

Multivariate Analysis and Agronomic Performance of Cowpea Pure Lines Under Semi-Arid Ecological Conditions

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Abstract

Objective: Cowpea (*Vigna unguiculata* [L.] Walp.) is a vital grain legume characterized by high protein content, rich nutritional value, and excellent adaptation to drought-prone environments. This study aimed to evaluate grain yield and yield-related traits of advanced cowpea pure lines derived from various hybridization combinations under the ecological conditions of Konya, Türkiye.

Materials and Methods: The field experiments were conducted over the 2024 and 2025 growing seasons using a randomized complete block design with three replications. The data were subjected to combined analysis of variance (ANOVA), Pearson correlation, and principal component analysis (PCA).

Results: The results indicated significant effects of both year and genotype for most traits. Grain yield was found to be strongly and positively correlated with the number of pods per plant ($r = 0.920^{**}$), number of seeds per plant ($r = 0.827^{**}$), plant height ($r = 0.686^{**}$), and 100-seed weight ($r = 0.628^{**}$), while PCA confirmed the predominant role of these yield components in yield formation. Among the tested lines, VS24SU showed high values for grain yield and number of seeds per plant, reaching 198.62 kg da⁻¹ and 321.65 seeds per plant, respectively. Furthermore, VS24SU, VS24AP, and VS24MA were among the genotypes with relatively high yield potential under the climatic conditions of the study.

Conclusion: These findings reveal substantial genetic variation within the advanced lines and underscore that several genotypes are well-adapted to the Konya environment, offering desirable traits for cultivar

development. Consequently, these genotypes are recommended as promising parental materials for future breeding programs, although their stability should be further validated across multi-location trials.

Anahtar Kelimeler: Cowpea, year × genotype interaction, pure line, grain yield, genotype evaluation

Yarı Kurak Ekolojik Koşullarda Börülce Saf Hatlarının Agronomik Performansı ve Çok Değişkenli Analizi

Öz

Amaç: Börülce (*Vigna unguiculata* [L.] Walp.), yüksek protein içeriği, zengin besin değeri ve kurak koşullara uyum yeteneği nedeniyle önemli bir baklagil türüdür. Bu çalışmanın amacı, farklı melezleme kombinasyonlarından geliştirilen ileri generasyon börülce saf hatlarının Konya ekolojik koşullarındaki verim, verim unsurları belirlemek, üstün performans gösteren genotipleri ortaya koymak ve ıslah programlarında kullanılabilecek aday hatları belirlemektir.

Materyal ve Yöntem: Tarla denemeleri; 2024 ve 2025 yetiştirme sezonlarında, üç tekerrürlü Tesadüf Blokları Deneme Desenine göre yürütülmüştür. Elde edilen veriler; birleştirilmiş varyans analizi (ANOVA), Pearson korelasyonu ve temel bileşenler analizine (PCA) tabi tutulmuştur.

Araştırma Bulguları: Sonuçlar, incelenen özelliklerin büyük çoğunluğu üzerinde hem yılın hem de genotipin istatistiksel olarak önemli etkilere sahip olduğunu göstermiştir. Tane veriminin; bitkide bakla sayısı ($r = 0.920$), bitkide tohum sayısı ($r = 0.827^{**}$),

bitki boyu ($r = 0.686^{**}$) ve 100 tohum ağırlığı ($r = 0.628^{**}$) ile güçlü ve pozitif yönde ilişkili olduğu belirlenmiştir. Ayrıca, Temel Bileşenler Analizi (PCA), bu verim unsurlarının tane veriminin oluşumunda baskın bir role sahip olduğunu doğrulamıştır. Denemeye alınan hatlar arasında VS24SU, tane verimi ve bitki başına tohum sayısı bakımından yüksek değerler göstermiş; bu değerler sırasıyla 198,62 kg da⁻¹ ve 321,65 tohum olarak belirlenmiştir. Ayrıca VS24SU, VS24AP ve VS24MA, çalışmanın yürütüldüğü iklim koşulları altında nispeten yüksek verim potansiyeline sahip genotipler arasında yer almıştır.

Sonuç: Bu bulgular, ileri hatlar arasında önemli düzeyde genetik varyasyon bulunduğunu ortaya koymakta ve bazı genotiplerin Konya ekolojik koşullarına iyi uyum sağladığını, ayrıca çeşit geliştirme açısından arzu edilen özelliklere sahip olduğunu göstermektedir. Bu nedenle, söz konusu genotipler gelecekteki ıslah programları için umut verici ebeveyn materyaller olarak önerilmekte; ancak performans kararlılıklarının çok lokasyonlu denemelerle daha ileri düzeyde doğrulanması gerekmektedir.

Anahtar kelimeler: Börülce, yıl $\times$ genotip etkileşimi, tane verimi, genotip değerlendirme

Introduction

Grain legumes are vital for sustainable agriculture, human nutrition, and soil fertility. Their high protein content makes them crucial for food security, especially in developing countries (Harmankaya et al., 2016; Dalgıç et al., 2025). Cowpea (*Vigna unguiculata* [L.] Walp.) is particularly significant due to its adaptation to arid and semi-arid conditions and its ability to improve soil fertility through nitrogen fixation (Kyei-Boahen et al., 2017; Yılmaz and Elmas, 2024). Its versatile use for grain, fresh pods, and forage increases its economic importance (Bozokalfa and Sürmeli, 2019; Erdoğan, 2019). The high genetic variation and environmental adaptability of cowpea make it a valuable resource for breeding (Kır et al., 2015; Ceyhan and Karadaş, 2023). Therefore, enhancing cowpea yield traits is essential (Santos et al., 2014; Bozokalfa and Sürmeli, 2019). However, many studies have been conducted under limited environmental conditions, reducing the generalizability of the results (İdikut et al., 2019; Özçelebi and Erman, 2021).

