



Integrative Assessment of Nitrogen and Irrigation Regimes on Chickpea Productivity Using Treatment-by-Trait Biplot Modeling

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Abstract: This research aimed to study the interactive impacts of nitrogen fertilization and irrigation regimes on the performance of chickpea (*Cicer arietinum* L.). A split-plot layout based on a randomized block scheme with five replications was done during the 2024–2025 growing season. The main plots consisted of four irrigation treatments: well-watered (I1), rainfed (I2), and supplementary irrigation applied at flowering (I3) or at both flowering and seed formation stages (I4). The sub-plots included three levels (N1, N2, and N3) of nitrogen starter fertilizer (0, 20, and 40 kg ha⁻¹). The first and second components of treatment-by-trait interaction model accounted for 87% of variation, allowing for reliable graphical interpretation. Biplot analysis revealed that well-watered combined with nitrogen application at 20 or 40 kg ha⁻¹ (I1-N2 and I1-N3) significantly enhanced seed yield and yield components. However, supplementary irrigation during key reproductive stages (I3-N2, I4-N2, and I4-N3) also produced favorable results, offering a water-efficient alternative to full irrigation. Traits such as yield performance, pods and seeds of plant, plant height, and chlorophyll content were identified as highly representative and responsive, while root depth, harvest index, and water use efficiency showed greater variability across treatments. The findings confirm that nitrogen fertilization is essential not only for improving early growth and establishment in semi-arid soils, but also for maximizing yield when synchronized with strategic irrigation. These results support the development of integrated nutrient and irrigation management strategies tailored to semi-arid agroecosystems to improve legume yield, resilience, and resource use efficiency.

Key words: rainfed condition, seed yield, supplementary irrigation, normal irrigation..

As a cool-season legume, chickpea (*Cicer arietinum* L.), is valued both for its nutritional content and agricultural benefits. Archaeological evidence traces its domestication back to Mediterranean regions of Asia, particularly modern-day Syria, with cultivation records dating as far back as ten thousand years ago (Igolkina *et al.*, 2021). The resilience to environmental

challenges like heat and drought, combined with its natural capacity to fix atmospheric nitrogen and high seed protein content, has made chickpea an important focus of agricultural research, particularly in Mediterranean climates and developing nations. In light of the growing impact of climate change, including reduced precipitation and rising temperatures in semi-arid regions, the adoption of climate-resilient crops and sustainable farming practices has become increasingly critical (Dutta *et al.*, 2022). Semi-arid regions extending from West Asia to North Africa which are the major chick pea growing areas are expected to be severely impacted by climate change. In these regions, adopting climate-smart management strategies has become an urgent priority. Traditionally, winter cereals dominate the cropping systems in these areas. However, the limited diversity in crop rotations has rendered local agroecosystems fragile and highly susceptible to environmental stresses (Liu *et al.*, 2022). Introducing drought-tolerant species into crop rotations, especially those that combine desirable agronomic traits with economic viability under arid conditions, offers a promising path toward greater resilience.

Above strategy often involves revisiting lesser-known or previously underutilized species, and they were historically overlooked due to their incomplete domestication or suboptimal performance under high-input farming systems. The escalating challenges posed by climate change have renewed interest in these alternative crops (Shahzad *et al.*, 2021). Among them, cool-season food legumes stand out as promising climate-smart options. Their relatively short growing cycles, suitability for cultivation during mild winters, efficient use of seasonal rainfall, deep root systems, and capacity to adjust phenological and morphophysiological traits in response to water scarcity position them as valuable components of sustainable cropping systems (Arenas-Corraliza *et al.*, 2022). However, rainfed agriculture in semi-arid regions often faces the challenge of inherently poor soil quality. These soils typically exhibit a range of limiting factors, including low organic matter content, high pH levels, coarse texture, nutrient deficiencies in the rhizosphere, shallow depth, compaction, and poor permeability, all of which negatively affect the growth and productivity

of cool-season food legumes like chickpeas (Nthebere *et al.*, 2024). In such constrained soil environments, strategic nutrient management becomes essential, particularly with regard to nitrogen supplementation. One effective approach is the application of starter fertilizer—small, targeted doses of essential nutrients applied at planting. This method supports early seedling development, root establishment, and the initiation of nitrogen-fixing nodules before the plant becomes fully capable of independent nutrient uptake.

Although, legumes possess the inherent ability to fix atmospheric nitrogen through symbiosis with diazotrophic bacteria, the provision of external nutrients, particularly during the early stages of growth, is often necessary until the plant establishes a fully functional root system and effective nodulation occurs (Becker *et al.*, 2024). This dependency becomes especially critical in semi-arid regions, where several constraints hinder chickpea production. These include low populations of native rhizobia in the soil, suboptimal temperature and moisture conditions, poor soil fertility, unscientific fertilizer application practices, and uneven rainfall distribution. Under such challenging conditions, the application of starter nitrogen fertilizer can significantly enhance early seedling vigor and expedite plant establishment (Blandino *et al.*, 2022). However, determining the optimal nitrogen dosage for each agro-climatic zone remains an area requiring targeted research. In rainfed chickpea-producing regions, irregular rainfall patterns and the concentration of precipitation during colder months frequently lead to water deficits during the crop's reproductive phase. Climate change has further intensified this issue in recent decades and given the limited availability of irrigation resources, careful irrigation scheduling has become essential (Darko *et al.*, 2024). Research indicates that one or two irrigation events, applied during critical growth stages, can alleviate terminal drought stress in rainfed chickpeas and this strategy, known as supplementary irrigation, can significantly improve yield performance. However, its effectiveness depends on several factors, including the volume and timing of irrigation, environmental and soil conditions, and the genetic characteristics of the crop (Si *et al.*, 2023). The present study was designed

to assess the impact of varying nitrogen starter doses and the application of supplementary irrigation at different growth stages on chickpea.

