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Research article

Agronomic performance yield stability and principal component analysis of chickpea (*Cicer arietinum* L.) genotypes under two rainfed environments

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ABSTRACT

The stable varieties discover high yield and under rainfed settings, it is necessary to review performance of chickpea (*Cicer arietinum* L.) genotypes patterns in response to different environmental conditions. The purpose of this study was to Assessing apparent diversity and field performance of chickpea genotypes cultivated in Talaskef and Rabia, the two rainfed settings in the northern Iraq, during the 2025–2026 growing season. Used three repetitions were at each site on the randomize completes block design (R.C.B.D.) experiment. Agricultural characteristics were evaluated, Like this vegetative growth parameters, seed yield, and seed composition. Additionally, the principal component analysis (PCA) was used to investigated the relationships between genetic diversity and characteristics. The most of the qualities under study were shown to be significantly impacted by region, genotype, and their interaction to factors environmental. Because of more ideal environmental conditions for chickpea growing, the Rabia location produced noticeably best biological and seed yields than the Talaskef location. Rafidian variety performed exceptionally well among the genotypes that were evaluated, it produced the high harvest index and seed yield, in addition superior performance in number of production components at both locations, demonstrating its high stability and broad adaptability under rainfed conditions. Quadrature the Principal Component Analysis, in the Talaskef and Rabia location, the first two principal components PC1 and PC2 accounted for 86.55% and 80.58% of the total data, respectively, strong relationships were found between variety productid and biological product, alone index, number of pods, and variety. These results highlight of environmental multi evaluation in identify chickpea genotypes with high adapt ability and consistent performance is highlighted in these findings. The Rafidian genotype is a major genetic resource for upcoming chickpea breeding and development initiatives, it has shown itself to be one of most promising types for cultivation under rainfed circumstances in northern Iraq.

1. Introduction

Chickpeas is one of the most major legume crops, famous third globally among food legumes in terms of cultivated area and production. They are mature in more than 50 countries under diverse environmental conditions, especially in semi-arid regions where rainfall is the primary water source.

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Globally, the area under chickpea cultivation ranges from approximately 13 to 14.8 million hectares, with an annual production exceeding 15–16.5 million tons and an average yield of about one ton per hectare. This relatively low average yield highlights the significant gap between actual production and the potential for achieving high yields for this crop (Zhang et al., 2024).

Global hummus chickpea production has attended significant growth in recent decades, primarily due to increased agricultural projects and the development of improved varieties. From 2015 to 2020, global annual chickpea production averaged around 2.6%, further highlighting the crop's importance in the global health insurance sector (Phiri et al., 2023). India stays one of the world's largest producers, contributing about 70-75% of total global production, followed by Australia and Ethiopia, indicating that chickpea production is largely concentrated in areas with dry climatic conditions (Joshi, 2001).

As its agricultural and nutritional importance, chickpea production continues to face significant challenges due to environmental constraints. Among these constraints, environmental pressures and climate change, particularly drought and rising temperatures, are considered major determinants of crop productivity and can reduce seed yield by 10% or more, depending on the severity of the pressure. (Zhang et al., 2024). Globally, more than 80% of chickpea cultivation area depends on rainfall. This makes the harvest susceptible to climate change and fluctuations in productivity, especially in arid and semi-arid regions. (Technavio Logo 2024, n.d.).

In northern Iraq the problem has appeared, especially in Nineveh Governorate, where semi-arid climatic conditions dominate. Annual rainfall generally ranges between (300-400 mm), with considerable variation in both quantity and seasonal distribution. This variability often leads to significant differences in crop yields from one growing season to the next (FAO, 2023). Water scarcity during the flowering and seed formation stages is considered one of the most important factors limiting chickpea productivity in these environments (Abbas et al., 2018).

Under such circumstances, assessing phenotypic variation between genotypes becomes essential, as phenotypic diversity provides the basis for identifying superior varieties in plant breeding programs. Phenotypic variation represents the observed differences between genotypes resulting from the interaction between genetic factors and environmental conditions (Sadras et al., 2013). Recent studies have shown that wide phenotypic variation in seed crops and associated traits is a prerequisite for successful genetic improvement and selection efficiency (Fasoula et al., 2020).