Given the impact of genotype $\times$ environment interaction on yield and adaptation, identifying stable genotypes through multi-environment and multi-year trials is critical (Santos et al., 2014; Kır et al.,

2015; Bozokalfa and Sürmeli, 2019; Ceyhan and Karadaş, 2023).

Grain yield in cowpea is a complex trait resulting from the interaction of genotype, environment, and crop management practices. Yield components, including plant height, number of pods per plant, number of seeds per pod, and 100-seed weight, are the primary determinants of grain yield. Understanding the relationships among these traits is essential for developing effective selection strategies. Previous studies have demonstrated that grain yield is particularly strongly associated with the number of pods per plant, highlighting the importance of this trait in cowpea breeding (Santos et al., 2014). In addition, genotype $\times$ environment interaction plays a key role in determining yield stability, as the same genotype may exhibit varying performance under different ecological conditions. Therefore, multi-environment and multi-year evaluations are essential for the reliable identification of superior genotypes (İdikut et al., 2019).

Agronomic practices such as sowing time, plant density, and fertilizer application also have a substantial influence on cowpea growth and productivity. Delayed sowing, in particular, may lead to considerable yield losses due to exposure to high-temperature stress during the reproductive stage (İdikut et al., 2019). Likewise, appropriate plant density is critical for optimizing the balance between individual plant performance and yield per unit area (El Naim and Jabereldar, 2010). Fertilizer application, especially the adequate supply of nutrients, contributes significantly to yield improvement (Toy and Ünlü, 2015). However, the effectiveness of these agronomic practices may vary with the genotype's genetic background. Therefore, agronomic management should be evaluated alongside genotypic characteristics to optimize production practices and maximize yield potential.

The adoption of sustainable agricultural practices has increased the importance of cowpea because of its ability to fix atmospheric nitrogen, adapt to drought-prone environments, and contribute to environmentally friendly production systems (Kyei-Boahen et al., 2017). The broad genetic diversity of local cowpea genotypes provides valuable breeding material for improving yield and quality traits and developing high-yielding cultivars (Kır et al., 2015; Dalgıç et al., 2025). Since yield performance is determined by the interaction of genetic background, environmental conditions, and agronomic practices,

statistical approaches such as correlation and principal component analysis (PCA) are valuable tools for elucidating relationships among yield-related traits and identifying effective indirect selection criteria in breeding programs (Santos et al., 2014). These approaches facilitate the identification of superior genotypes and support the development of breeding strategies adapted to diverse environmental conditions. The objective of this study was to evaluate the performance of newly developed cowpea pure lines from diverse genetic backgrounds in terms of yield characteristics, identify lines with superior traits, and determine potential candidates for integration as genetic material into breeding programs. Furthermore, the study aimed to characterize the variation among the examined lines and elucidate the relationships between yield-related traits. The findings are expected to contribute to the development of high yielding, high quality cowpea cultivars adapted to varying ecological conditions and to provide a scientific foundation for future cultivar development programs.

Materials and Methods

Ten cowpea (*Vigna unguiculata* [L.] Walp.) genotypes (VS24AU, VS24US, VS24UA, VS24MP, VS24UM, VS24PM, VS24MA, VS24SU, Madagascar, and VS24AP), developed by Prof. Dr. Ercan Ceyhan, were evaluated under field conditions during the 2024 - 2025 growing season. The experiment was conducted at the Prof. Dr. Abdülkadir Akçin Research and Application Station of Selçuk University, Konya, Türkiye (37°52'N, 32°30'E; 1020 m), which is characterized by a continental climate.

The trial was established in a randomized complete block design with three replications. Seeds were sown manually on 24 May 2024 and 28 May 2025 at a spacing of 50 × 15 cm in plots consisting of four 4 m rows. Before sowing, the field was conventionally prepared, and 150 kg ha⁻¹ DAP fertilizer was applied. Standard cultural practices, including sprinkler irrigation and manual weed control, were carried out throughout the growing season. Plants were harvested manually on 15 September 2024 and 10 September 2025 at physiological maturity, and the seeds were dried and threshed for evaluation.

The experimental soil had a clay loam texture, alkaline reaction (pH ≈ 8.0), high calcium carbonate content (34.4–37.6%), low available phosphorus and zinc, and no salinity limitation (EC: 0.80–0.85 dS m⁻¹), conditions that may reduce nutrient availability

(Ceyhan and Karadaş, 2023; Karadaş and Ceyhan, 2023).

The region has a continental, semi-arid climate. During the 2024 growing season (May–September), total precipitation was 145.6 mm, while mean monthly temperatures ranged from 22.2 to 32.7 °C and relative humidity varied between 36.4% and 57.4% (Yılmaz, 2025). During the 2025 growing season (May–September), precipitation decreased to 131.2 mm, whereas temperature and relative humidity ranged from 18.7 to 27.8 °C and from 32.2% to 46.4%, respectively (Turkish State Meteorology General Directorate, 2025).

