

Original Research Article**CODEN: PJZSAZ e-ISSN: 1331-7776****Interrelationships among morphological traits and their contribution to the performance of different chickpea lines under semi-arid conditions**

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Croatia***How to Cite:***

Sabaghnia N., Nouraein M., Nasiri Y., Janmohammadi M. (2027). Interrelationships among morphological traits and their contribution to the performance of different chickpea lines under semi-arid conditions. Agric Conspec Sci 92: e002.

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ABSTRACT

This research evaluated the relationships among 18 traits in 36 chickpea genotypes grown at Maragheh, Iran, over two seasons. Correlation, regression, and path analyses were used to elucidate direct and indirect associations with yield. The traits were classified into six levels encompassing vegetative growth and plant architecture (Level 1), branching (Level 2), pod formation (Level 3), grain number (Level 4), pod/grain mass and grain size (Level 5), and grain yield (Level 6). Grain yield showed positive associations with most of the traits, although the magnitude of relationships differed between years. Path analysis identified husk weight per primary pod as the strongest proximal direct effect of grain yield in the first year, whereas grain weight per primary pod showed the strongest proximal direct effect in the second year. Grain number per primary and secondary pods, pod number, branching traits, and plant dry weight were associated with grain yield through different hierarchical pathways. The results indicate that chickpea grain yield is associated within interconnected hierarchy of vegetative, architectural, and reproductive traits, with reproductive traits showing the strongest and most proximal associations in the identified pathways. Grain number, pod production, grain weight, and branching capacity may represent candidate traits for indirect selection; however, their consistency and breeding value should be validated across diverse environments and populations.

Key words: morphology, direct effect, multiple regression, selection index

INTRODUCTION

Chickpea (*Cicer arietinum* L.), is one of the major cool-season pulse crops and the third most important food legume worldwide, and is cultivated in more than 50 countries. Approximately 95% of the global chickpea area and production occur in developing countries, where chickpea provides an important source of dietary protein and generally contains more protein than many cereals (Begum et al., 2023). Chickpea has a high protein content on a dry-weight basis and is widely consumed, particularly in developing countries, particularly in developing countries. In 2022, the global production of chickpea was estimated at almost 18 million tons with reported yields ranging from 0.3 t ha⁻¹ in Libya to 5.5 t ha⁻¹ in China (FAOSTAT, 2022). In Iran, the area cultivated with chickpea is approximately 430 thousand ha and with an annual production of approximately 176 thousand tons, making chickpea one of the most important pulse crops in Iran. Although, chickpea ranks third in terms of cultivated area among the major food legumes worldwide, chickpea is the most important pulse crop in Iran and Iran is considered an important centre of chickpea origin and diversity. The crop is cultivated throughout Iran, except in the humid northern regions. Although, chickpea is one of the major crops cultivated in Iran, its mean yield in Iran (approximately 0.4 t ha⁻¹) is considerably lower than the global average yield (1.2 t ha⁻¹) (FAOSTAT, 2022).

In plant breeding, associations among traits are important because they indicate the magnitude and direction of relationships among them (Mohebodini et al., 2018). Examining these associations, including relationships among yield-related traits and yield components and their potential causal relationships can assist breeders in identifying trait combinations with greater potential for yield improvement. Although, simple correlation coefficients are useful but cannot

distinguish direct from indirect associations and under such circumstances path analysis, which decomposes correlations into standardized direct and indirect effects, is therefore recommended (Lambe et al., 2024). Path analysis partitions correlation coefficients into direct effects and indirect effects of predictor traits on a target variable through different paths. This approach is particularly useful for identifying traits associated with yield performance (Janmohammadi et al., 2014). Thus, breeders can use this technique to assess the contribution of specific traits to yield performance. Grain yield is a quantitative trait which is influenced by genetic and environmental factors so selection for yield-associated traits may contribute to improving yield (Nikita and Lal, 2022). However, indirect selection based on heritable and yield-associated traits may provide more reliable responses than direct selection on basis of yield, so path analysis helps to quantify direct and indirect effect of traits on yield. Tsehaye et al. (2020), based on 100 chickpea genotypes, reported that chickpea seed yield was significantly and positively associated with traits pods of plant, days to flowering, biomass and hundred-seed weight, and negatively associated with traits secondary branches. They recommended that to improve yield, breeder should focus on pod of plant, harvest index, hundred-seed weight, secondary branches, and biomass.

Chickpea genotypes exhibited considerable genetic variation whereas the phenological traits, plant height, number of primary branches, first pod height, the number of seeds of pods, pods of plants and yield were identified as important traits associated with yield (Jain et al., 2023). Based on trait interrelationships, the same authors classified yield-related traits into three as follows: biomass and pods per plant as one group, days to flowering and flowering duration as another group, and finally plant height and first pod height as the distinct group. Jain et al. (2023), mentioned that hundred-seed weight, should be taken into account apart from other groups because it may serve as an additional selection criterion when selecting the breeding lines. According to