Seed crop productivity is a complex quantitative characteristic influenced by several interrelated factors, including the number of pods per plant, the number of seeds, seed weight, and biological yield, all of which contribute differently to the final yield depending on environmental conditions. In moisture-deficient environments, biological yield and pod count are key determinants of seed yield due to their crucial role in improving resource use efficiency, promoting dry matter accumulation, and enhancing the allocation of metabolites to economically valuable plant parts, such as seeds. Therefore, these characteristics are closely linked to the plant's ability to convert biomass into an economically viable crop under drought conditions (Varshney et al., 2018) ;(Avila et al., 2020);(López-Goldar & Agrawal, 2021);(Sadras & Calderini, 2021).

Principal component analysis (PCA) is one of the most widely used multivariate statistical techniques for assessing genetic diversity among crop genotypes. This approach reduces a large number of related variables to a limited number of principal components that explain most of the total

variance. Furthermore, PCA facilitates the interpretation of relationships between agricultural traits and enables the classification of genotypes according to their degree of similarity or divergence, providing a reliable basis for identifying superior genotypes and selecting appropriate parent lines for breeding and genetic improvement programs (Singh et al., 2025). Furthermore, principal component analysis is an effective tool for summarizing complex multivariate datasets, improving genotype characterization, and supporting more accurate selection decisions in modern breeding programs (S. Kumar et al., 2023).

Therefore, the present study aimed to evaluate the phenotypic variation in seed yield and its associated components among a set of chickpea genotypes grown under rainfed conditions in semi-arid environments. The study also sought to identifying the agriculture traits most closely associated with productivity, thereby providing valuable information to support chickpea breeding programs and enhance yield stability under changing climatic conditions.

2. Materials and Methods

The experiment was conducted during the 2025-2026 season growing at two rainfed region representing two contrasting agricultural environments in Nineveh Governorate, northern Iraq Talaskef, located in Tel Keif District, and Rabia, located in Tal Afar District. The experiment was carried out under rainfed farming conditions, relying entirely on seasonal rainfall as the water source.

Ten chickpea genotypes were evaluated, including local varieties exhibiting variation in agricultural and yield related characteristics. The experiment was designed as a randomized complete block design (R.C.B.D.) with three replicates at each site.

Each experimental plot consisted of six rows, each 5 m in length, with 45 cm spacing between rows. Sixty seeds were sown in each row, resulting in a total of 360 seeds per experimental plot. The total plot area was 13.5 m².

All recommended agronomic practices for chickpea cultivation in the study region were uniformly applied throughout the growing season. At physiological maturity, the following agronomic traits were recorded: days to maturity (DM), plant height (PH), lowest pod height (LPH), pods per plant (PPP), grains per plant (GPP), biological yield (BY), grain yield (GY), harvest index (HI), and 100-grain weight (HGW).

The data were subjected to statistical analysis using SAS statistical software. Combined analysis of variance (ANOVA) was performed according to a two-factor factorial arrangement within a randomized complete block design (RCBD) with three replications. Mean comparisons were conducted using the least significant difference (LSD) test at the 5% probability level (Al-Rawi & Khalaf Alallh, 2000). To assess the variation among chickpea genotypes and identify the traits contributing most to the observed variability, principal component analysis (PCA) was performed based on the mean values of the genotypes at each experimental location.

1- Results and Discussion

3-1 Effect of Location on Growth and Yield Traits

The results of the statistical analysis presented in Table 1 revealed significant differences between the two experimental locations for several of the evaluated traits, indicating the substantial influence of environmental

conditions on chickpea growth and productivity. Rabia location record a significantly longest growing period, averaging 160.60 days compare to 124.93 days in Talaskef. This difference is attributed to the contrasting climatic conditions between the two locations, particularly the distribution of temperature and rainfall during the growing season, both of which directly affect crop growth and physiological maturity. Varshney (Varshney et al., 2021) reported that the duration of growth and maturity in chickpea is strongly influenced by the interaction between genotype and environmental conditions, especially temperature and moisture availability throughout the growing season.

A significant advantage of the Rabea location was also observed for PH, which averaged 43.43 cm compared with 36.32 cm at Talaskf. The superior plant growth at Rabea may be attributed to more favorable environmental conditions that enhanced vegetative development by improving water and nutrient uptake, thereby promoting stem elongation and canopy growth. These findings agree with those of (Rani et al., 2020a), who reported that favorable environmental conditions during the vegetative growth stage enhance vegetative development and improve the overall field performance of chickpea.