Materials and Methods

This research was carried out during the 2024–2025 cropping season on agricultural land located in Sararood, Kermanshah province, in western Iran (34°33'N, 47°32'E; elevation: 1356 m). According to long-term meteorological records for the region, the average annual rainfall is approximately 485 mm. The mean yearly temperature is 13.85 °C, with recorded extremes ranging from a maximum of 39 °C to a minimum of -19°C. On average, the region experiences 78 rainy days and 88 days with sub-zero temperatures per year. Annual sunshine duration averages around 1618 hours. Based on the FAO classification, the soil in the experimental area is categorized as Lixisols. The soil and temperature properties are characterized as dry xeric and mesic. According to station data and laboratory analysis, the soil has a silty loam texture up to a depth of 40 cm, composed of 22% sand, 47% silt, and 31% clay. Key chemical properties of the soil include an EC of 0.6 dS m⁻¹, total nitrogen content of 0.1%, potassium at 256 mg kg⁻¹, organic matter at 0.8 g kg⁻¹, phosphorus at 11.4 mg kg⁻¹, and a pH of 7.2.

Initial tillage operations, including plowing with a moldboard plow, were carried out in October 2023. Following primary tillage, farmyard manure was used at a rate of 20 t ha⁻¹. Secondary tillage took place in the third decade of March 2024, involving clod crushing using disk plows and rotary cultivators. After delineating the main and sub-plot areas, border discs were used to mark plot boundaries. Prior to sowing, harrows and trowels were employed to refine the soil surface, and a ridge-furrow planting system was prepared using furrowers. Phosphorus fertilizer in the form of triple superphosphate was applied via furrow placement along the ridge at an amount of 80 kg ha⁻¹. Starter nitrogen fertilizer is applied to the sub-plots equivalent to 0, 20, and 40 kg ha⁻¹, through. Seeds were manually sown in March using a ridge-furrow planting method, placing them 10 cm deep at inter-row and intra-row spacings of 25 cm and 5 cm, respectively. Each experimental plot measured 16 m² (4 m × 4 m).

Irrigation was applied using polyethylene pipes and tape lines connected to volumetric flow meters for precise water measurement. Weed were controlled through manual weeding at various stages of crop development. The research was laid out as a split-plot design (irrigation regimes as main plots and nitrogen as sun-plots) within a randomized block scheme with five replications. The four irrigation regimes were assigned as well-watered (I1), rainfed (I2), supplemental irrigation in the flowering (I3), and supplemental irrigation in the flowering and seed formation (I4). Sub-plots were allocated to three (N1, N2, and N3) nitrogen starter amounts of fertilizers (0, 20, and 40 kg N ha⁻¹).

Leaf chlorophyll content (LCC), was measured at full flowering using a SPAD-502 chlorophyll meter (Minolta, Japan). Depth of root (DR), was assessed at the end of flowering by excavating soil pits to determine maximum root penetration. At maturity, above-ground biomass was harvested by cutting the entire plant at soil level. Samples were used to obtain biomass. Seed yield (SY) and yield components consist on pod number per plant (PNP), and seed number per plant (SNP), were evaluated from a randomly selected 1 m² area within each plot using a quadrat. Plant height (PH), canopy spread (CS), hundred seed weight (HSW), and potential evapotranspiration (PE), were obtained. Regarding the ration of seed yield to biomass, the harvest index (HI), was calculated. Yield water use efficiency (YWUE) was computed as the ratio of seed yield to the total volume of water applied (irrigation plus rainfall) during the crop cycle.

The treatment by trait interaction model was via GGEbiplot application using this equation:

$$\frac{\chi_{ij} - \xi_j}{\delta_j} = \sum_{n=1}^2 \Lambda_n \Phi_{in} \Psi_{jn} + \Omega_{ij}$$

where χ_{ij} is the observed treatment i for each trait (j), ξ_j is the grand mean of χ_i in trait j , δ_j is the root square of each trait variance, Λ_n is the singular value for each component, Φ_{in} and Ψ_{jn} were amounts for χ_{ij} on each component, and Ω_{ij} is the residual amount.

Results and Discussion

The treatment-by-trait interaction biplot model effectively explained 87% of the total variability in the dataset, providing

a comprehensive overview of chickpea performance under various treatment conditions. The first and second principal components accounted for 75% and 12% of the variation, respectively. This substantial proportion of explained variance highlights the complex interrelationships among measured traits across the different experimental treatments (Sabaghnia *et al.*, 2024). As noted by Janmohammadi *et al.* (2016), an effective biplot model must reveal the underlying structure of trait associations, and the validity of the treatment-by-trait interaction analysis largely depends on the interpretability of the first two principal component axes. Consistent with findings of Sabaghnia and Janmohammadi (2016) and Porkabiri *et al.* (2019), the first two PCs were deemed sufficient for predictive purposes in two-dimensional data visualizations, such as the applied biplot model. Therefore, the interaction effects observed between treatments

and chickpea traits in this study were most accurately represented by the first two principal components, reinforcing the utility of this method in multivariate agronomic analyses.