Yadav et al. (2020), a direct and positive association was reported between yield and pods of plant, harvest index and biomass. The path analysis indicated that harvest index, biomass, pods of plant and hundred-seed weight as traits with direct effects on yield, and can be considered promising for developing of superior chickpea genotypes (Yadav et al., 2020). In the study by Nikita and Lal (2022), yield showed significant and positive relationship with pods of plant, biomass and harvest index, whereas path decomposition indicated strong direct effects of days to maturity, pods of plant, harvest index, biomass and lateral branches. According to correlation analysis, biomass and harvest index were the main traits associated with yield of chickpea (Kushwah et al., 2021), while pod growth rate exerted a direct but negative effect on yield, and pods of plant, harvest index and biomass exerted a direct positive effect. In a recent study, pods of plant had the strongest association with yield performance together with days to maturity, plant canopy, plant height and hundred-seed weight (Lambe et al., 2024). This study aims to characterize the interrelationships between yield and some agronomic traits among chickpea genotypes using correlation and path coefficient analyses. Current investigation was designed to examine the hierarchical relationships of 18 morphological characteristics of 36 chickpea accessions to identify traits most associated with grain yield under semi-arid conditions. By integrating regression and path coefficient analysis along with correlation within a biologically informed hierarchical framework of the assessed traits, the study aims to identify upstream vegetative and architectural traits that influence yield components so as to guide the development of effective selection criteria for chickpea breeding projects.

MATERIALS AND METHODS

Trials

Eighteen ICARDA (International Center for Agricultural Research in the Dry Areas) lines, 17 lines from Iran's national pulse breeding program, and the check cultivar Arman were studied under a randomized complete block design with three replications. The experimental fields were prepared before sowing, with ploughing, levelling and bordering by tractor. This field was located in Maragheh, Iran in the coordinates of 37°23'21"N and 46°14'17"E. The site has a cool, semi-arid upland climate, field plot size was 4 m² in three replicates, while the genotypes were randomly assigned in plots according to the experimental design. Seeds were sown in 4 rows, with 1 meter long with 50 cm among rows and 10 cm apart between plants in rows in March via hand-sowing across 2022 and 2023 growing seasons. Weeding was performed three times during season. Seeds were treated with Benomyl fungicide before sowing to prevent soil-borne diseases. The site has a cold-steppe climate with an average annual rainfall of approximately 270-370 mm. Characteristics were measured and recorded when they became observable during growth stages of chickpea and at maturity. At maturity, ten plants selected randomly from each line and all traits evaluated. Measured traits included plant height (PH), first branch height (FBH), first pod height (FPH), number of the primary branches (NPB), number of the secondary branches (NSB), one-grain pod of the primary branch (OPPB), one-grain pod of the secondary branch (OPSB), two-grain pod of the primary branch (TPPB), two-grain pod of the secondary branch (TPSB), grain number of the primary pod (GNPP), grain number of the secondary pod (GNSP), grain weight of the primary pod (GWPP), grain weight of the secondary pod (GWSP), plant dry weight (PDW), husk weight of the primary pod (HWPP), and husk weight of the secondary pod (HWSP). Finally, grain yield

performance (GYP) was measured from two central rows for removing the marginal effects and hundred grain weight (HGW) was recorded from a random grain sample from each experimental unit.

Statistical analysis

The normality was assessed using the Ryan-Joiner test, which assesses the correlation between the data and expected normal score, using Minitab version 18.0 (Minitab Inc., PA, USA). The experimental unit was the plot, with three replicated plots assigned to each genotype according to the randomized complete block design. Ten plants were randomly sampled within each plot for measurements of plant-level morphological traits. For statistical analyses, measurements of the ten sampled plants were first averaged within each plot, and plot means were subsequently averaged across the three replications to obtain a single genotype mean for each trait in each year. Grain yield was calculated at the plot level from the two central rows and similarly averaged across the three replications. Thus, Pearson correlation, multiple regression, and hierarchical path analyses were conducted using the genotype means as the statistical observations, resulting in 36 genotype-level observations per year. The three field replications were therefore accounted for during calculation of genotype means and were not treated as independent observations in the correlation, regression, or path analyses. The ten sampled plants were considered subsamples within each experimental plot rather than independent experimental units. Pearson correlations of the traits were presented in correlation matrices using Minitab. The confidence intervals of the correlation coefficients were assessed using 1,000 bootstrap resampling using SPSS version 27.0 (IBM-SPSS Corp, NY, USA), to assess the uncertainty and standard errors of the estimated correlations. To facilitate the biological interpretation of trait relationships, the morphological traits were classified

within a hierarchical layout representing the progression from vegetative growth to reproductive development based on the presumed biological sequence of chickpea development prior to regression and path analyses being conducted; from vegetative and architecture to reproductive development or grain yield. Multiple linear regression was performed separately for each growing year using the genotype-level means as the analytical observations. A hierarchical and sequential framework was used in which traits were organized according to their presumed biological sequence from vegetative growth and plant architecture to branching, pod formation, grain-number traits, grain/pod mass traits, and finally grain yield. At each stage, traits assigned to the preceding level were considered as candidate predictors of the corresponding downstream target trait. Stepwise regression was used for variable selection, with variables eligible for entry or removal according to the significance criteria specified in the statistical software. The selected standardized regression coefficients were used to identify the variables contributing most strongly to variation in each target trait. Sequential path analysis was subsequently used to decompose the relationships among traits into standardized direct and indirect effects within the predefined hierarchical structure. The analysis was conducted separately for each year, and the resulting pathways were interpreted according to the biological order specified a priori rather than as evidence of unrestricted causal relationships. Level-1 included vegetative growth properties include PH, FBH, FPH and PDW. These traits represent basic vegetative and architectural characteristics of the plant. Level-2 consist of branching features include NPB and NSB. This level represents how many reproductive branches were produced by the plant. Level-3 comprised pod-production traits, including OPPB, OPSB, TPPB, TPSB. This group represented intermediates on reproductive development associated with subsequent seed production. Level-4 included seed forming features like GNPP and GNSP, which reflect sink capacity of the plant. Level-5 comprised seed-filling and pod/grain

mass traits, including GWPP, GWSP, HWPP, HWSP, and HGW. This group included traits associated with the filling of seeds. Finally, level-6 was the target trait or grain yield performance (GYP), is the final response variable. Regression and path analyses were conducted according to this hierarchical framework in order to ensure a biologically informed approach for interpreting the relative contribution of the varied traits.