All genotypes included in the study were sown according to the experimental design, and all observations and measurements were performed on these materials. Genotype performance was assessed based on morphological, agronomic, and yield-related traits. Plant height (cm), number of pods per plant, number of seeds per pod, and number of seeds per plant were determined from 10 randomly selected plants per plot. The 100-seed weight (g) was determined by weighing groups of 100 seeds, whereas grain yield (kg da⁻¹) was calculated based on the total grain yield obtained from each plot. Combined analysis over two years was performed using analysis of variance (ANOVA) to determine the effects of year, genotype, and their interaction. Mean comparisons were conducted using the LSD test at the 5% significance level. Pearson correlation and principal component analyses (PCA) were also applied to examine relationships among traits and genotype performance. All analyses were carried out using JMP Pro 17.0 (SAS Institute Inc., Cary, NC, USA), with significance declared at $p < 0.05$ and $p < 0.01$.

Results and Discussion

The agronomic performance of ten cowpea genotypes was evaluated under Konya ecological conditions during the 2024 and 2025 growing seasons. Plant height, number of pods per plant, number of seeds per pod, number of seeds per plant, 100 seed weight, and grain yield were assessed.

Analysis of variance (ANOVA), Pearson correlation, and principal component analysis (PCA) revealed significant differences among genotypes and years, while genotype × year interactions were significant for several traits. These results demonstrate that both genetic and environmental factors contribute to variation in yield and its components.

Plant height

The effects of year and genotype on plant height were statistically significant (Table 1). The mean plant height increased from 66.66 cm in 2024 to 96.25 cm in 2025, reflecting the favorable environmental conditions that promoted vegetative growth. This finding is consistent with previous studies reporting that improved environmental conditions increase cowpea plant height (Ünlü and Padem, 2005; El Naim and Jabereldar, 2010).

According to the two-year averages, plant height ranged from 70.52 to 88.80 cm among the evaluated genotypes. The tallest plants were recorded in genotypes VS24AU (88.80 cm) and VS24PM (88.68

cm), both of which were classified in the highest LSD group (a), whereas the shortest plants were observed in the Madagascar genotype (70.52 cm) (Table 2). The fact that most genotypes were classified in the “ab” group indicates a gradual variation in plant height among the evaluated materials. This genetic variation demonstrates the broad diversity of the germplasm for plant height. Plant height is an important agronomic trait in cowpea because it is closely associated with photosynthetic capacity, light interception, and biomass production. Therefore, the observed variation provides valuable genetic resources for breeding programs, as taller genotypes may contribute to improved yield potential through greater biomass production.

Table 1. Combined Analysis of Variance for Agronomic Traits in Cowpea Genotypes

Sources of Variation	SD	Plant Height	Number of Pods per Plant	Number of Seeds per Pod
Mean	59			
Year	1	13136.481**	421.880**	5.046**
Replication (Year)	4	23.499	3.392	0.194
Genotype	9	182.278**	44.934**	1.959**
Year × Genotype	9	114.161**	14.599**	0.988**
Error	36	33.422	2.931	0.180

Sources of Variation	SD	Number of Seeds per Plant	100 Seed Weight	Grain Yield
Mean	59			
Year	1	21800.828**	15.100**	13216.504**
Replication (Year)	4	389.478	0.222	94.463
Genotype	9	5424.220**	10.336**	1417.293**
Year × Genotype	9	2719.209**	3.438**	663.710**
Error	36	364.754	0.574	63.350

*: $p < 0.05$; **: $p < 0.01$

The present findings are consistent with previous studies reporting plant height ranges of 62.66–108.90 cm (Idikut et al., 2015), 65–350 cm (Kır et al., 2015), and 55.0–80.7 cm (Özçelebi and Erman, 2021) in cowpea. The significant year × genotype interaction indicates that the genotypes differed in their responses to environmental conditions. For example, VS24AU, VS24MP, and VS24SU moved into the highest LSD group in the second year, whereas the Madagascar genotype remained in the lower group, showing only a slight increase. These results suggest that some genotypes were more responsive to environmental changes, while others exhibited greater stability.

Variations in plant height are influenced not only by genetic background but also by factors such as plant density (El Naim and Jabereldar, 2010), sowing time (Çulha and Bozoğlu, 2016; Öncan Sümer, 2024), and nutrient management (Yılmaz and Elmas, 2024). Overall, the superior plant height exhibited by genotypes VS24AU and VS24PM highlights their potential as promising breeding materials for

improving biomass production and grain yield (Table 2).

Number of pods per plant

The effects of year and genotype on the number of pods per plant were statistically significant (Table 1). Comparing the two growing seasons, the mean number of pods per plant increased from 24.27 in 2024 to 29.57 in 2025 (Table 2). This increase indicates that the environmental conditions in 2025 were more favorable for flowering and pod setting.

The obtained results are consistent with previous studies reporting that environmental conditions play a decisive role in pod formation. High temperatures and drought stress during the flowering period have been reported to reduce the number of pods per plant, whereas favorable moisture and temperature conditions promote pod set (Ünlü and Padem, 2005; El Naim and Jabereldar, 2010; Çulha and Bozoğlu, 2016; Öncan Sümer, 2024). These findings indicate that the number of pods per plant is an important yield component influenced by both genetic factors and environmental conditions.