In the polygon view of the biplot (Fig. 1), traits are considered testers, while treatments act as entries, enabling visual identification of which treatments performed best for specific traits. Treatments founded at the vertices of the heptagon represent those with either the highest or lowest performance for the traits grouped within their related sections. As indicated in Fig. 1, the treatment I1-N3 (well-watered + 40 kg ha⁻¹ nitrogen) exhibited superior performance across nearly all traits, including seed yield (SY) and yield components, except for root depth (DR), harvest index (HI), and grain yield water use efficiency (YWUE). These results suggest that applying 40 kg ha⁻¹ nitrogen under optimal irrigation conditions offers the most

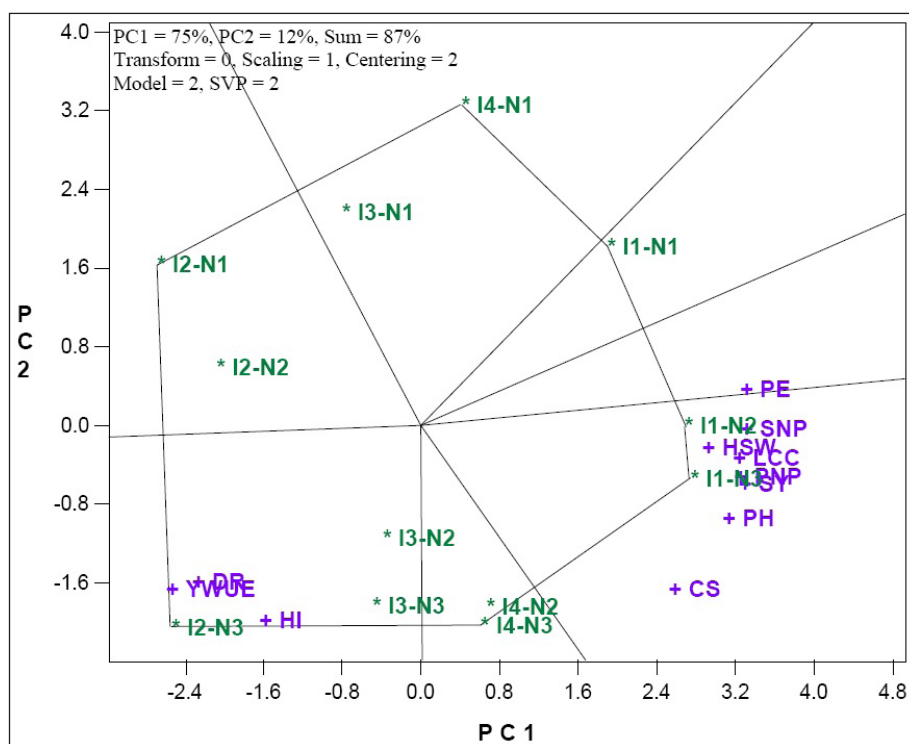


Fig. 1. Which won where utility of treatment-trait interaction biplot model.

Traits are: plant height (PH), depth of root (DR), leaf chlorophyll content (LCC), canopy spread (CS), pod number per plant (PNP), seed number per plant (SNP), hundred seed weight (HSW), seed yield (SY), harvest index (HI), potential evapotranspiration (PE), and yield water use efficiency (YWUE).

Treatments are: I1-N1 (well-watered + 0 kg ha⁻¹ nitrogen), I1-N2 (well-watered + 20 kg ha⁻¹ nitrogen), I1-N3 (well-watered + 40 kg ha⁻¹ nitrogen), I2-N1 (rainfed + 0 kg ha⁻¹ nitrogen), I2-N2 (rainfed + 20 kg ha⁻¹ nitrogen), I2-N3 (rainfed + 40 kg ha⁻¹ nitrogen), I3-N1 (supplemental irrigation in the flowering + 0 kg ha⁻¹ nitrogen), I3-N2 (supplemental irrigation in the flowering + 20 kg ha⁻¹ nitrogen), I3-N3 (supplemental irrigation in the flowering + 40 kg ha⁻¹ nitrogen), I4-N1 (supplemental irrigation in the flowering and seed formation + 0 kg ha⁻¹ nitrogen), I4-N2 (supplemental irrigation in the flowering and seed formation + 20 kg ha⁻¹ nitrogen), and I4-N3 (supplemental irrigation in the flowering and seed formation + 40 kg ha⁻¹ nitrogen).

favorable environment for chickpea growth and productivity, particularly enhancing agronomic traits. This finding aligns with the report by Sabaghnia and Janmohammadi (2023), which demonstrated the positive impact of nitrogen fertilization on chickpea yield and related traits under well-watered conditions. Interestingly, treatment I2-N3 (rainfed + 40 kg ha⁻¹ nitrogen) was the most effective in improving DR, HI, and YWUE. This reflects the chickpea plant's adaptive response to water scarcity by extending root depth to access deeper moisture and reallocating more assimilates toward seed production, thereby increasing harvest index and water use efficiency. On the other hand, I1-N2 (well-watered + 20 kg ha⁻¹ nitrogen) was identified as the top-performing treatment for potential evapotranspiration (PE).