Bootstrap resampling with 1000 resamples was used to assess the precision and robustness of the estimated coefficients of direct effects. Multicollinearity was not formally evaluated using variance inflation factor (VIF) or tolerance statistics in the original analysis. Therefore, these diagnostics were not used as evidence for the absence of multicollinearity. Because stepwise regression does not by itself eliminate multicollinearity, the regression and path coefficients are interpreted as statistical associations within the specified hierarchical framework rather than as definitive independent effects. Statistical procedures were carried out in Minitab, SPSS and AMOS (IBM-SPSS Corp, NY, USA). Modelling assessment achieved by calculate of the root mean square error of approximation (RMSEA) for direct effects.

RESULTS AND DISCUSSION

The combined analysis across the two growing years showed a significant genotype $\times$ year interaction for all traits (Table 2). This interaction indicated that the relative performance of genotypes varied between years. Therefore, subsequent correlation, regression, and sequential path analyses were conducted separately for each year to characterize trait relationships under the respective growing conditions. Correlation coefficients (Table 3) indicated the positive associations of plant height on all traits except first and second branches (NPB and NSB), two-grain pod of first branch (TPPB), and hundred grain weight (HGW) during first year. The plant

height was strongly and positively associated with most traits except NPB, NSB, TPPB, HGW, and two-grain pod of second branch (TPSB) during second year. A similar positive relationship of plant height with pods per plant was reported by Richards et al. (2022). Grain yield performance (GYP) was positively associated with most traits of chickpea except first branch height (FBH), first pod height (FPH), NSB, and HGW in the first year, while GYP has positive associations with all of the traits except NPB, TPSB and HGW in the second year. These findings are consistent with previous results of Janghel et al. (2020), who have observed more or less the same types of positive interrelationships among yield and some morphological traits particularly pods per plant, grains per pod and primary and secondary branches. These traits may serve as candidate indicators of grain yield in chickpea and hence they may be useful as candidate traits for indirect selection in chickpea for yield improvement of chickpea. In order to get some indication about the reliability of these relations, evaluating these relationships jointly within the path model, can reveal the impact of the directly and indirectly influences on yield. This approach can help clarify the complex interrelationships among traits and its impact on yield performance and support more reliable identification of selection criteria in chickpea breeding program.

Multiple linear regression analysis was used for estimating chickpea traits for grain yield, so firstly, all characters used as the primary order variables with grain yield as the criterion variable. Standardized regression coefficient was computed using a stepwise procedure, and the corrected coefficient of determination indicated that the husk weight of the primary pod (HWPP) was primary-order variable contributing most strongly to the variation in yield in the first year (Table 4). Also, grain weight of the primary pod (GWPP) was primary-order variable contributing most strongly to the variation in yield in the second year. Model fit was assessed using the root mean square error of approximation (RMSEA; 0.06 and 0.07, for the first and second years,

respectively). Positive effect of grain and husk weight has been reported by Navanath (2021), in chickpea with grain yield as well as for the other crops like safflower (Zeinalzadeh-Tabrizi et al. 2025), whereas other studies identified the pods per plant and hundred grain weight as the most important traits (Astereki et al. 2017).

When the primary-order traits were considered as target variables, the results indicated that the grain number of the primary pod (GNPP) positively influenced HWPP in the first year, while grain number of the secondary pod (GNSP), positively impacted GWPP (Table 4). The corresponding models explained approximately 88% and 87% of the variation for the first and second years, respectively. (Table 4). The significant interaction between year and genotype (Table 2) demonstrates the genotypes responded differently to the environment. Therefore, analyses were conducted separately for each year, although the consistent relative performance for primary yield components in both years suggest that these traits may have potential as selection criteria even with environmentally variable years. The significance of the grain number of the primary and secondary pods in influencing chickpea performance has been highlighted by Janghel et al. (2020) and Eker et al. (2022).

To identify relationships involving tertiary-order traits, the secondary-order traits were considered as target variables, separately. The results indicated that one-grain pod of the primary branch (OPPB), and two-grain pod of the primary branch (TPPB) positively affected GNPP in the first year (Table 4). However, OPPB showed a larger standardized coefficient than TPPB in the first year, while the indirect component of OPPB on yield via TPPB was small and positive ($0.49 \times 0.24 = 0.12$, direct effect $\times$ correlation = indirect effect), whereas the indirect component of TPPB on yield via OPPB was positive and moderate ($0.49 \times 0.84 = 0.41$, direct effect $\times$ correlation = indirect effect) in the first year. Also, it was observed that one-grain pod of the secondary branch