In contrast, no significant differences were detected between the two locations for LPH or PPP, suggesting that these traits were influenced predominantly by genetic factors rather than environmental conditions. (Varshney et al., 2021) indicated that several morphological traits in chickpea possess relatively high heritability, making them less responsive to environmental variation than yield-related traits.

overall, in terms seed yield, the sites of Rabia significantly outperform Talaskef, the produce an average of 40.80 seeds per plant compared to 30.68 seeds per plant. This improvement is attributed to increased the flowering, pod formation, and seed filling under more environmental conditions favorable during in stage of germination. According to previous research, one of the most important factors influencing final seed output in chickpeas is the quantity of grains per plant (Merga & Haji, 2019).

The location Rabea outperformed Talaskf in terms of significantes BY and GY. The average BY reached (3628.2 kg ha⁻¹) at Rabea compare with (2201.8 kg ha⁻¹) at Talaskf, along with GY averaged (1546.10 and 940.87 kg ha⁻¹), respectively. Under the more favorable environmental condition at Rabea, these benefits are like linked to higher photosynthetic efficiency and increased dry matter, which leads to improved biomass production and more effectives assimilate transfer to developing seeds. These findings are same with of (Rani et al., 2020a), who show that in rain dependent environment, sufficient moisture availability during growth stages promote dry matter buildup and increases chickpea productivity.

On the contrary, no significant differences was observed between the locations regarding the harvest index (HI) or seeds weight (HGW), indicating that the distribution of dry matter between vegetative and reproductive organs, as well as seed size, remained relatively stable across different environments. This finding suggests that these traits are under stronger control from genetic factors and exhibit greater environmental stability than most growth and yield traits. It has been recorded by (Yadav et al., 2012) in their evaluation of diverse chickpea genotypes.

Overall, the results high light the crucial role of environmental conditions in determining chickpea performance under rainfed conditions. The Rabia environment consistently improved most crop components and final seed yield compared to the Talaskef environment, indicating that its prevailing climatic conditions are more conducive to chickpea production under rainfed conditions in northern Iraq.

Table (1) Effect of locations on agronomic and yield-related traits of chickpea

LOCATIONS	DM	PH (CM)	LPH (CM)	PPP (PLANT ⁻¹)	GPP (PLANT ⁻¹)	BY (KG HA ⁻¹)	GY (KG HA ⁻¹)	HI %	HGW (G)
TALASKF	124.9333	36.3167	19.6167	18.4333	30.675	2201.8	940.87	39.290	28.9650
RABEA	160.6000	43.4333	18.4333	36.360	40.800	3628.2	1546.10	41.151	28.8417
LSD'S	0.6548	1.1275	N.S	N.S	3.7269	276.77	122.2	N.S	N.S

DM: Days to Maturity; **PH:** Plant Height; **LPH:** Lowest Pod Height; **PPP:** Pods per Plant; **GPP:** Grains per Plant; **BY:** Biological Yield; **GY:** Grain Yield; **HI:** Harvest Index; **HGW:** 100-Grain Weight.

3-2 Performance of Chickpea Genotypes at the Talaskf Location

The high genetic diversity that might be applied in chickpea breeding programs targeted at increasing productivity under rainfed condition is indicated by results in Table (2), which demonstrate notable variances across chickpea genotypes for the major of the measured standers at the Talaskef location. This diversity differences reflects variations in genotype capacity to made use of environmental resources and adjust to local growth conditions, which is in line with the findings of (A. Kumar et al., 2024).

In terms of primary plant productivity, all total plant productivity, seed yield, harvest index, the Rafidian genotypes performs best than other genotype, Reaching physiological maturity early. These findings showing Rafidian is very effective at making used of the growth season and metabolite allocating to the development of seeds. In area rainfed, maturity early is a crucial adaptation strategy because help plant avoid of heat stress and drought terminal, which happen later in growing season. This improves crop components and overall production (Rani et al., 2020b).

On the other sides, the genotype F97-73c was distinct by its high height and weight, while the F91-120c and genotype Degla generated the tall plants. These traits are a reflection of genetic variation in vegetative growth and the seeds capacity to acquire dry matter. These character, however, was not consistently linked to higher seed yields, indicating that the final chickpea yield is dependent on the combined performance of several crop components rather than just one. Prior research has shown that the primary yield per pod and total primary yield are the important factors that determine seed yield, and that an increased in seed weight, when paired with an increase in the pods number and seeds, positively affects yield(A. Kumar et al., 2024).

