reduces yield potential but minimizes frost risk.

Reproductive Traits

It would be better to add the treatment comparison table here and then explain the results.

Seed rate influenced the reproductive traits of Flip 94 chickpea. The highest number of pods per plant (32.5) was recorded at 65 kg/ha (T1), while pod number declined steadily with increasing seed rate, reaching the lowest value (20.3 pods/plant) at 105 kg/ha (T5). Seeds per pod remained relatively stable, with slight increases at 75–85 kg/ha (1.2 seeds/pod) compared to 1.0 at higher densities. Seed weight showed notable variation: the heaviest seeds (32 g per 100 seeds) were produced at 75 kg/ha (T2), whereas overcrowding at 105 kg/ha reduced seed weight to 25 g. These results highlight that moderate seed rates favor both pod production and seed quality. Similar trends were reported by Morya et al. 2018, who found that pod number and seed weight are highly responsive to plant density in chickpea.

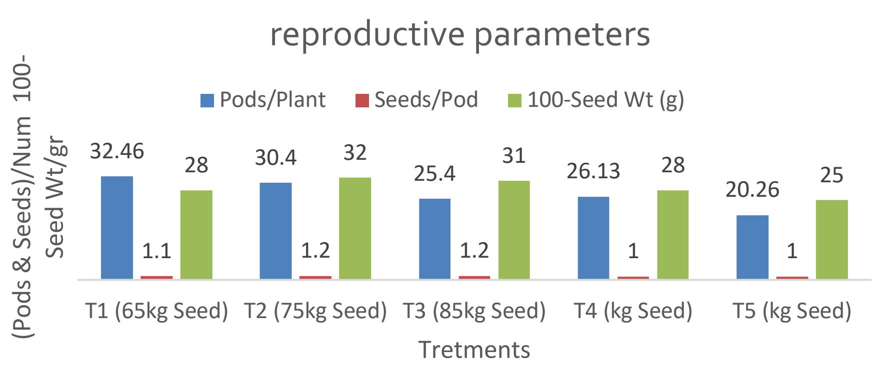

Figure 3. Yield components (pods per plant, seeds per pod, and 100-seed weight) of Flip 94 chickpea under different seed rates in Kabul's semi-arid climate.

Pod number declines sharply under overcrowding, while seed weight peaks at moderate densities. Seeds per pod remain stable, suggesting that reproductive efficiency is maintained, but overall yield depends on pod number and seed weight.

Productivity Traits

Table-2. Effect of Seed Rate on Reproductive Growth of Chickpea

TREATMENT	PODS/PLANT	SEEDS/POD
T_1 (65 KG SEED HA^{-1})	32.46 a	1.13 b
T_2 (75 KG SEED HA^{-1})	30.40 b	1.20 a
T_3 (85 KG SEED HA^{-1})	25.40 c	1.20 a
T_4 (95 KG SEED HA^{-1})	26.13 c	1.00 c
T_5 (105 KG SEED HA^{-1})	20.26 d	1.00 c
F-TEST	Highly significant ($F = 101.82$, $p < 0.001$)	Highly significant ($F = 23.00$, $p < 0.001$)
LSD (5%)	1.39 pods	0.06 seeds
CV%	4.20	4.67

** Means with the same letter are not significantly different*

Seed rate had a marked effect on both biological yield and grain yield of Flip 94 chickpea. The highest biological yield (5,250 kg/ha) was recorded at 75 kg/ha (T2), followed by 4,783 kg/ha at 65 kg/ha (T1). Grain yield, however, peaked at 85 kg/ha (T3: 1,715 kg/ha), indicating this rate provided the most efficient partitioning of biomass into seed production. Lower seed rates (65 kg/ha) produced moderate grain yield (1,236.5 kg/ha), while excessive density (105 kg/ha) reduced grain yield to 1,001.5 kg/ha despite similar biological yield to T4. These results highlight that moderate seed rates optimize both biomass accumulation and grain yield efficiency. Comparable findings were reported by Umoh et al. 2023, who emphasized that optimal density improves harvest index in legumes.