(OPSB) showed a positive direct effect on GNSP, explaining approximately all of the variation in the second year. The number of the primary branches (NPB) positively influenced OPPB in the first year (Table 4). Also, number of the secondary branches (NSB) positively impacted OPSB, with the model explaining less than one-fourth of the variation in the second year. Previous studies by Tehulie and Yimam (2021), and Moulya et al. (2024), have reported similar findings, highlighting the positive direct effects of branches per plant, on chickpea yield. Finally, it was found that plant dry weight (PDW), showed a positive direct effect on NSB in the second year (Table 4). However, current analysis categorized these traits into primary, secondary, tertiary and quaternary orders in the first year, while traits were classified into primary, secondary, tertiary, quaternary and quinary orders in the second year, indicating year-specific differences in the hierarchical pathways associated with grain yield. Thus, the path $NPB \rightarrow OPPB \rightarrow GNPP \rightarrow HWPP \rightarrow GYP$ emerged as an important pathway associated with grain yield in chickpea in the first year (Fig. 1), potentially serving as valuable candidate selection traits for breeding programs focused on improving yield performance. Also, path $NPB \rightarrow TPPB \rightarrow GNPP \rightarrow HWPP \rightarrow GYP$ is identified as the critical factor influencing yield in chickpea in the first year (Fig. 1). In the second year, path $PDW \rightarrow NSB \rightarrow OPSB \rightarrow GNSP \rightarrow GWPP \rightarrow GYP$ emerge as critical factors influencing yield in chickpea in the second year (Fig. 1), so selection of individuals with favourable values for GNPP, GNSP, GWPP, HWPP, NPB, NSB, OPPB, OPSB, PDW, and TPPB may be considered for achieving higher grain yield.

Breeders often consider point estimates together with their associated uncertainty when identifying robust relationships among traits, and resampling methods can provide additional information on the precision of estimated parameters. In the present study, the relatively small bootstrap standard errors obtained from the 1,000 bootstrap resamples indicate that several

estimated direct effects had relatively high precision in the evaluated population (Table 5). However, bootstrap standard errors alone cannot be used to demonstrate statistical significance and do not establish the absence of multicollinearity. Multicollinearity was therefore considered separately from the precision of the estimates and should be evaluated using appropriate diagnostic statistics, such as variance inflation factors and tolerance values. The use of a hierarchical regression and path-analysis framework reduced the number of predictors considered simultaneously at each stage and thereby facilitating interpretation of relationships among highly interconnected traits. Stepwise regression was used to identify influential predictors within the specified stages; however, it should not be regarded as eliminating multicollinearity. Organizing traits according to their biological position in the developmental sequence provided a structured approach for decomposing the associations among traits and identifying direct and indirect contributions to grain yield. Similar regression-based approaches have been used to investigate complex trait relationships in spring oilseed rape (Kumar et al., 2021) and *Brassica* species (Zeinalzadeh-Tabrizi, 2023). Thus, the combination of hierarchical modelling and bootstrap assessment provided a useful statistical framework for evaluating the relative effects and their estimation precision, while recognizing that further validation is required before these relationships are considered broadly applicable to chickpea breeding.

The multiple linear regression analysis, which identified the relative contribution of predictor traits of several measurements on yields, also provided information on the relative contributions of measured traits on yield, including plant height, two grain pods, grain number, pod number, and grain weight were associated with yield in a consistent with Güler et al. (2001), Aycicek and Babagil (2013), and Nitesh et al. (2018), who give the evidence of a contribution of these traits with chickpea grain yield, directly or indirectly. These traits may provide useful criteria for indirect

selection, although their breeding value requires further validation. The results from all statistical methods employed (phenotypic correlations, multiple linear regression, and decomposition of association into standardized path coefficients and indirect effects) reveal consistent associations of pod traits, and grain related characters, with yield performance of chickpea. These traits could potentially be considered as components of selection indices after their genetic associations, heritability, economic weights, and stability across environments have been established. Although, the present study provides useful information on trait relationships within the evaluated germplasm, the applicability of these relationships to broader breeding populations and environments requires validation using larger, genetically diverse segregating populations and multi-environment field trials..

Although, the identified primary predictors were different, they were closely related to reproductive processes and have been indicated to yield components (Yadav et al., 2020). The optimal predictors of grain yield may vary among years because environmental conditions can alter assimilate partitioning, pod retention, and grain filling. Regardless of that, the prominence of these traits suggests their potential usefulness in estimating selection potential among genotypes. Also, following hierarchical models further confirmed that grain number occupied an important intermediate position in the hierarchical pathways, which accounting for a substantial proportion of the variance in each first level character. For instance, grain number per primary pod and grain number per secondary pod contributed on the variation of primary pod. This illustrates greater grain number may reflect successful reproductive development and effective grain formation, has been suggested in previous reports (Tsehaye et al., 2020; Nikita and Lal, 2022). Because grain number integrates the effects of flowering success, pod set, fertilization, and early seed development, it may represent a useful selection criterion under semi-arid conditions. Its consistent

identification among the top indicators of grain yield across both years supports this interpretation, although validation across environments is required. Similarly pod related traits found at middle level of hierarchy network are also very important. Number of pods with one seed and with two seeds were positively related to grain number, emphasizing on development of pods as intermediate step. Thus, they contributed to seed production based on dependence structure of branching traits. In fact, number of pods has often been considered to be among important predictors in chickpea due to its relation to total sink capacity (Tsehaye et al., 2020; Nikita and Lal, 2022). This is confirmed by many researchers and demonstrated the strong relationship between number of pods and grain yield potentially reflecting the contribution of assimilate availability during grain filling (Yadav et al., 2020; Kushwah et al., 2021). In the present study, the direct effect of one-seeded pod number was greater than that of two-seeded pod number, suggesting that one-seeded pod production may be more sensitive to the prevailing environmental conditions.