As well as no major variation was observed through genotypes most for BY, significantly variation was remark for GY and HI, indicating that differences in dry matter partitioning between vegetative and reproductive organs played a decisive role in determining productivity. The cultivar Rafidian recorded the highest HI, reflecting greater efficiency in translocating photosynthetic assimilates to developing seeds during the seed-filling stage, a characteristic closely associated with increased seed yield under rainfed conditions(Gimenez et al., 2025).

comprehensive, the verities Rafidian exhibited superior performance across most productivity-related traits, demonstrating its high adaptation and yield potential under the environmental conditions of Talaskf. In contrast, F97-73c and F97-113c were distinguished by their relatively higher 100-grain weight (HGW) and favorable morphological characteristics. On the other hand, Marakishi and Dessi regularly reported low values for the majority of evaluated features, suggesting insufficient adaptation to the Talaskf location's rainfed environment.

Table (2) Effect of genotypes chickpea on agronomic and yield related traits at Talaskf location

GENOTYPE S	DM	PH (CM)	LPH (CM)	PPP	GPP	BY	GY	HI%	HGW (G)
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					(PLANT -1)	(PLANT -1)	(KG HA ⁻¹)	(KG HA ⁻¹)		
1	F91-120c	124.3	47.6	30.3	40.10	33.15	2592.	1155.	44.51	29.3
		3	6	3			0	3	7	5
2	F92-120c	125.6	38.3	19.6	40.26BC	35.50	2555.	1055.	41.31	29.2
		6	3	6			3	3	0	0
3	F97-41c	125.3	40.6	20.6	44.63B	42.45AB	2229.	1137.	51.38	31.9
		3	6	6			3	0	3	5
4	F97-73c	124.0	37.0	18.0	29.36	23.95	2744.	1151.	41.98	38.7
		0	0	0			0	7	7	0
5	F97-113c	123.6	34.3	18.6	33.83	36.50	2807.	1229.	43.67	36.4
		6	3	6			0	3	7	5
6	F98-26c	122.3	43.6	21.3	38.50	29.15	2533.	1166.	45.84	33.0
		3	6	3			3	3	3	0
7	Rafidian	121.0	29.0	14.0	53.20	47.80	2647.	1400.	52.88	26.1
		0	0	0			7	0	3	5
8	Degla	124.0	45.0	31.0	30.26	32.00	2021.	692.3	34.28	22.2
		0	0	0			7		0	0
9	Dessi	129.0	22.5	9.50	16.60	17.95	1199.	377.3	30.61	27.6
		0	0				3		7	5
10	Marakishi	130.0	25.0	13.0	9.00	8.30	688.0	44.0	6.400	15.0
		0	0	0						0
	LSD's	1.941	3.14	3.60	7.31	7.26	795.4	399.0	6.906	1.90
			5	7			1	2		8

DM: Days to Maturity; **PH:** Plant Height; **LPH:** Lowest Pod Height; **PPP:** Pods per Plant; **GPP:** Grains per Plant; **BY:** Biological Yield; **GY:** Grain Yield; **HI:** Harvest Index; **HGW:** 100-Grain Weight.

3-3 Performance of Chickpea Genotypes at the Rabea Location

Table (3) Significant genetic variation in genotype responses under rainfed conditions is indicated by the results, which demonstrate significant differences across chickpea genotypes for the majority of the evaluation variables at the Rabea location. This variation highlights the significance of multi-environment evaluation for identifying genotypes with superior adaptability and yield stability by showing that the evaluated genotypes varied in their capacity to use available environmental resources and convert them into vegetative growth and seed production. These results are in line with those published by (A. Kumar et al., 2024), who highlighted that the basis for successful selection and genetic improvement initiatives is the genetic heterogeneity across chickpea genotypes.

Contain evaluated genotype, Rafidian showed the highest performance at Rabea. It common relatively early DM with superior PPP, GPP, GY, and HI, demonstrating an excellent capacity to exploit the favorable environmental conditions at this location and efficiently allocate photosynthetically produced assimilates to reproductive organs. Such efficient assimilate partitioning contributes to improved reproductive development and ultimately enhances seed yield. The superior performance of Rafidian indicates a high level of adaptation to the rainfed environments of northern Iraq. Maturity early combine with the maintenance of highest yield component enables plants to escape terminal drought and other environmental occurring stresses during the stage final of development crop. (Rani et al., 2020a) reported similarly that mature early genotype chickpea capable of maintaining pod set and seed filling under rainfed conditions possess a greater potential to achieve high productivity than late-maturing genotypes.