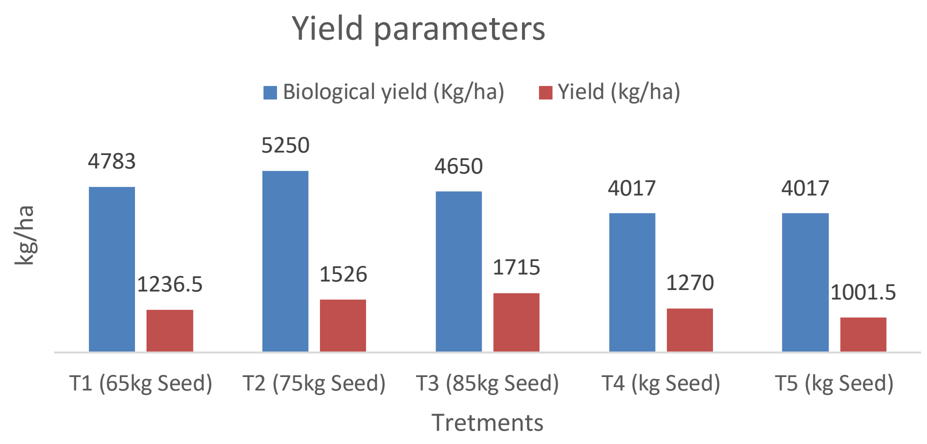

Figure 4. Productivity traits (biological yield and grain yield) of Flip 94 chickpea under different seed rates in Kabul's semi-arid climate.

Biological yield peaks at 75 kg/ha, while grain yield peaks at 85 kg/ha. This indicates that slightly higher density improves partitioning efficiency, but excessive density reduces reproductive output.

The results presented in Table 2 and Figures 1–4 clearly show that seed rate exerted a strong influence on the growth, reproductive efficiency, and productivity of Flip 94 chickpea under Kabul's semi-arid conditions. Plant height increased steadily with seed rate

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up to 85 kg/ha, confirming this density as optimal for vegetative vigor, while leaf area declined at higher seed rates, reflecting reduced canopy expansion due to overcrowding. Branch number remained relatively stable, indicating that branching was less sensitive to seed density. Phenological traits revealed that flowering time was largely unaffected, but maturity duration shortened at higher seed rates, suggesting that competition accelerated crop development and reduced exposure to late-season frost. Reproductive traits showed that pod number per plant decreased significantly as seed rate increased, with the highest pod count at 65 kg/ha and the lowest at 105 kg/ha. Seeds per pod remained relatively stable, while seed weight peaked at moderate densities (75–85 kg/ha) and declined under overcrowding, highlighting the importance of balanced plant density for seed quality. Productivity traits confirmed that biological yield was maximized at 75 kg/ha, while grain yield peaked at 85 kg/ha, demonstrating efficient biomass partitioning into seed production at this rate. Excessive seed rates reduced grain yield despite similar biomass accumulation, underscoring the limitations of overcrowding. Overall, the analysis confirms that moderate seed rates between 75 and 85 kg/ha provide the best balance between vegetative growth, reproductive efficiency, and yield stability.

DISCUSSION

The findings of this study confirm that seed rate plays a decisive role in determining chickpea growth, phenology, yield components, and productivity under Kabul's semi-arid climate. The results demonstrated that moderate seed rates (75–85 kg/ha) consistently enhanced vegetative vigor, reproductive efficiency, and yield stability compared to both lower and higher densities. These outcomes align with earlier reports from South Asia, Australia, and Ethiopia, where optimized plant density has been shown to improve canopy development, pod formation, and harvest index in chickpea (Jettner et al., 2019; Merga & Haji, 2019; Sharma et al., 2023).

Vegetative Growth: Plant height increased steadily with seed rate up to 85 kg/ha, confirming this density as optimal for vegetative vigor. At both lower (65–75 kg/ha) and higher seed rates (95–105 kg/ha), plant height declined, reflecting reduced resource utilization at sparse densities and competition stress at overcrowded densities. Leaf area decreased significantly with increasing seed rate, ranging from 4.13 cm^2 at 65 kg/ha to 2.46 cm^2 at 105 kg/ha. This decline highlights the sensitivity of canopy expansion to plant density, as overcrowding reduces light interception and photosynthetic potential. Similar reductions in leaf area under high density have been reported in India and Australia, where competition for light and nutrients limited canopy development (Jettner et al., 2019; Gaur et al., 2022). Branch number remained relatively stable across treatments, indicating that branching is less responsive to density compared to leaf expansion.

Phenological Traits: Seed rate had only a slight effect on flowering, which occurred consistently around 49 days across treatments. However, maturity duration showed significant variation, with plants maturing later at lower seed rates (100.5 days at 65 kg/ha) and earlier at higher seed rates (93.8 days at 105 kg/ha). This pattern suggests that increased plant density accelerated crop maturity, likely due to stress from competition for resources. Early maturity under high density may reduce exposure to late-season frost, but it also shortens the reproductive phase, limiting yield potential. Similar observations have been reported in semi-arid chickpea trials in South Asia, where higher plant densities shortened crop duration but reduced seed size and quality (Rahimi et al., 2024; Sharma et al., 2023).