Branching traits occupied relatively high positions in the hierarchy of the path models. Primary branch number was associated with reproductive development in the first growing year, whereas secondary branch number was associated with reproductive development in the second year. They may represent the sites on which the plants support reproduction. Similar to these results, it is expected that the number of branches in general contribute to the development of reproductive structures, but it could directly or indirectly impact grain yield depending on resource allocation to flowering and pod initiation (Tsehaye et al., 2020). At the first position of the path models are vegetative characteristics of the plant. In second growing year, plant dry weight was associated with secondary branch production, meaning that greater vegetative biomass may support the development of reproductive branches with capacity to bear flower and developing

seeds, even though no direct effect on yield was recorded. Biomass may represent an important potential source of assimilates for reproductive development and grain filling, although its contribution to final yield depends on assimilate partitioning and reproductive sink development. Ultimately, the relationship between biomass and yield may depend on the plant's ability to efficiently transport assimilates to developing reproductive sinks. The current models confirm that these traits contribute to yield indirectly through their relationships with branching traits and components directly relating to reproductive development (Lambe et al., 2024).

The final analysis indicated consistency between the two experimental years in the general framework of hierarchically relationships among different traits contributing for chickpea yield. Reproductive traits occupied the most proximal positions in the identified pathways leading to grain yield. This suggests that grain number and pod-related traits may be useful candidate selection traits across contrasting growing seasons, although their stability requires further validation. Bootstrap resample analysis also provided additional information on the precision of the estimated coefficients. The findings of the present study can be of interest for plant breeders aiming to improve chickpea grain yield in semi-arid regions. Because direct selection for yield can be influenced by environment, it is strongly affected by environmental variation, indirectly targeting yield through genetically correlated traits that explain significant proportion of variance at various levels might be of more value. Thus, grain number, pod production, grain weight and branches number could serve as candidate traits for indirect selection in selection programs aimed at improving chickpea productivity and stability, mainly because these are trait which is not difficult to measure in field condition. The integrative use of correlation, regression, and path-analysis approaches not only clarifies complex trait relationships but also provides a more comprehensive framework for identifying potential selection criteria in chickpea breeding.

CONCLUSION

The current research demonstrated that chickpea grain yield was associated with a hierarchical network of vegetative, architectural, pod, grain-number, and grain-mass traits. The path analysis distinguished proximal predictors of grain yield from traits associated with yield through indirect pathways. In the first season, husk weight per primary pod was identified as the strongest predictor of grain yield. In the second season, grain weight per primary pod was the strongest predictor. Thus, the traits differed between years, indicating that the magnitude and relative importance of direct effects were influenced by environmental conditions. Several other traits were associated with grain yield through indirect pathways. In the first year, primary branch number was associated with grain yield through pathways involving one- and two-grain pods on primary branches, grain number per primary pod, and husk weight of the primary pod. In the second year, plant dry weight was associated with grain yield through a pathway involving secondary branch number, one-grain pods on secondary branches, grain number per secondary pod, and grain weight of the primary pod. These pathways indicate that vegetative growth and branching may be associated with yield primarily through their relationships with reproductive development rather than through a direct effect on grain yield. Finally, grain number, pod production, branching capacity, and grain- or pod-weight traits occupied important positions, but their contributions should be interpreted according to their specific direct or indirect paths rather than being interpreted as uniformly direct effects on grain yield. The identified pathways should therefore be regarded as candidate relationships for breeding applications, while their genetic relevance and stability require further evaluation across multiple environments and genetically diverse chickpea populations.

ACKNOWLEDGEMENT

Sincere gratitude goes to Dryland Agricultural Research Institute of Iran for providing improved genotypes.

CRedit AUTHORSHIP CONTRIBUTION STATEMENT

Naser Sabaghnia: Supervised the research, analysed the data and wrote the manuscript.
Mojtaba Nouraein: Performed some of the trials and edited the draft. **Yousef Nasiri:** Conceptualization, performed some of the trials. **Mohsen Janmohammadi:** Conceptualization, edited the draft.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal associations that could have appeared to affect the research reported in current article.

ETHICS AND PERMIT APPROVALS

Not applicable.

DATA AVAILABILITY STATEMENT

Data will be made available on reasonable request from the corresponding author.

FUNDING STATEMENT

No funding was received to assist with the preparation of this paper.

AI USE STATEMENT

None AI-assisted technologies were employed in the preparation of this manuscript. All content was generated exclusively by the authors.

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Table 1. The name and source for the 36 chickpea genotypes.

#	Name	Origin	#	Name	Origin	#	Name	Origin
1	8/A2	ICARDA	13	4/A1	ICARDA	25	17/3 URCYT-93	Iran
2	6/A2	ICARDA	14	11/A1	ICARDA	26	7/3 URCYT-93	Iran
3	13/A2	ICARDA	15	10/A1	ICARDA	27	3/3 URCYT-93	Iran
4	15/A2	ICARDA	16	8/A1	ICARDA	28	1/3 URCYT-93	Iran
5	18/A2	ICARDA	17	14/A1	ICARDA	29	8/3 URCYT-93	Iran
6	2/A2	ICARDA	18	14/3 URCYT-93	Iran	30	2/3 URCYT-93	Iran
7	7/A2	ICARDA	19	4/3 URCYT-93	Iran	31	18/3 URCYT-93	Iran
8	16/A2	ICARDA	20	15/3 URCYT-93	Iran	32	13/3 URCYT-93	Iran
9	2/A1	ICARDA	21	10/3 URCYT-93	Iran	33	11/3 URCYT-93	Iran
10	17/A1	ICARDA	22	5/3 URCYT-93	Iran	34	9/3 URCYT-93	Iran
11	13/A1	ICARDA	23	6/3 URCYT-93	Iran	35	Arman	Iran
12	7/A1	ICARDA	24	12/3 URCYT-93	Iran	36	FLIP 99-6C	ICARDA

Table 2. The combined analysis of variance for chickpea traits across two years.