Degla genotype highest produced in PPP and GPP, however this distinction was not reflected in GY, this indicates higher productivity components that greater yield components alone do not necessarily result in higher productivity except if accompanied by efficient matter dry accumulation and distribution of nutrients to developing seeds. Also, F91-120c and Degla Show superiority PH and LPH, while Marakishi recorded the high HGW. Despite its larger size seed, Marakishi produced the low GY because of its substantially lower PPP, GPP, and HI. These results indicate that the weight of the seeds alone is not a reliable predictor of productivity in chickpea. Rather, final seed yield depends on the integrated contribution of pod number, seeds number, and the efficiency of transporting nutrients towards the growing seeds. Recent studies have also shown that the crop components work synergistically. and that increased seed weight cannot compensate for reductions in pod or grain number when determining final seed yield (Gimenez et al., 2025).

Despite that fact BY was relatively same among several genotypes, major differences were observed for GY and HI, indicating variation in the efficiency of dry matter allocation to reproductive organs. The Rafidian and F91-120c recorded the high HI values, reflecting greater efficiency in converting accumulated biomass into economic yield, whereas this efficiency was considerably lower in Marakishi. The Harvest index is widely recognized as one of the most important physiological indicators of crop productivity because it reflects the efficiency with which plants partition accumulated dry matter to the seeds. (Gimenez et al., 2025) show reported that higher harvest index values are closely associated with improved assimilate partitioning toward to seeds, ultimately resulting in enhanced chickpea productivity across different environments.

Generally, these results mention that Rafidian was the genotype better adapted to the environmental conditions of the Rabea location, exhibiting the most favorable balance between vegetative growth and yield-related traits. The genotypes F91-120c and F98-26c also demonstrated promising performance for several productivity-related characteristics, whereas Marakishi and F97-73c were distinguished by their relatively larger seed size without a corresponding increase in GY. These findings emphasize that genotype selection in chickpea breeding programs should be based on the integrated performance of yield components and the efficiency of dry matter partitioning rather than on individual traits, thereby facilitating the development of high-yielding cultivars well adapted to rainfed conditions in northern Iraq.

Table (3) Effect of chickpea genotypes on agronomic and yield-related traits at Rabea location

	Genotypes	DM	PH (CM)	PH (CM)	PP (plant ⁻¹)	P (plant ⁻¹)	Y (Kg ha ⁻¹)	GY (Kg ha ⁻¹)	HI%	HGW (g)
1	F91-120c	157.66	52.33	26.66	38.73	45.70	4100.0	2099.3	52.037	26.13
2	F92-120c	159.66	47.33	17.66	39.86	38.86	4585.0	1885.0	40.960	28.16
3	F97-41c	161.33	39.00	17.33	33.86	42.93	3481.7	1721.7	49.607	31.53
4	F97-73c	160.66	43.33	16.00	35.60	40.83	3590.0	1506.7	42.237	32.26
5	F97-113c	158.66	44.66	20.33	34.00	34.53	3820.0	1551.7	40.657	31.83
6	F98-26c	160.33	48.00	18.00	40.60	41.73	4118.3	1875.0	46.103	30.56
7	Rafidian	156.33	39.33	14.33	45.56	52.16	4735.0	2335.0	49.357	25.73
8	Degla	160.33	51.00	29.00	56.33	65.53	3591.7	1471.7	41.340	22.73

9	Dessi	162.00	33.66	10.66	34.63	41.50	1900.0	640.0	33.680	24.70
10	Marakishi	169.00	35.66F	14.33	4.40C	4.20	2360.0	375.0	15.537	34.75
	LSD's	2.423	4.031	5.243	13.53	16.06	952.68	382.35	7.239	1.494

DM: Days to Maturity; **PH:** Plant Height; **LPH:** Lowest Pod Height; **PPP:** Pods per Plant; **GPP:** Grains per Plant; **BY:** Biological Yield; **GY:** Grain Yield; **HI:** Harvest Index; **HGW:** 100-Grain Weight.

3-4 Genotype × Environment Interaction for Growth and Yield Traits

The results are show in table (4) revealed significant) genotype × environment interactions) for most of the evaluated traits, indicating that the performance of the chickpea genotypes varied across the two experimental environments. The results show in the genotype responses were strongest influenced by environmental conditions, emphasizing the importance of genotype adaptation to specific growing in environments. Such as these interactions are of particular importance in chickpea breeding because genotype performance is rarely consistent across diverse environments. Thus, multi environment estimate is fundamental for identifying genotypes patterns with broad adaptation, stable performance, and high productivity. These results are similar to what was found (Varshney et al., 2021), who emphasized that evaluating chickpea genotypes across contrasting environments is indispensable for selecting cultivars with superior adaptability and yield stability.