Table 2. Mean values and LSD groups for plant height, number of pods per plant, number of seeds per pod, number of seeds per plant, 100 seed weight, and grain yield in cowpea genotypes

Genotypes	Years					
	Plant Height (cm)			Number of Pods per Plant		
	2024	2025	Mean	2024	2025	Mean
Madagaskar	59.30 ^f	81.73 ^{cd}	70.52 ^c	21.00 ^f	25.07 ^{de}	23.03 ^e
VS24AP	67.20 ^{ef}	93.57 ^{abc}	80.38 ^{ab}	27.67 ^{cd}	32.87 ^{ab}	30.27 ^a
VS24AU	72.53 ^{de}	105.07 ^a	88.80 ^a	26.00 ^{cde}	29.47 ^{bc}	27.73 ^{abc}
VS24MA	63.43 ^{ef}	90.13 ^{bc}	76.78 ^{bc}	24.33 ^{def}	29.77 ^{bc}	27.05 ^{bcd}
VS24MP	61.87 ^{ef}	105.07 ^a	83.47 ^{ab}	24.33 ^{def}	34.30 ^a	29.32 ^{ab}
VS24PM	71.33 ^{def}	106.03 ^a	88.68 ^a	24.00 ^{def}	26.70 ^{cde}	25.35 ^{cde}
VS24SU	61.67 ^{ef}	105.07 ^a	83.37 ^{ab}	24.33 ^{def}	36.17 ^a	30.25 ^a
VS24UA	69.10 ^{def}	86.13 ^{bc}	77.62 ^{bc}	21.00 ^f	25.17 ^{de}	23.08 ^e
VS24UM	70.57 ^{def}	94.90 ^{ab}	82.73 ^{ab}	23.00 ^{ef}	26.60 ^{cde}	24.80 ^{de}
VS24US	69.57 ^{def}	94.80 ^{ab}	82.18 ^{ab}	27.00 ^{cd}	29.60 ^{bc}	28.30 ^{ab}
Mean	66.66	96.25	81.45	24.27	29.57	26.92
Genotypes	Number of Seeds per Pod			Number of Seeds per Plant		
	2024	2025	Mean	2024	2025	Mean
	2024	2025	Mean	2024	2025	Mean
Madagaskar	9.50 ^{ef}	9.70 ^{c-f}	9.60 ^c	199.20 ^g	243.53 ^{ef}	221.37 ^e
VS24AP	9.60 ^{def}	9.40 ^{efg}	9.50 ^c	265.50 ^{cde}	308.90 ^b	287.20 ^{bc}
VS24AU	10.30 ^{a-e}	8.50 ^g	9.40 ^c	268.67 ^{b-e}	250.13 ^{def}	259.40 ^{cd}
VS24MA	10.90 ^{ab}	9.80 ^{c-f}	10.35 ^{ab}	265.50 ^{cde}	291.73 ^{bcd}	278.62 ^c
VS24MP	10.80 ^{ab}	10.80 ^{ab}	10.80 ^a	262.33 ^{cde}	368.90 ^a	315.62 ^{ab}
VS24PM	10.87 ^{ab}	10.47 ^{a-d}	10.67 ^{ab}	260.77 ^{cde}	279.63 ^{b-e}	270.20 ^{cd}
VS24SU	11.20 ^a	10.23 ^{b-e}	10.72 ^a	273.10 ^{b-e}	370.20 ^a	321.65 ^a
VS24UA	10.23 ^{be}	10.90 ^{ab}	10.57 ^{ab}	214.87 ^{fg}	274.60 ^{b-e}	244.73 ^{de}
VS24UM	11.10 ^{ab}	10.63 ^{abc}	10.87 ^a	255.67 ^{c-f}	282.47 ^{b-e}	269.07 ^{cd}
VS24US	10.90 ^{ab}	9.17 ^{fg}	10.03 ^{bc}	294.00 ^{bc}	270.73 ^{b-e}	282.37 ^c
Mean	10.54	9.96	10.25	255.96	294.08	275.02
Genotypes	100-Seed Weight (g)			Grain Yield (kg da ⁻¹)		
	2024	2025	Mean	2024	2025	Mean
	2024	2025	Mean	2024	2025	Mean
Madagaskar	21.67 ^{fg}	22.23 ^{d-g}	21.95 ^e	141.00 ^j	161.37 ^{f-i}	151.18 ^e
VS24AP	23.00 ^{c-f}	23.43 ^{cde}	23.22 ^{a-d}	177.20 ^{def}	204.03 ^b	190.62 ^{ab}
VS24AU	22.33 ^{d-g}	23.07 ^{c-f}	22.70 ^{cde}	166.13 ^{e-h}	185.93 ^{cd}	176.03 ^c
VS24MA	23.33 ^{c-f}	25.27 ^{ab}	24.30 ^a	163.60 ^{gh}	200.27 ^{bc}	181.93 ^{bc}
VS24MP	22.33 ^{d-g}	22.13 ^{efg}	22.23 ^{de}	158.73 ^{gh}	201.80 ^{bc}	180.27 ^{bc}
VS24PM	22.33 ^{d-g}	24.67 ^{abc}	23.50 ^{abc}	157.33 ^{g-i}	181.70 ^{de}	169.52 ^{cd}
VS24SU	22.33 ^{d-g}	26.07 ^a	24.20 ^{ab}	158.67 ^{g-i}	238.57 ^a	198.62 ^a
VS24UA	22.33 ^{d-g}	23.83 ^{bcd}	23.08 ^{b-e}	143.80 ^{ij}	169.90 ^{d-g}	156.85 ^e
VS24UM	22.00 ^{efg}	22.87 ^{def}	22.43 ^{cde}	151.33 ^{hij}	171.53 ^{d-g}	161.43 ^{de}
VS24US	20.67 ^g	18.80 ^h	19.73 ^f	161.60 ^{fgh}	161.13 ^h	161.37 ^{de}
Mean	22.23	23.24	22.73	157.94	187.62	172.78