Sources	df	PH	FBH	FPH	NPB	NSB	OPPB
Year (Y)	1	1152.78**	1963.25**	1,119.30**	27.4491**	236.986**	150.334**
Block /Y	4	6.78	1.90	22.06	0.0061	0.119	0.484
Genotype (G)	35	9.17**	4.94**	6.98**	0.0741**	1.417**	6.398**
G×Y	35	1.71**	1.44**	3.14**	0.0131**	0.374**	1.144**
Error	140	0.44	0.25	0.51	0.0038	0.140	0.400

Sources	df	OPSB	TPPB	TPSB	GNPP	GNSP	GWPP
Year (Y)	1	0.107 ^{ns}	7.973**	0.0150 ^{ns}	0.30571**	4.1485**	17.582**
Block /Y	4	0.302	0.011	0.0889	0.00011	0.0031	0.007
Genotype (G)	35	4.928**	0.685**	0.1282**	0.00233**	0.0297**	0.394**
G×Y	35	0.889**	0.126**	0.0263**	0.00082**	0.0088**	0.077**
Error	140	0.244	0.044	0.0066	0.00014	0.0021	0.012

Sources	df	GWSP	PDW	HWPP	HWSP	HGW	GYP
Year (Y)	1	18.979**	5578347.0**	2.3271**	0.2985**	3228.36**	89286299.4**
Block /Y	4	0.007	340.3	0.0101	0.0067	1.39	8110.7
Genotype (G)	35	0.439**	36080.0**	0.1548**	0.0763**	65.65**	1363441.7**
G×Y	35	0.051**	9020.0**	0.0254**	0.0132**	9.97**	395487.1**
Error	140	0.015	496.8	0.0093	0.0041	1.93	67593.9

Traits included plant height (PH), first branch height (FBH), first pod height (FPH), number of the primary branches (NPB), number of the secondary branches (NSB), one-grain pod of the primary branch (OPPB), one-grain pod of the secondary branch (OPSB), two-grain pod of the primary branch (TPPB), two-grain pod of the secondary branch (TPSB), grain number of the primary pod (GNPP), grain number of the secondary pod (GNSP), grain weight of the primary pod (GWPP), grain weight of the secondary pod (GWSP), plant dry weight (PDW), husk weight of the primary pod (HWPP), husk weight of the secondary pod (HWSP), hundred grain weight (HGW), and grain yield performance (GYP).

** and * are significant at 0.01 and 0.05 statistical level, respectively, and ^{ns} is nonsignificant with related df (degrees of freedom).

Table 3. The correlations of chickpea traits for the first (up-diagonal) and second (down-diagonal) years.