Significant differences in genotype responses were observed between the two locations. Rafidian genotype produced give high GY at the Rabea local while maintaining superior performance at Talaskf, show both broad adaptation and high yield stability across to environments. In contrast, the Degla genotype exhibited a substantial increase in PPP and GPP at Rabea compared with Talaskf. however, this improvement was not accompanied by a proportional increase in GY. This result show suggests that the efficiency of dry matter accumulation and assimilate partitioning to seed developing was low than some other genotypes. These findings indicate that improvements in yield components alone do not necessarily translate into higher grain yield unless supported by efficient physiological utilization of photosynthetic assimilates. (Gimenez et al., 2025) show the result similarly reported that the relationship between number of pod and grain yield depends largely on the efficiency of dry matter translocation to seeds rather than on pod number alone.

The results also showed that genetic F91-120c and F98-26c maintained relatively consistent performance across both locations for most evaluated traits, indicating satisfactory level of phenotypic stability and adaptability environmental. On the contrary Marakishi and Dessi exhibited performance poor for most productivity related traits in both locations, this indicates a limited ability to adapt to rainfed conditions in the northern Iraq. These observations confirm that genotype performance is determined by its capacity to efficiently use environmental resources and tolerate climatic of variability, characteristics that represent selection criteria in chickpea breeding programs. (Rani et al., 2020a) The study also concluded that adapting to environmental stress in chickpea depends on the integrated expression of phenological and physiological traits together with yield components rather than on any individual characteristic.

Total the genotype × environment interaction the results were determined Rafidian as the most stable and widely adapted genotype across both experimental environments. It consistently maintained high values for GY, HI, and the major yield components at both locations. In contrast, a few other genotypes exhibited environment specific responses, high lighting the needed of evaluating chickpea genotypes across multiple locations before recommending them for commercial cultivation or incorporating them into breeding programs aimed at developing broadly adapted, high-yielding cultivars.

Table (4) Interaction effects of Locations and Genotypes on agronomic and yield-related traits of Chickpea

Locations	Genotypes	DM	PH	LPH (CM)	PP (plant ⁻¹)	GP (plant ⁻¹)	BY	GY	HI	HGW
			(CM)				(Kg ha ⁻¹)	(Kg ha ⁻¹)	(%)	(g)
Talaskf	F91-120c	124.333	47.667	30.333	40.100	33.150	2592.0	1155.3	44.517	29.35
	F92-120c	125.667	38.333	19.667	40.267	35.500	2555.3	1055.3	41.310	29.20
	F97-41c	125.333	40.667	20.667	44.633	42.450	2229.3	1137.0	51.383	31.95
	F97-73c	124.000	37.000	18.000	29.367	23.950	2744.0	1151.7	41.987	38.70
	F97-113c	123.667	34.333	18.667	33.833	36.500	2807.0	1229.3	43.677	36.45
	F98-26c	122.333	43.667	21.333	38.500	29.150	2533.3	1166.3	45.843	33.00
	Rafidian	121.000	29.000	14.000	53.200	47.800	2647.7	1400.0	52.883	26.15
	Degla	124.000	45.000	31.000	30.267	32.000	2021.7	692.3	34.280	22.20
	Dessi	129.000	22.500	9.500	16.600	17.950	1199.3	377.3	30.617	27.65
	Marakishi	130.000	25.000	13.000	9.000	8.300	688.0	44.0	6.400	15.00
Rabea	F91-120c	157.667	52.333	26.667	38.733	45.700	4100.0	2099.3	52.037	26.13
	F92-120c	159.667	47.333	17.667	39.867	38.867	4585.0	1885.0	40.960	28.16
	F97-41c	161.333	39.000	17.333	33.867	42.933	3481.7	1721.7	49.607	31.53
	F97-73c	160.667	43.333	16.000	35.600	40.833	3590.0	1506.7	42.237	32.26
	F97-113c	158.667	44.667	20.333	34.000	34.533	3820.0	1551.7	40.657	31.83
	F98-26c	160.333	48.000	18.000	40.600	41.733	4118.3	1875.0	46.103	30.56
	Rafidian	156.333	39.333	14.333	45.567	52.167	4735.0	2335.0	49.357	25.73
	Degla	160.333	51.000	29.000	56.333	65.533	3591.7	1471.7	41.340	22.73
	Dessi	162.000	33.667	10.667	34.633	41.500	1900.0	640.0	33.680	24.70
	Marakishi	169.000	35.667	14.333	4.400	4.200	2360.0	375.0	15.537	34.75
LSD's		2.0706	3.5656	4.2967	10.625	11.786	875.22	386.42	6.756	1.6413

DM: Days to Maturity; **PH:** Plant Height; **LPH:** Lowest Pod Height; **PPP:** Pods per Plant; **GPP:** Grains per Plant; **BY:** Biological Yield; **GY:** Grain Yield; **HI:** Harvest Index; **HGW:** 100-Grain Weight.