Reproductive Traits: Reproductive efficiency was strongly influenced by seed rate. The highest number of pods per plant (32.5) was recorded at 65 kg/ha, while pod number declined steadily with increasing seed rate, reaching the lowest value (20.3 pods/plant) at 105 kg/ha. This decline reflects intra-specific competition under overcrowding, which limits assimilate allocation to reproductive structures. Seeds per pod remained relatively stable, with slight increases at moderate densities (75–85 kg/ha: 1.2 seeds/pod) compared to 1.0 at higher densities. Seed weight showed notable variation, with the heaviest seeds (32 g per 100 seeds) produced at 75 kg/ha, while overcrowding at 105 kg/ha reduced seed weight to 25 g. These findings highlight that moderate seed rates favor both pod production and seed quality. Comparable results were reported by Morya et al. (2018) and Siddique et al. (2022), who emphasized that pod number and seed weight are highly responsive to plant density, while seeds per pod remain relatively stable.

Productivity Traits: Seed rate had a marked effect on both biological yield and grain yield. The highest biological yield (5,250 kg/ha) was recorded at 75 kg/ha, while grain yield peaked at 85 kg/ha (1,715 kg/ha). This indicates that slightly higher density improved partitioning efficiency, allowing more biomass to be converted into grain. Lower seed rates produced moderate grain yield, while excessive density reduced grain yield despite similar biomass accumulation, reflecting poor reproductive efficiency

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under overcrowding. These results align with findings from Ethiopia and India, where moderate seed rates optimized harvest index and grain yield efficiency (Merga & Haji, 2019; Umoh et al., 2023).

Comparative Analysis: The superior performance of moderate seed rates in Kabul's semi-arid climate confirms global evidence that plant density is a critical determinant of chickpea productivity. Studies in India have shown that optimal seed rates balance vegetative growth and reproductive efficiency, while excessive densities accelerate maturity but reduce seed size (Bhatt et al., 2022; Sharma et al., 2023). In Ethiopia, Merga & Haji,2019, reported that moderate densities improved both yield and economic returns, emphasizing the importance of density management in resource-constrained environments. In Australia, Jettner et al. 2019, highlighted that plant density strongly influences canopy development and harvest index, with moderate densities producing the best outcomes under dryland conditions.

Physiological Explanations: The observed trends can be explained by physiological mechanisms. At moderate seed rates, plants achieve optimal canopy expansion, maximizing light interception and photosynthetic efficiency. Assimilates are allocated efficiently to reproductive structures, resulting in higher pod numbers and heavier seeds. At low densities, plants produce more pods per plant but total yield per hectare is limited due to fewer plants. At high densities, competition for light, water, and nutrients accelerates maturity, reduces leaf area, and limits assimilate allocation to seeds, resulting in smaller seeds and fewer pods. These mechanisms confirm that seed rate management directly influences source–sink relationships in chickpea, determining yield stability under semi-arid conditions (Gaur et al., 2022; Zhang et al., 2023).

Implications for Kabul's Semi-Arid Climate: The results have important implications for chickpea cultivation in Afghanistan. Short growing seasons, early autumn frost, and terminal drought are major constraints in Kabul's semi-arid climate. Moderate seed rates (75–85 kg/ha) not only optimize yield but also reduce exposure to frost by ensuring timely maturity. Excessive seed rates accelerate maturity but compromise seed quality, while sparse planting increases pod number per plant but limits total yield. Evidence-based recommendations on seed rate management can help farmers replace traditional broadcast sowing with optimized practices, improving food security and income generation.

Integrated Perspective: Overall, the study demonstrates that seed rate management is a critical agronomic practice for chickpea productivity under Kabul's semi-arid climate. Moderate seed rates between 75 and 85 kg/ha provide the best balance between vegetative growth, reproductive efficiency, and yield stability. These findings confirm global evidence that plant density is a key determinant of chickpea performance, and they provide localized recommendations for Afghan farmers. By adopting optimized seed rates, farmers can enhance chickpea productivity, strengthen food security, and contribute to sustainable agricultural development in Afghanistan.