	PH	FBH	FPH	NPB	NSB	OPPB	OPSB	TPPB	TPSB	GNPP	GNSP	GWPP	GWSP	PDW	HWPP	HWSP	HGW	GYP
PH		0.76**	0.45**	0.09 ^{ns}	0.01 ^{ns}	0.57**	0.53**	0.29 ^{ns}	0.43**	0.52**	0.51**	0.45**	0.38*	0.42**	0.57**	0.53**	-0.02 ^{ns}	0.52**
FBH	0.73**		0.59**	-0.08 ^{ns}	-0.16 ^{ns}	0.30 ^{ns}	0.34*	0.03 ^{ns}	0.27 ^{ns}	0.22 ^{ns}	0.32 ^{ns}	0.24 ^{ns}	0.28 ^{ns}	0.01 ^{ns}	0.24	0.33*	0.21	0.27
FPH	0.74**	0.66**		-0.23 ^{ns}	0.20 ^{ns}	0.19 ^{ns}	0.30 ^{ns}	0.06 ^{ns}	0.16 ^{ns}	0.13 ^{ns}	0.25 ^{ns}	0.11 ^{ns}	0.15 ^{ns}	0.05 ^{ns}	0.09	0.22 ^{ns}	0.01 ^{ns}	0.06
NPB	0.09 ^{ns}	0.06 ^{ns}	0.09 ^{ns}		0.34*	0.46**	0.21 ^{ns}	0.30 ^{ns}	0.01 ^{ns}	0.46**	0.21 ^{ns}	0.36*	0.19 ^{ns}	0.27 ^{ns}	0.46**	0.24 ^{ns}	-0.06 ^{ns}	0.48**
NSB	0.31 ^{ns}	0.12 ^{ns}	0.38*	0.49**		0.17 ^{ns}	0.17 ^{ns}	0.28 ^{ns}	-0.06 ^{ns}	0.25 ^{ns}	0.10	0.07 ^{ns}	-0.01 ^{ns}	0.45**	0.16	0.09 ^{ns}	-0.25 ^{ns}	0.22
OPPB	0.55**	0.38*	0.57**	0.26 ^{ns}	0.38*		0.83**	0.49**	0.58**	0.96**	0.83**	0.89**	0.73**	0.36*	0.96**	0.85**	-0.13 ^{ns}	0.91**
OPSB	0.60**	0.35*	0.45*	0.13 ^{ns}	0.41**	0.72**		0.48**	0.64**	0.82**	0.98**	0.76**	0.82**	0.24	0.79**	0.95**	-0.17 ^{ns}	0.82**
TPPB	0.23 ^{ns}	0.02 ^{ns}	0.14 ^{ns}	0.38*	0.43**	0.46**	0.44**		0.20 ^{ns}	0.65**	0.47**	0.46**	0.33*	0.33*	0.54**	0.41**	-0.44**	0.56**
TPSB	0.31 ^{ns}	0.42**	0.32*	-0.19 ^{ns}	0.01 ^{ns}	0.18 ^{ns}	0.39*	-0.06 ^{ns}		0.57**	0.75**	0.61**	0.67**	0.07	0.61**	0.77**	-0.02 ^{ns}	0.53**
GNPP	0.49**	0.27 ^{ns}	0.44**	0.32*	0.42**	0.86**	0.68**	0.78**	0.11 ^{ns}		0.83**	0.84**	0.68**	0.38*	0.94**	0.83**	-0.25 ^{ns}	0.92**
GNSP	0.59**	0.34*	0.36*	0.16 ^{ns}	0.29 ^{ns}	0.67**	0.94**	0.46**	0.41**	0.71**		0.80**	0.86**	0.20	0.80**	0.98**	-0.12 ^{ns}	0.82**
GWPP	0.57**	0.36*	0.48**	0.33*	0.34*	0.91**	0.67**	0.64**	0.19 ^{ns}	0.91**	0.69**		0.90**	0.22	0.88**	0.83**	-0.01 ^{ns}	0.84**
GWSP	0.57**	0.35*	0.31 ^{ns}	0.16 ^{ns}	0.18 ^{ns}	0.62**	0.85**	0.32*	0.42**	0.60**	0.94**	0.69**		0.04	0.72**	0.88**	0.07 ^{ns}	0.73**
PDW	0.50**	0.23 ^{ns}	0.48*	0.20 ^{ns}	0.44**	0.62**	0.61**	0.38*	0.04 ^{ns}	0.54**	0.50**	0.56**	0.42**		0.34*	0.19	-0.33 ^{ns}	0.33*
HWPP	0.62**	0.48*	0.58**	0.27 ^{ns}	0.32*	0.92**	0.70**	0.52**	0.26 ^{ns}	0.86**	0.68**	0.94**	0.64**	0.54**		0.85**	-0.13 ^{ns}	0.90**
HWSP	0.60**	0.41**	0.39*	0.10 ^{ns}	0.23 ^{ns}	0.67**	0.92**	0.33*	0.50**	0.65**	0.97**	0.68**	0.94**	0.48**	0.72**		-0.06 ^{ns}	0.83**
HGW	-0.02 ^{ns}	0.13 ^{ns}	-0.12 ^{ns}	-0.02 ^{ns}	-0.20 ^{ns}	-0.02 ^{ns}	-0.13 ^{ns}	-0.48**	-0.04 ^{ns}	-0.25 ^{ns}	-0.08 ^{ns}	-0.04 ^{ns}	0.05 ^{ns}	-0.09 ^{ns}	0.03 ^{ns}	0.06 ^{ns}		-0.19 ^{ns}
GYP	0.60**	0.40*	0.54**	0.30 ^{ns}	0.42**	0.90**	0.80**	0.63**	0.13 ^{ns}	0.90**	0.75**	0.90**	0.68**	0.72**	0.85**	0.71**	-0.14 ^{ns}	

Traits included plant height (PH), first branch height (FBH), first pod height (FPH), number of the primary branches (NPB), number of the secondary branches (NSB), one-grain pod of the primary branch (OPPB), one-grain pod of the secondary branch (OPSB), two-grain pod of the primary branch (TPPB), two-grain pod of the secondary branch (TPSB), grain number of the primary pod (GNPP), grain number of the secondary pod (GNSP), grain weight of the primary pod (GWPP), grain weight of the secondary pod (GWSP), plant dry weight (PDW), husk weight of the primary pod (HWPP), husk weight of the secondary pod (HWSP), grain yield performance (GYP) and hundred grain weight (HGW).

** and * are significant at 0.01 and 0.05 statistical level, respectively, and ^{ns} is nonsignificant (with 34 degrees of freedom).

Table 4. Standardized coefficients of path analysis for dependent and independent traits in stepwise regression model

First year				Second year			
DT	IT	SC	CD	DT	IT	SC	CD
GYP	HWPP	0.90	0.81	GYP	GWPP	0.89	0.79
HWPP	GNPP	0.94	0.88	GWPP	GNSP	0.93	0.87
GNPP	OPPB	0.84	0.96	GNSP	OPSB	0.94	0.87
	TPPB	0.24		OPSB	NSB	0.41	0.17
OPPB	NPB	0.46	0.21	NSB	PDW	0.44	0.20

DT, dependent trait; IT, independent trait, SC, standardized coefficient; CD, coefficient of determination.