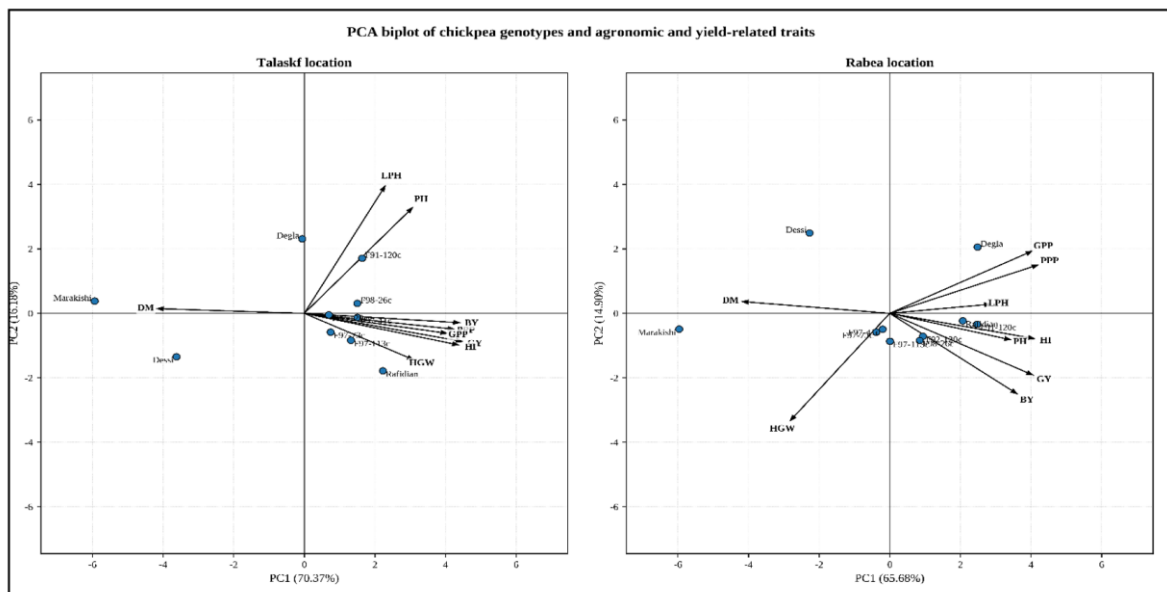
3-5 Principal Component Analysis (PCA) of Chickpea Genotypes

The biplots presented in principal component analysis (PCA) in Figure (1) explain the relationships between chickpea genotypes and the evaluated agronomic traits at the Talaskf and Rabea locations. First main

component (PC1) explains 70.73% of total apparent variance at Talaskf and 65.68% at Rabea, While the second main component (PC2) accounted for 16.18% and 14.90%, respectively. Then, the first two principal components jointly explained 86.55% of the total variation at Talaskf and 80.58% at Rabea. These high proportions indicate that the first two main components are adequately represented the overall variability among the evaluated genotypes, to be sure the effectiveness of PCA in characterizing genotype performance and elucidating relations between agronomic traits. This observation is consistent with the results (Jolliffe & Cadima, 2016), This has proven of the main component analysis PCA effectively reduces large multivariate datasets to a limited number of components while retaining most of the original information.

The sub charts for principal component analysis PCA show a strong positive correlation between GY, BY, and HI at both locations. Also, PPP and GPP were closely associated with one another, indicating that yield components working synergistically in determining chickpea productivity. The relationship suggests that an increase in number of pods generally results in a corresponding increase in number of grains, this ultimately contributes to increased seed productivity. Similar relationships has been reported in previous studied, which identified yield components as the principal determinants of final chickpea productivity.