There were no statistically significant differences among the means sharing the same letter.

According to the two year averages, the number of pods per plant ranged from 23.03 to 30.27. The highest values were recorded in genotypes VS24AP (30.27), VS24SU (30.25), and VS24MP (29.32), whereas the lowest values were observed in Madagaskar (23.03) and VS24UA (23.08) (Table 2). These results indicate substantial genetic variation among the evaluated genotypes in terms of pod production capacity. The year $\times$ genotype interaction was statistically significant (Table 1), and all genotypes produced more pods per plant in 2025 than in 2024. The greatest increases were observed in VS24SU (from 24.33 to 36.17 pods per plant) and VS24MP (from 24.33 to 34.30 pods per plant), indicating that these genotypes had a high reproductive potential under favorable environmental conditions. In contrast, Madagaskar and VS24UA consistently exhibited low pod numbers in both years.

The present findings are consistent with those of Santos et al. (2014), who identified the number of pods per plant as one of the major components of grain yield. They also agree with previous studies reporting substantial variation in this trait among genotypes and environments (İdikut et al., 2015; Bozokalfa and Sürmeli, 2019; Bilen Binici and Bozokalfa, 2020; Ceyhan and Karadaş, 2023; Karadaş and Ceyhan, 2023; Polat and Ceyhan, 2024). Furthermore, earlier studies have shown that high temperature and drought stress reduce pod set (Ünlü and Padem, 2005), whereas favorable growing conditions increase the number of pods per plant (El Naim and Jabereldar, 2010; Sert and Ceyhan, 2012; Çulha and Bozoğlu, 2016; Kyei-Boahen et al., 2017; İdikut et al., 2019, 2020; Yılmaz and Elmas, 2024). Accordingly, the superior performance of genotypes VS24AP, VS24SU, and VS24MP for the number of pods per plant suggests that they are promising parental

materials for future breeding programs and should be further evaluated under different environmental conditions to develop high yielding and stable cowpea cultivars.

Number of seeds per pod

The effects of year and genotype on the number of seeds per pod were statistically significant (Table 1). The mean number of seeds per pod decreased from 10.54 in 2024 to 9.96 in 2025. Although plant height and the number of pods per plant increased in 2025, the seed-setting capacity per pod declined slightly. This reduction may be attributed to competition for assimilates among reproductive organs. An increase in the number of pods per plant can reduce the assimilate supply available to individual pods, resulting in fewer seeds per pod. Santos et al. (2014) similarly reported that an increase in pod number does not necessarily lead to a higher number of seeds per pod because of resource competition. In addition, environmental conditions during flowering and fertilization, such as high temperature and water deficit, may reduce pollen viability and fertilization success, thereby decreasing the number of seeds per pod (Ünlü and Padem, 2005; Öncan Sümer, 2024). Therefore, the decline in seeds per pod observed in 2025, despite the increase in pod number, may reflect changes in the balance between reproductive sink strength and assimilate partitioning.

According to the two-year averages, the number of seeds per pod ranged from 9.40 to 10.87. The highest value was recorded in genotype VS24UM (10.87), followed by VS24MP (10.80) and VS24SU (10.72), whereas the lowest values were observed in VS24AU (9.40), VS24AP (9.50), and Madagaskar (9.60) (Table 2). This range is consistent with previous reports and confirms the presence of significant genetic variation among the evaluated genotypes. Although the number of seeds per pod is an important yield component, it is not the sole determinant of grain yield. Previous studies have shown that its contribution to grain yield should be evaluated together with other yield components, particularly the number of pods per plant and seed weight (Santos et al., 2014). Therefore, the superior performance of genotypes with a high number of seeds per pod is expected to contribute more effectively to grain yield when combined with a high pod number and greater 100-seed weight.

The significant year $\times$ genotype interaction (Table 1) was also reflected in changes in genotype rankings between years. For example, genotypes such as

VS24MP and VS24SU moved from the intermediate group in 2024 to the upper group in 2025, whereas Madagaskar consistently exhibited low performance in both years. These results indicate that some genotypes were highly responsive to environmental conditions, whereas others were more stable but less productive. In particular, VS24AU and VS24PM combined relatively high performance with good adaptation, while VS24MP and VS24SU showed high performance under favorable conditions but greater environmental sensitivity. In contrast, Madagaskar exhibited consistently low but stable performance. Therefore, genotype selection should consider not only mean performance but also stability and adaptability across environments.