Under moderate nitrogen levels in well-irrigated conditions, limited foliage expansion may lead to elevated evapotranspiration compared to conditions with either low or high nitrogen input. Biomass accumulation serves as an indicator of crop adaptability under different treatment conditions, with variations in biomass reflecting differences in photosynthetic capacity and assimilate production (Priyadarsini *et*

al., 2022). As Kaur *et al.* (2021) noted, water stress limits both the source (photosynthate production) and sink (growth potential), thereby disrupting the partitioning and transport of photo-assimilates. However, the extent of this disruption varies based on crop species, growth stage, stress duration, and drought severity. Four treatments located at polygon vertices; namely I1-N1 (well-watered + 0 kg ha⁻¹ nitrogen), I2-N1 (rainfed + 0 kg ha⁻¹ nitrogen), I4-N1 (supplemental irrigation at flowering and seed filling + 0 kg ha⁻¹ nitrogen), and I4-N3 (supplemental irrigation at flowering and seed filling + 40 kg ha⁻¹ nitrogen); did not exhibit desirable performance for any of the evaluated traits, indicating their limited effectiveness in optimizing chickpea growth and productivity under the tested conditions.

In the vector-view of the biplot (Fig. 2), vectors radiating from the origin represent trait associations, where the cosine of the traits indicates the strength and direction of their correlation. The length of each vector corresponds to the proportion of variability in that trait explained by the fitted model. Several key relationships were identified: a strong positive association among root depth

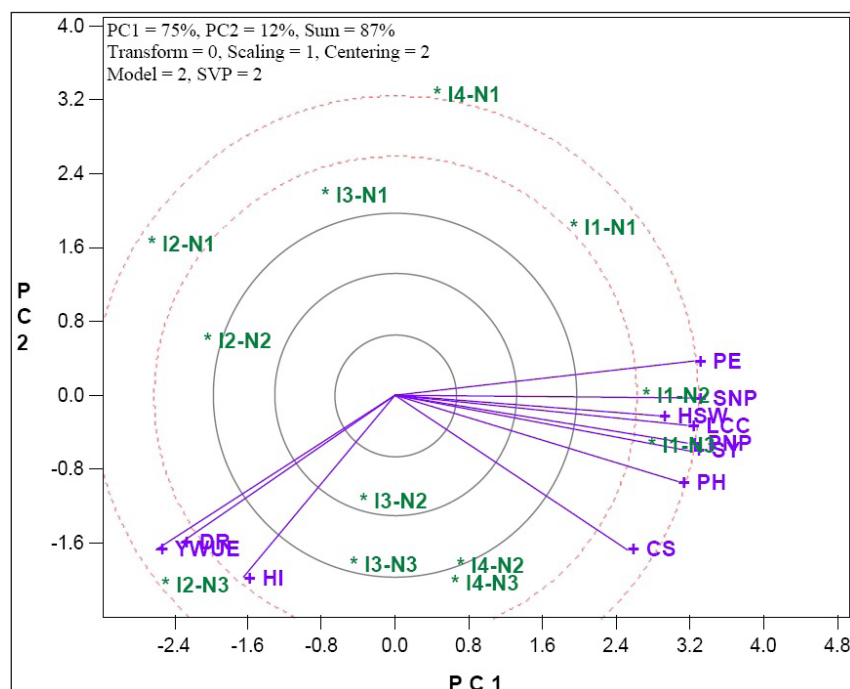


Fig. 2. Vectors of traits of treatment-trait interaction biplot model.

Traits are: plant height (PH), depth of root (DR), leaf chlorophyll content (LCC), canopy spread (CS), pod number per plant (PNP), seed number per plant (SNP), hundred seed weight (HSW), seed yield (SY), harvest index (HI), potential evapotranspiration (PE), and yield water use efficiency (YWUE).

(DR), harvest index (HI), and grain yield water use efficiency (YWUE), as well as among plant height (PH), seed yield (SY), number of seeds per plant (SNP), leaf chlorophyll content (LCC), number of pods per plant (PNP), hundred seed weight (HSW), and potential evapotranspiration (PE), as found by the acute angles. Additionally, a near-zero association was observed between canopy spread (CS) and harvest index (HI), indicated by the near-perpendicular orientation of their vectors.

Conversely, a negative relationship was detected between traits such as DR and YWUE with PE, illustrated by the wide obtuse angles between their respective vectors (Fig. 2). While most of these visual inferences are consistent with Pearson correlation coefficients, minor discrepancies are expected given that the biplot model accounts for 87% of the total variation, falling short of a complete (100%) explanation. Despite these limitations, the treatment-by-trait interaction biplot provides a more holistic and interpretable overview of the dataset's structure, often offering more robust insights than individual correlation metrics alone (Yari *et al.*, 2018). Previous findings support these

relationships. For instance, Gebremariam and Tesfay (2021) reported significant positive correlations between chickpea seed yield and key yield components such as pods and seeds of plant, and hundred seed weight. Similarly, Sabaghnia *et al.* (2024) found strong associations between seed yield and pod- and seed-related traits, although their study did not observe a consistent relationship with hundred seed weight.