In contrast, DM was positioned in the opposite direction to most productivity related attributes in both locations, indicating a negative association in the yield and its components. This pattern high lights the advantage of early-maturing genetic patterns under rainfed conditions, where completing the life cycle before the commencement of terminal drought and high temperatures contribute to improved productivity. Moreover, HGW was relatively independent of PPP, suggesting that increased the size seed is not necessarily accompanied by a greater pod number. Therefore, improving chickpea productivity requires an appropriate balance between size of the seed and numbers seed rather than maximizing either trait individually.



DM: Days to Maturity; **PH:** Plant Height; **LPH:** Lowest Pod Height; **PPP:** Pods per Plant; **GPP:** Grains per Plant; **BY:** Biological Yield; **GY:** Grain Yield; **HI:** Harvest Index; **HGW:** 100-Grain Weight.

Figure 1. PCA biplots of chickpea genotypes and agronomic and yield-related traits at Talaskf and Rabea locations.

Among the genetic makeups that were evaluated, Rafidian was positioned closest to the vectors representing GY, BY, HI, PPP, and GPP at both locations, indicating its superior productivity, wide adaptation, and high

stability in various environments. The F91-120c and F98-26c genotypes were also located near the cluster of productivity related traits, reflecting their outstanding agricultural performance and considerable potential for utilization in chickpea breeding programs. In contrast, Marakishi was positioned away from most yield related vectors and was more closely associated with DM, indicating relatively low productivity and adaptation poor to rainfed dependent conditions at both experimental sites. The Degla genotypes show strong association with PH and LPH, while at the Rabea location it was also closely associated with PPP and GPP. But these favorable yield components did not translate into the highest GY, this indicates its efficiency in breaking down dry matter partitioning toward developing seeds was lower than that of Rafidian.

Comprehensive, PCA Principal component analysis showed that the relationships between agricultural traits were generally consistent across the two experimental environments. Although the strength of genotype-trait associations varies according to environmental conditions, reflecting differential genotype responses to environmental variation. As a whole, the PCA identified Rafidian as the general productive, stable, and broadly adapt genotypes across both environments. As well as, F91-120c and F98-26c exhibited relatively stable performance, indicating that these genotypes represent promising candidates for chickpea improvement programs targeting rainfed environments in northern Iraq.

Recommendations

1. **Rafidian** genotype is recommended for advanced yield evaluation and potential cultivation under rainfed conditions because of its superior grain yield, favorable yield components, and stable performance across different environments.
2. The multi-location and multi season trials are recommended to further validate the yield stability and environmental adaptability of the superior chickpea genotypes before their large-scale release and cultivation.
3. The outstanding genotypes, particularly **Rafidian**, **F91-120c**, and **F98-26c**, are recommended as promising parental materials for chickpea breeding programs aimed at improving grain yield, yield stability, and adaptation to rainfed environments.
4. Multivariate statistical methods, particularly principal component analysis (PCA), should be integrated with conventional statistical analyses to improve the evaluation of genotype performance and facilitate the identification of superior genotypes based on multiple agronomic traits.
5. Future studies should incorporate physiological and molecular characterization of the superior genotypes to identify the genetic mechanisms underlying productivity and adaptation to rainfed environments, thereby supporting the development of improved chickpea cultivars.

Research Gap

Despite the agronomic importance of chickpea under rainfed conditions, limited information is available regarding the evaluation of chickpea genotypes across different rainfed environments in northern Iraq. In particular, studies integrating multi-environment evaluation with multivariate statistical approaches, such as principal component analysis (PCA), remain scarce. As a result this study was conducted to assess the phenotypic variability among chickpea genotypes and to investigate the relationships among agronomic and yield related traits in order to identify genotypes with superior adaptation, yield stability, and productivity under rainfed conditions. The findings are expected to provide valuable information for supporting chickpea breeding and genetic improvement programs.

Conclusion

- 1- The evaluated chickpea genotypes showed significant variation in most agricultural and productivity related traits under rainfed conditions, indicating the presence of exploitable genetic diversity.
- 2- The marked interaction between genotype and environment underscored the importance of multi-environmental evaluation for identifying stable and well-adapted chickpea genotypes.
- 3- The Rafidian cultivar consistently outperformed other genotypes in grain yield, harvest index, and several other yield components at both sites, demonstrating broad adaptability and high productivity potential.
- 4- Principal component analysis (PCA) effectively explained the apparent variance and identified grain yield, biological yield, harvest index, number of pods per plant, and number of grains per plant as key traits contributing to genotype differentiation.
- 5- The integration of traditional statistical analysis with PCA enhanced the interpretation of genotype performance and trait relationships, providing valuable information for chickpea breeding and selection in rainfed environments.

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