Number of seeds per plant

The effects of year and genotype on the number of seeds per plant were statistically significant (Table 1). The mean number of seeds per plant increased from 255.96 in 2024 to 294.08 in 2025, with a two-year mean of 275.02 seeds per plant (Table 2). This increase was consistent with the higher number of pods per plant observed in 2025, indicating that favorable environmental conditions promoted reproductive development. In particular, adequate soil moisture and optimum temperature conditions have been reported to reduce flower abortion and enhance pod and seed formation (Ünlü and Padem, 2005; Öncan Sümer, 2024). Similarly, Santos et al. (2014) reported that the number of seeds per plant is strongly associated with grain yield and is highly influenced by environmental conditions.

According to the two-year averages, the number of seeds per plant ranged from 221.37 to 321.65. The highest value was recorded in genotype VS24SU (321.65 seeds per plant), followed by VS24MP (315.62 seeds per plant), whereas the lowest value was observed in the Madagaskar genotype (221.37 seeds per plant). Genotype VS24UA (244.73 seeds per plant) was also included in the lower-performing group (Table 2). These results indicate substantial genetic variation among the evaluated genotypes in terms of seed production capacity.

The significant year $\times$ genotype interaction (Table 1) indicates that the genotypes responded differently to environmental conditions. In particular, VS24SU and VS24MP showed marked increases in the number of seeds per plant in 2025, whereas VS24AU exhibited a decrease, and VS24UA and VS24UM showed only limited changes between years. These findings suggest that high-performing genotypes responded

more positively to improved environmental conditions, whereas some genotypes exhibited greater stability but lower overall performance.

The results of this study are consistent with previous reports indicating that the number of seeds per plant and related yield components in cowpea are highly influenced by environmental conditions. Santos et al. (2014) reported that grain yield is closely associated with the number of pods per plant and other yield components, all of which are affected by environmental factors. Similarly, El Naim and Jabereldar (2010) demonstrated that yield and its components vary considerably among years due to differences in environmental conditions. Ünlü and Padem (2005) and Öncan Sümer (2024) also emphasized that sowing time, water availability, and temperature stress are major factors affecting flowering, pod set, and seed formation. Accordingly, the substantial increases observed in some genotypes during 2025 may be attributed to improved environmental conditions that enhanced their reproductive capacity.

Previous studies have also highlighted the importance of genotype $\times$ environment interaction in determining yield stability in grain legumes. The variation in genotype rankings across years indicates that selection should not be based solely on mean performance. In the present study, VS24SU and VS24MP showed a greater response to improved environmental conditions, whereas genotypes with moderate increases exhibited relatively more stable but lower overall performance. Therefore, genotypes with a high number of seeds per plant should be evaluated across multiple years and locations, and their performance should be supported by stability analyses together with other yield components to ensure reliable selection in cowpea breeding programs.

100 seed weight

The effects of year and genotype on 100 seed weight were statistically significant (Table 1). The mean 100-seed weight increased from 22.23 g in 2024 to 23.24 g in 2025. This overall increase indicates that the environmental conditions during the grain-filling period in 2025 (temperature, humidity, and nutrient uptake) were more favorable, which is consistent with the literature (Ünlü and Padem, 2005; Yilmaz and Elmas, 2024).

According to the two-year averages, 100-seed weight ranged from 19.73 to 24.30 g. The highest value was recorded in genotype VS24MA (24.30 g), followed by

VS24SU (24.20 g) and VS24PM (23.50 g), whereas the lowest 100-seed weight was observed in VS24US (19.73 g) (Table 2). This wide range indicates substantial genetic variation for seed size among the evaluated genotypes and is consistent with previous studies reporting that 100-seed weight is a reliable selection criterion in cowpea breeding (Ceyhan and Karadaş, 2023; Karadaş and Ceyhan, 2023; Polat and Ceyhan, 2024).

The significant year $\times$ genotype interaction (Table 1) indicated that the genotypes responded differently to changing environmental conditions. The greatest increases in 100-seed weight were observed in VS24SU (from 22.33 to 26.07 g), followed by VS24MA (23.33–25.27 g) and VS24PM (22.33–24.67 g). These results suggest that these genotypes were more efficient in allocating photosynthetic assimilates to seed filling under favorable environmental conditions. In contrast, the marked reduction in 100-seed weight observed in VS24US (from 20.67 to 18.80 g) indicates that this genotype was more sensitive to stress conditions during the grain-filling period, such as high temperature and water deficit (Ünlü and Padem, 2005; El Naim and Jabereldar, 2010).

Overall, VS24MA, VS24SU, and VS24PM, which exhibited superior and relatively stable 100-seed weight, can be considered promising parental lines for developing high-yielding cowpea cultivars.

Grain yield

Year and genotype effects on grain yield were statistically significant in the evaluated cowpea genotypes (Table 1). The mean grain yield increased from 157.94 kg da⁻¹ in 2024 to 187.62 kg da⁻¹ in 2025. This increase indicates that more favorable environmental conditions during the 2025 growing season promoted pod formation, seed production per plant, and seed filling. Similar findings have been reported by Ünlü and Padem (2005), El Naim and Jabereldar (2010), and Yilmaz and Elmas (2024), who concluded that adequate water availability and favorable temperature conditions significantly enhance cowpea grain yield.