Traits are: grain yield performance (GYP), husk weight of the primary pod (HWPP), grain weight of the primary pod (GWPP), grain number of the primary pod (GNPP), grain number of the secondary pod (GNSP), one-grain pod of the primary branch (OPPB), two-grain pod of the primary branch (TPPB), one-grain pod of the secondary branch (OPSB), number of the primary branches (NPB), number of the secondary branches (NSB), and plant dry weight (PDW).

Table 5. Bootstrapping indices for path analysis for target and independent traits.

First year					Second year				
DT	IT	Mean	Bias	SD	DT	IT	Mean	Bias	SD
GYP	HWPP	0.899	-0.004	0.153	GYP	GWPP	0.894	0.001	0.091
HWPP	GNPP	0.942	0.002	0.065	GWPP	GNSP	0.933	0.003	0.043
GNPP	OPPB	0.838	-0.001	0.041	GNSP	OPSB	0.933	-0.005	0.080
	TPPB	0.239	0.002	0.129	OPSB	NSB	0.517	0.109	0.083
OPPB	NPB	0.460	0.002	0.032	NSB	PDW	0.450	0.007	0.175

DT, dependent trait; IT, independent trait, and bootstrap statistics using 1000 resamples including Mean as standardized coefficient of direct effect, Bias as the amount of bias and SD as the bootstrap standard deviation.

Traits are: grain yield performance (GYP), husk weight of the primary pod (HWPP), grain weight of the primary pod (GWPP), grain number of the primary pod (GNPP), grain number of the secondary pod (GNSP), one-grain pod of the primary branch (OPPB), two-grain pod of the primary branch (TPPB), one-grain pod of the secondary branch (OPSB), number of the primary branches (NPB), number of the secondary branches (NSB), and plant dry weight (PDW).

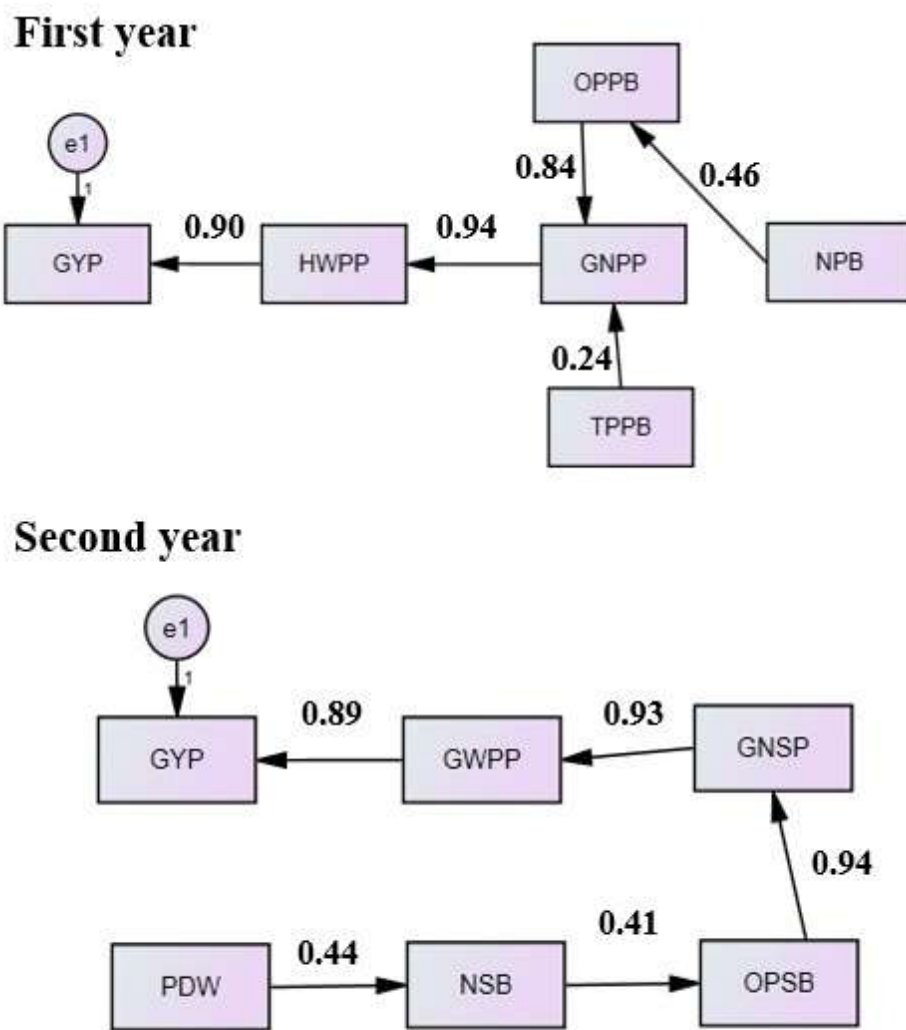


Figure 1. Sequential path analysis showing the direct relationships among selected morphological traits and grain yield in 36 chickpea genotypes during two consecutive years. The arrows represent the direction of the specified statistical pathway, while the numerical values adjacent to the arrows represent standardized path coefficients (direct effects). Residual or error of the independent variable in each year is shown by e1.

Traits are: grain yield performance (GYP), husk weight of the primary pod (HWPP), grain weight of the primary pod (GWPP), grain number of the primary pod (GNPP), grain number of the secondary pod (GNSP), one-grain pod of the primary branch (OPPB), two-grain pod of the primary branch (TPPB), one-grain pod of the secondary branch (OPSB), number of the primary branches (NPB), number of the secondary branches (NSB), and plant dry weight (PDW).