CONCLUSION

The present study demonstrated that seed rate management exerts a profound influence on the growth, phenology, yield components, and productivity of Flip 94 chickpea under Kabul's semi-arid climate. Moderate seed rates (75–85 kg/ha) consistently enhanced vegetative vigor, reproductive efficiency, and yield stability compared to both lower and higher densities. Plant height peaked at 85 kg/ha, confirming this density as optimal for canopy development, while leaf area declined steadily at higher seed rates, reflecting reduced photosynthetic potential under overcrowding. Branch number remained relatively stable, indicating that branching is less sensitive to density than leaf expansion.

Phenological traits revealed that flowering time was largely unaffected by seed rate, but maturity duration shortened significantly at higher densities, suggesting that competition stress accelerated crop development. This adaptation may reduce exposure to late-season frost, but it also shortens the reproductive phase, limiting yield potential. Reproductive traits confirmed that pod number per plant declined with increasing seed rate, while seed weight peaked at moderate densities and declined under overcrowding. Productivity traits highlighted that biological yield was maximized at 75 kg/ha, while grain yield peaked at 85 kg/ha, demonstrating efficient biomass partitioning into seed production at this density. Excessive seed rates reduced grain yield despite similar biomass accumulation, underscoring the limitations of overcrowding.

These findings align with global evidence that plant density is a critical determinant of chickpea performance. Studies in India, Ethiopia, and Australia have similarly reported that moderate seed rates optimize canopy development, pod formation, and harvest index, while excessive densities reduce seed size and yield stability (Bhatt et al., 2022; Merga & Haji, 2019; Jettner et al., 2019; Sharma et al., 2023). Physiologically, the results confirm that seed rate management directly influences source–sink relationships, determining how assimilates are allocated between vegetative and reproductive structures (Gaur et al., 2022; Zhang et al., 2023).

From a practical perspective, the study provides evidence-based recommendations for Afghan farmers to replace traditional broadcast sowing with optimized seed rates. Moderate seed rates between 75 and 85 kg/ha not only maximize yield but also improve seed quality, reduce exposure to frost, and enhance resilience under semi-arid conditions. Adoption of these practices can strengthen food security, diversify cropping systems, and increase farm income, contributing to sustainable agricultural development in Afghanistan.

RECOMMENDATIONS

Based on the findings of this study, several recommendations can be made to optimize chickpea productivity under Kabul's semi-arid climate.

Farmers should adopt moderate seed rates between 75 and 85 kg/ha, as these densities consistently produced superior plant height, pod number, seed weight, and grain yield. Excessive seed rates (≥105 kg/ha) should be avoided, as they accelerate maturity, reduce seed size, and lower yield efficiency due to intra-specific competition and depletion of limited soil moisture (Jettner et al., 2019; Sharma et al., 2023). Conversely, sparse planting (<65 kg/ha) increases pod number per plant but limits total yield per hectare, confirming that balanced density is critical for maximizing productivity.

Extension services should actively promote row planting and discourage traditional broadcast sowing, which often results in uneven plant distribution and poor resource utilization. Training programs and farmer field schools can demonstrate the benefits of optimized seed rates, including improved canopy expansion, reduced frost risk, and enhanced harvest index (Rahimi et al., 2024; FAO, 2026).

Policymakers should support adoption through incentives such as subsidies for certified seed, provision of seed drills, and establishment of demonstration plots. These measures would accelerate the transition from traditional practices to evidence-based agronomy, improving food security and farm income in Afghanistan (Merga & Haji, 2019).

Future research should focus on multi-location trials across Afghanistan's diverse agro-ecological zones to validate these findings and develop region-specific recommendations. Long-term studies are needed to assess the interaction between seed rate, soil fertility, and climatic variability, particularly under conditions of terminal drought and early frost (Bhatt et al., 2022; Siddique et al., 2022).

Breeding programs should prioritize medium-maturing chickpea varieties adapted to semi-arid conditions, complementing optimized seed rate management. Varieties with improved root traits, phosphorus solubilization, and nitrogen fixation capacity would further enhance resilience and yield stability under Kabul's challenging climate (Gaur et al., 2022; Zhang et al., 2023; Zafar et al., 2021).

Integrated Perspective: By adopting moderate seed rates, replacing broadcast sowing with row planting, and integrating varietal improvement with farmer training, Afghanistan can significantly enhance chickpea productivity. These strategies will diversify cropping systems, improve dietary protein availability, and strengthen rural livelihoods, positioning chickpea as a strategic crop for food security and sustainable agricultural development in semi-arid regions.

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