In the search for an ideal treatment, the goal is to identify one that exhibits superior performance across a broad range of desirable traits. In Fig. 3, the single-arrow line represents the mean-trait axis, along which treatments are ranked according to their overall trait responses. This axis is divided into two segments: the right side represents treatments with above-average performance, while the left side indicates below-average responses. According to the biplot in Fig. 3, treatments I4-N2 and I4-N3 (supplementary irrigation during flowering and seed formation with 20 and 40 kg ha⁻¹ nitrogen, respectively) showed above-average performance across most traits. In contrast, treatments such as I2-N1, I2-N2, and I2-N3 (all

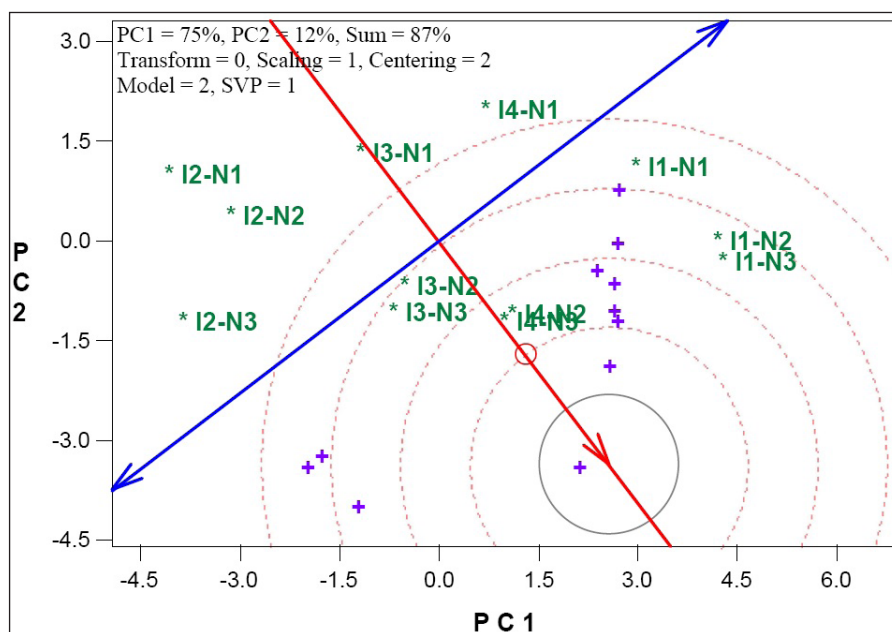


Fig. 3. Ideal treatment utility of treatment-trait interaction biplot model.

Treatments are: I1-N1 (well-watered + 0 kg ha⁻¹ nitrogen), I1-N2 (well-watered + 20 kg ha⁻¹ nitrogen), I1-N3 (well-watered + 40 kg ha⁻¹ nitrogen), I2-N1 (rainfed + 0 kg ha⁻¹ nitrogen), I2-N2 (rainfed + 20 kg ha⁻¹ nitrogen), I2-N3 (rainfed + 40 kg ha⁻¹ nitrogen), I3-N1 (supplemental irrigation in the flowering + 0 kg ha⁻¹ nitrogen), I3-N2 (supplemental irrigation in the flowering + 20 kg ha⁻¹ nitrogen), I3-N3 (supplemental irrigation in the flowering + 40 kg ha⁻¹ nitrogen), I4-N1 (supplemental irrigation in the flowering and seed formation + 0 kg ha⁻¹ nitrogen), I4-N2 (supplemental irrigation in the flowering and seed formation + 20 kg ha⁻¹ nitrogen), and I4-N3 (supplemental irrigation in the flowering and seed formation + 40 kg ha⁻¹ nitrogen).

nitrogen levels under rainfed conditions), along with I3-N1 and I4-N1 (supplementary irrigation without nitrogen), demonstrated below-average performance. The superior outcomes observed with nitrogen application (20 and 40 kg ha⁻¹) under well-watered and both supplementary irrigation regimes, as well as the moderate performance of the no-nitrogen treatment under full irrigation (I1-N1), are consistent with the findings of Wang *et al.* (2019). Their study confirmed that nitrogen fertilization under optimal moisture conditions enhances crop performance by improving nutrient uptake and assimilation efficiency. An ideal treatment is characterized by a high projection onto the mean-trait axis, indicating strong overall performance, and a short perpendicular distance from this axis, reflecting trait stability. In this study, I4-N2 and I4-N3, followed closely by I3-N2 and I3-N3 (supplementary irrigation during flowering with 20 and 40 kg ha⁻¹ nitrogen), were positioned nearest to the ideal treatment point. These treatments demonstrated both high and balanced trait responses, making them strong candidates for optimizing chickpea production under semi-arid conditions.

These results are further supported by Kamran *et al.* (2023), who reported that under semi-arid circumstances, the application of moderate nitrogen levels in conjunction with supplementary irrigation during flowering stages led to improved nitrogen use efficiency and better utilization of starter nitrogen. Hence, these treatments may offer viable, resource-efficient alternatives to conventional full irrigation strategies.