According to the two-year averages, grain yield ranged from 151.18 to 198.62 kg da⁻¹. The highest grain yield was recorded in genotype VS24SU (198.62 kg da⁻¹), followed by VS24AP (190.62 kg da⁻¹), VS24MA (181.93 kg da⁻¹), and VS24MP (180.27 kg da⁻¹). The lowest grain yields were obtained from the Madagascar (151.18 kg da⁻¹) and VS24UA (156.85 kg da⁻¹) genotypes (Table 2). These results indicate the

presence of substantial genetic variation for grain yield among the evaluated genotypes.

The year $\times$ genotype interaction was significant for grain yield (Table 1), indicating that the genotypes responded differently to environmental conditions. The greatest increase was observed in genotype VS24SU, whose grain yield increased from 158.67 to 238.57 kg da⁻¹. Similarly, VS24AP, VS24MA, and VS24MP exhibited substantial yield increases in the second growing season. In contrast, VS24US (161.60–161.13 kg da⁻¹) and Madagascar showed only minor changes between years, indicating relatively stable but lower grain yield performance. These findings suggest that genotype selection in breeding programs should be based not only on mean grain yield but also on performance consistency across different growing seasons.

Previous studies have also emphasized that grain yield in cowpea is strongly influenced by environmental factors and that genotype $\times$ environment interaction plays a critical role in yield stability. Ünlü and Padem (2005) reported a significant increase in grain yield under adequate water supply, whereas El Naim and Jabereldar (2010) demonstrated that yield and yield components varied considerably across years due to differences in environmental conditions. Similarly, Ceyhan and Karadaş (2023) and Karadaş and Ceyhan (2023) reported that cowpea genotypes responded differently to environmental conditions, with some genotypes exhibiting superior performance under specific environments. In the present study, the pronounced yield increases observed in several genotypes under more favorable conditions suggest that these genotypes possess a high adaptation potential.

Pearson's correlation coefficients among agronomic characteristics

The correlation between various traits and grain yield was studied to facilitate the selection of beneficial traits for higher grain yield in cowpea breeding programs (Figure 1). The extent and nature of the correlation between crop yield components and grain yield have been intensively studied. Correlation analyses are valuable tools in breeding programs, helping identify traits that may contribute to improving grain yield in cowpeas. Grain yield is positively correlated with pods per plant ($r = 0.920^{**}$), seeds per plant ($r = 0.827^{**}$), plant height ($r = 0.686^{**}$), and 100-seed weight ($r = 0.628^{**}$). The grain yield indicated a weak negative correlation with

seeds per pod ($r = -0.189$). Grain yield showed positive and significant correlations with these traits, consistent with previous findings that direct selection for these traits may result in higher grain yield in cowpeas.

These traits should be given special emphasis in cowpea breeding programs because they are yield traits. Grain yield is also influenced by the environmental factors, which are responsible for non-genetic variations. Therefore, simultaneous selection for the traits in which a significant correlation exists will increase the efficiency of grain yield improvement in cowpea.

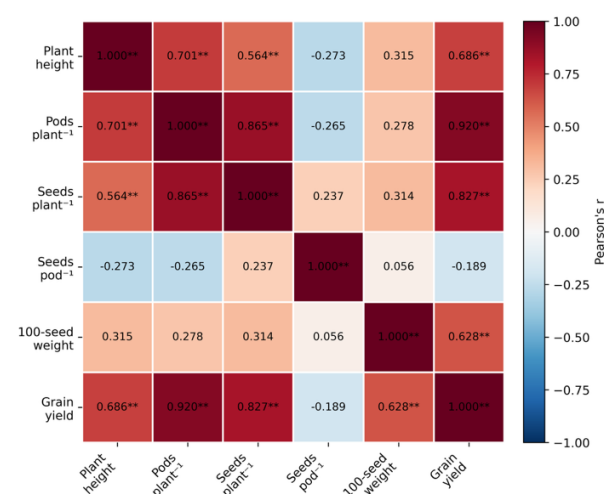


Figure 1. Pearson correlation matrix for agronomic traits evaluated in cowpea genotypes.

The results largely align with previous studies examining the relationships among yield components in fava beans. In particular, numerous studies have reported that the number of pods per plant and the number of seeds per pod are the most decisive traits affecting grain yield. Santos et al. (2014) noted that grain yield is determined by the combined effect of numerous yield components and that these traits must be evaluated together when identifying high yielding genotypes.

Similarly, in a study conducted by Kir et al. (2015) using a broad genetic material, it was emphasized that the high variation in the number of pods and seeds per plant is important for selection purposes. Ceyhan and Karadaş (2023), on the other hand, reported that under appropriate growing conditions, increases in pod number were parallel to increases in grain yield. These studies support the biological consistency of the positive correlations identified in the present study.

Multivariate Evaluation of Genotypes by Principal Component Analysis (PCA)

Despite its importance, the genetic variability and superior genotypes are seldom utilized by cumulative evaluation of these traits, hence require a multivariate analysis. The aim of this study was to investigate the interrelationships of agronomic traits of cowpea genotypes and the effect of those traits on grain yield through principal component analysis.

The first principal component (PC1), explaining 59.18% of the total variation, was mainly associated with grain yield, number of pods per plant, number of seeds per plant, and plant height, whereas PC2 (20.30%) was primarily influenced by seeds per pod and, to a lesser extent, 100 seed weight. The PCA biplot further revealed that grain yield, number of pods per plant, and number of seeds per plant were closely grouped and oriented in nearly the same direction, indicating a strong positive association among these traits. Plant height was also positioned within the same quadrant, suggesting that taller genotypes tended to exhibit higher yield potential under the experimental conditions.