In the treatment-by-trait interaction biplot, the ideal trait is characterized by its association with a broad range of favorable treatments. In Fig. 4, the single-arrow line represents the average-tester axis, which ranks traits based on their mean response across treatments. Traits positioned closer to this axis with longer projections are considered more representative of treatment effects and more capable of distinguishing among treatments. According to Fig. 4, plant height (PH) displayed characteristics closely aligned with those of the ideal trait, demonstrating above-average performance. In contrast, depth of root (DR), harvest index (HI), and grain yield water use efficiency (YWUE) exhibited relatively poor performance across treatments. Other traits,

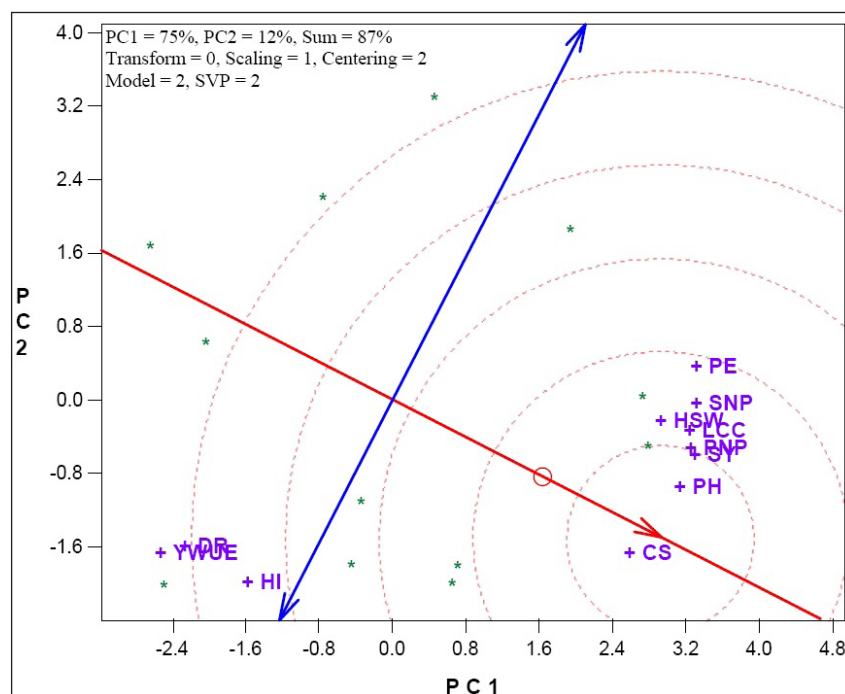


Fig. 4. Ideal trait utility of treatment-trait interaction biplot model.

Traits are: plant height (PH), depth of root (DR), leaf chlorophyll content (LCC), canopy spread (CS), pod number per plant (PNP), seed number per plant (SNP), hundred seed weight (HSW), seed yield (SY), harvest index (HI), potential evapotranspiration (PE), and yield water use efficiency (YWUE).

including seed yield (SY) and its components (pod per plant, hundred seed weight, and seed number per plant), along with leaf chlorophyll content (LCC) and potential evapotranspiration (PE), showed moderate to high alignment with the ideal trait and can be considered effective indicators of treatment performance.

These findings suggest that most of the evaluated traits have strong discriminative power and can effectively detect treatment differences. Similar observations were reported by Janmohammadi and Sabaghnia (2024), who found significant responsiveness in chickpea seed yield and two major yield components (PNP and SNP), although they did not observe a similar trend for HSW. The typical capability of a trait, its representativeness of the overall treatment effect, is estimated by the angle between the trait vector and the average-tester axis. Traits with smaller angles are more typical and desirable in terms of stability and reliability. In this study, traits such as canopy spread (CS), plant height (PH), seed yield (SY), PNP, SNP, LCC, and HSW formed small angles with the average-tester axis and thus demonstrated high typical potential. Conversely, DR, HI, and YWUE formed large

angles with the average-tester axis, indicating lower representativeness and less consistent behavior across treatments. Current issue is similar to the report by Sabaghnia *et al.* (2024), which identified PH, SY, PNP, and SNP as having strong discriminatory and typifying capabilities in chickpea trials under various treatment conditions.

In the vector-view biplot model presented in Fig. 5, treatments closely associated with the target trait, high seed yield in chickpea, are clearly identified. Among all treatments, I1-N2 (well-watered + 20 kg ha⁻¹ nitrogen) and I1-N3 (well-watered + 40 kg ha⁻¹ nitrogen) emerged as the most effective in enhancing seed yield, indicating their potential suitability for maximizing productivity under non-stress, well-irrigated conditions. These findings suggest that nitrogen application under optimal moisture availability not only improves seed yield but also positively influences other agronomic traits, thereby supporting broader adoption of nitrogen fertilization practices in chickpea cultivation. The positive role of nitrogen in promoting chickpea growth and development has been previously documented by Rafique *et al.* (2021), who attributed its

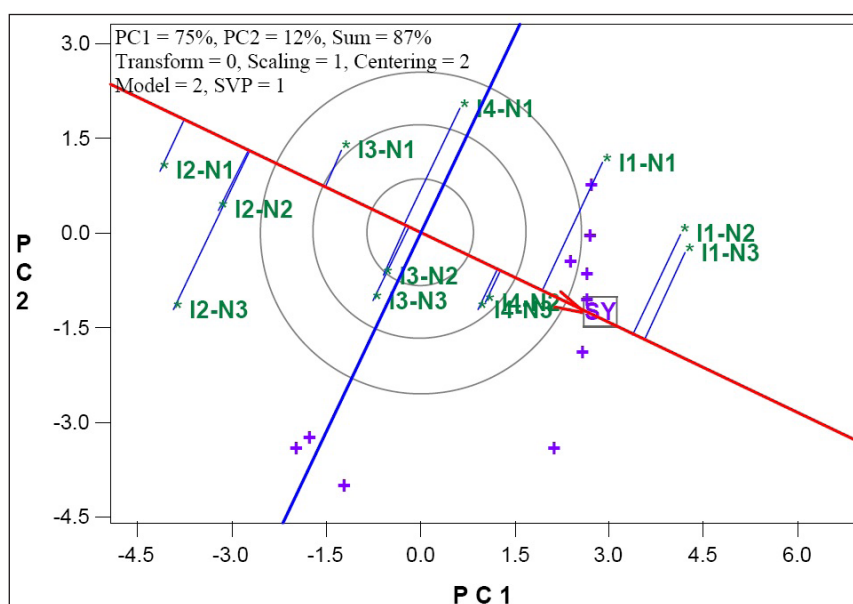


Fig. 5. Examine seed yield (SY) utility of treatment-trait interaction biplot model.

Treatments are: I1-N1 (well-watered + 0 kg ha⁻¹ nitrogen), I1-N2 (well-watered + 20 kg ha⁻¹ nitrogen), I1-N3 (well-watered + 40 kg ha⁻¹ nitrogen), I2-N1 (rainfed + 0 kg ha⁻¹ nitrogen), I2-N2 (rainfed + 20 kg ha⁻¹ nitrogen), I2-N3 (rainfed + 40 kg ha⁻¹ nitrogen), I3-N1 (supplemental irrigation in the flowering + 0 kg ha⁻¹ nitrogen), I3-N2 (supplemental irrigation in the flowering + 20 kg ha⁻¹ nitrogen), I3-N3 (supplemental irrigation in the flowering + 40 kg ha⁻¹ nitrogen), I4-N1 (supplemental irrigation in the flowering and seed formation + 0 kg ha⁻¹ nitrogen), I4-N2 (supplemental irrigation in the flowering and seed formation + 20 kg ha⁻¹ nitrogen), and I4-N3 (supplemental irrigation in the flowering and seed formation + 40 kg ha⁻¹ nitrogen).

effectiveness to the stimulation of growth hormone activity. Other treatments; such as I1-N1 (well-watered + 0 kg ha⁻¹ nitrogen), I4-N2, and I4-N3 (supplementary irrigation during both flowering and seed formation stages with 20 and 40 kg ha⁻¹ nitrogen, respectively); demonstrated intermediate performance and were ranked just below I1-N2 and I1-N3 in terms of seed yield.

In rainfed circumstances, however, the usage of two irrigations (during flowering and seed formation) combined with either 20 or 40 kg ha⁻¹ nitrogen (I4-N2 and I4-N3) proved to be a more useful way for enhancing yield. In contrast, treatments involving nitrogen application under strictly rainfed conditions (I2-N2 and I2-N3), or those with no nitrogen application under rainfed or supplementary irrigation scenarios (I2-N1, I3-N1, and I4-N1), did not result in significant yield improvements. Although, chickpea is capable of atmospheric nitrogen fixation through symbiosis with *Mesorhizobium ciceri* (Ben Romdhane *et al.*, 2022), the use of starter nitrogen fertilizer appears to be critical in semi-arid soils. It ensures proper seedling establishment and root development prior to the onset of effective nodulation. This is especially important in environments where low soil fertility, limited native rhizobia populations, and erratic moisture availability constrain early plant growth. Supporting this, Liu *et al.* (2022) found that under semi-arid climatic conditions, moderate nitrogen application in conjunction with supplementary irrigation during flowering significantly enhanced nitrogen use efficiency and contributed to optimal crop performance. However, excessive nitrogen under full irrigation can lead to increased vegetative growth and inefficient water consumption, potentially reducing water availability for the reproductive stages. Therefore, a balanced approach that combines moderate nitrogen input with timely irrigation is needed for achieving both high yield and resource use efficiency in chickpea production under variable climatic conditions.

The current study investigated the interactive effects of nitrogen and irrigation regimes on chickpea under semi-arid conditions. The use of treatment-by-trait interaction biplot models provided a powerful multivariate framework for evaluating the combined response of several key agronomic traits to a range of management strategies. The principal components of the