In contrast, 100 seed weight was separated from the other yield components along the negative direction of PC2, indicating that seed weight contributed relatively independently to phenotypic variation. This distribution suggests that simultaneous selection for pod number and seed number would be more effective for improving grain yield than selection based solely on seed weight.

This implies that variation in yield is driven by the number of seeds and pods per plant. This indicates a direct reflection of one variable on the other. The third PC accounts for 4.29% of the variability, and the character contributing to its variability is 100 seed weight. The fourth and last PC accounts for 4.00% of the total variability, and its contributing variable is the number of pods per plant. This indicates that the number of pods per plant does not provide independent variation for yield improvement; rather, it indirectly affects yield through pods per plant and grain yield (Figure 2). This also states that the number of pods per plant is inseparable from the number of seeds per plant and grain yield.

The identification of these interrelationships will provide important information to plant breeders, enabling the use of these traits as selection criteria to accelerate improvement in cowpea productivity. The observed grouping of agronomic traits indicates that

indirect selection based on the number of pods per plant and the number of seeds per plant may improve grain yield more efficiently than selection based on individual traits alone. Therefore, these traits can serve as reliable selection criteria in future cowpea breeding programs.

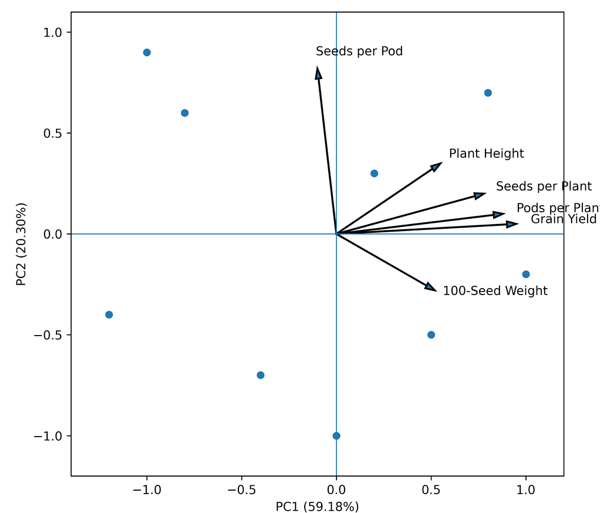


Figure 2. Principal component analysis (PCA) biplot of the agronomic traits examined in cowpea genotypes.

The fact that the first two components in the principal component analysis explain 79.48% of the total variation and, in particular, that the number of pods per plant and the number of seeds per plant fall within the same component indicates that these traits are the primary characteristics determining grain yield. These results are consistent with the findings reported by Santos et al. (2014), who noted that yield in fava bean genotypes is shaped by the combined effect of numerous yield components. Similarly, Mofokeng et al. (2020) noted that in principal component analysis, the number of pods, the number of seeds per plant, and grain yield clustered along the same axis and that these traits should be prioritized in breeding. Furthermore, Yılmaz and Elmas (2024) indirectly supported the close relationship among these traits by reporting simultaneous increases in plant height, pod number, and grain yield following phosphorus and boron applications.

Therefore, the combined evaluation of traits such as number of pods per plant, number of seeds per plant, plant height, and seed weight, which, alongside grain yield, stand out in principal component analysis, will enhance the effectiveness of selection for developing high yielding fava bean genotypes.

Conclusions

This study comprehensively evaluated the yield and yield-related traits of newly developed cowpea pure lines against a standard cultivar. Significant variation was observed among genotypes for most of the traits investigated, confirming substantial genetic diversity within the germplasm. The differences identified in grain yield, number of pods per plant, number of seeds per pod, and 100 seed weight provide a robust basis for selecting superior genotypes for breeding programs.

Several pure lines outperformed the standard cultivar, highlighting their potential as promising candidates for new cultivar development. The results demonstrated that grain yield is a complex trait determined by the synergistic effects of plant height, number of pods per plant, number of seeds per pod, and 100 seed weight. Therefore, future selection efforts should integrate these components rather than focusing solely on grain yield to achieve higher breeding efficiency.

The findings are consistent with previous literature regarding genetic variation and yield component relationships. Notably, the superior performance of these new lines under the calcareous and drought-prone conditions of Central Anatolia indicates high regional adaptation and underscores the importance of utilizing local genetic resources.

However, as genotypic performance is influenced by environmental factors, these superior lines must be further evaluated across different locations and years. Multi-environment trials will be essential to determine yield stability and adaptation before formal registration. Future research should expand to include functional quality traits and utilize molecular markers or genomic selection to accelerate genetic progress. Overall, these results provide a scientific foundation for developing high-yielding cowpea cultivars, contributing to sustainable agricultural production and regional food security.

Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

Author Contribution Statement

The authors declare that they have contributed significantly to the conception, design, execution, and interpretation of the study. İAÇ, SK, MAA, HD, and EC participated in the planning and conduct of the research, data collection, analysis, and manuscript preparation. İAÇ specifically reviewed and verified

the statistical analyses. EC critically reviewed the manuscript and approved the final version before submission. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

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