biplot accounted for 87% of the total variation, indicating a strong model fit and sufficient dimensionality for reliable interpretation. The first two principal components, effectively summarizing the complex trait interactions and allowing for the discrimination of treatment performance. This aligns with prior studies (Mohebodini *et al.*, 2024) that have validated the use of two-dimensional biplots in agronomic experiments. The biplot structure confirmed significant associations among traits, particularly those related to yield and its components, which clustered closely with plant height, chlorophyll content, and potential evapotranspiration. In contrast, traits like depth of root (DR), harvest index (HI), and yield-based water use efficiency (YWUE) formed separate groupings, showing distinct patterns of response that were often negatively associated with evapotranspiration and biomass-related traits. These trait clusters reveal the physiological trade-offs that chickpea plants make under varying moisture and nutrient conditions; a common phenomenon in stress physiology where adaptation mechanisms prioritize root development and resource allocation efficiency over vegetative growth. The polygon biplot revealed distinct treatment performances across traits. Treatments such as I1-N3 (well-watered + 40 kg ha⁻¹ nitrogen) and I1-N2 (well-watered + 20 kg ha⁻¹ nitrogen) consistently ranked highest across yield and associated agronomic traits, with I1-N3 emerging as the top performer in most metrics except DR, HI, and YWUE. This result underscores the efficacy of nitrogen application in enhancing chickpea productivity under optimal water conditions. The improved performance is likely due to the promotion of vegetative vigor and reproductive capacity facilitated by increased nitrogen availability, as supported by Nabati *et al.* (2025), who linked nitrogen-enhanced yield to hormonal stimulation and nutrient assimilation efficiency. Interestingly, I2-N3 (rainfed + 40 kg ha⁻¹ nitrogen) exhibited the highest performance for root depth, harvest index, and WUEG, suggesting that in water-limited environments, chickpea plants adopt adaptive strategies such as deeper rooting and more efficient biomass partitioning to sustain reproductive success. These findings corroborate earlier reports (Akinlade *et al.*, 2022; Bakala *et al.*, 2024) on the role of moderate nitrogen fertilization in promoting root system

development and efficient use of limited soil moisture prior to full nodulation.

Treatments with supplementary irrigation during key growth stages; particularly I4-N2 and I4-N3 (flowering and seed formation with 20 and 40 kg ha⁻¹ N); also demonstrated favorable performance. These treatments were identified as close to the “ideal treatment” point in the biplot analysis, indicating balanced trait responses across both yield and resource use traits. These results point to the effectiveness of well-timed irrigation combined with moderate nitrogen as a resource-efficient strategy for enhancing chickpea production in semi-arid regions, where full irrigation is often impractical. Bouras, *et al.* (2023) similarly emphasized the benefits of moderate nitrogen application under supplementary irrigation, highlighting the importance of synchronizing nitrogen availability with periods of high physiological demand, such as flowering. The improved nitrogen use under these conditions may be attributed to enhanced root-soil interactions, improved microbial activity in the rhizosphere (Djouider *et al.*, 2022), and reduced nitrogen losses due to leaching or volatilization, factors commonly associated with limited rainfall and controlled irrigation. The vector-view biplots provided deeper insight into trait interdependencies. Traits such as SY, PNP, SNP, LCC, HSW, and PH showed acute angles with the mean-trait axis, indicating strong positive correlations and high typical potential for reflecting treatment performance. On the contrary, DR, HI, and YWUE exhibited wide obtuse angles, implying inconsistent behavior across treatments and lower predictive value. These distinctions are important for breeders and agronomists seeking efficient trait proxies for yield optimization, especially when rapid field phenotyping or resource limitations necessitate the prioritization of key indicators. As described by Naveed *et al.* (2024), traits like pod and seed number per plant consistently demonstrate stronger correlations with yield than HSW, which appears to be more variable and environment-dependent. This pattern was evident in the current study, where HSW contributed to overall performance but was less consistent across treatments compared to PNP and SNP.

The findings of this study hold important implications for sustainable chickpea

production in semi-arid environments. First, while chickpea is known for its nitrogen-fixing ability through symbiosis with *Mesorhizobium ciceri*, the use of starter nitrogen appears critical in early growth stages, particularly in soils with low fertility and sparse native rhizobial populations (Zhang *et al.*, 2024). Early nitrogen supplementation supports seedling establishment and root development, laying the groundwork for successful nodulation and sustained vegetative and reproductive growth. Second, the observed performance differences among irrigation regimes highlight the necessity of strategic water management. While full irrigation maximizes yield under high-input systems, supplementary irrigation applied at flowering or both flowering and seed formation stages offers a more efficient approach in water-limited conditions. This aligns with prior findings (Mukherjee *et al.*, 2022; Korbu *et al.*, 2022) that targeted irrigation during sensitive phenological phases can mitigate terminal drought stress and enhance water productivity. Third, excessive nitrogen application under full irrigation may promote excessive vegetative growth, leading to increased evapotranspiration and inefficient resource use. Balancing nitrogen input with the crop's phenological demand and moisture availability is essential to prevent such losses and ensure high nitrogen use efficiency.

Conclusions

Well-watered conditions combined with moderate to high nitrogen inputs (20 or 40 kg ha⁻¹) resulted in superior yield and yield component performance. Supplementary irrigation combined with moderate nitrogen doses emerged as a water-efficient and agronomically viable alternative of above option. The treatment-by-trait biplot analysis provided valuable insights into the multifaceted response of chickpea to nitrogen and irrigation treatments under semi-arid conditions. Traits such as yield, chlorophyll content, pods and seeds per plant, and were identified as reliable indicators of treatment effectiveness and should be prioritized in future chickpea improvement programs. Current findings underscore the potential for integrated water and nutrient management strategies to optimize chickpea productivity and resilience in challenging environments.

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