Acta Biologica Szegediensis

Volume 68(1):1-8, 2024
Acta Biologica Szegediensis
http://abs.bibl.u-szeged.hu/index.php/abs

DOI:10.14232/abs.2024.1.1-8

ARTICLE

Path analysis of morphological traits influencing performance in *Cicer arietinum* genotypes under semi-arid conditions

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ABSTRACT Identification of the most desirable genotypes and determining the correlation of different traits with seed yield performance, as well as understanding their cause and effect, provides plant breeders with the ability to select the most appropriate and logical combination of yield components that lead to higher economic performance. In order to identify yield components of chickpea, 50 genotypes were investigated in Gavshaleh, Saqqez, Iran (36°19'54"N and 47°19'07"E). Statistical analysis included simple correlation coefficients of traits, multiple stepwise regression, and path analysis. The traits measured included days to flower initiation (DF), canopy width (CW), days to maturity (DM), the first pod height from the ground (FPH), chlorophyll content (CHL), plant height (PH), number of subsidiary branches (SB), number of pods per plant (NPP), pod weight (PW), shuck weight per plant (SW), plant dry weight (PDW), number of seeds per pod (SP), hundred-seed weight (HSW), protein percentage (PP), and seed yield (SY). The results of simple correlations demonstrated positive significant association of seed yield with SB, SP, and NPP, while it was negatively associated with DF, DM, and PW. Path analysis revealed the primary-order roles of SP and HSW in determining SY, with SP having a larger direct effect (1.04) compared to HSW (0.25). Estimation of direct effects via bootstrapping indicated reliable results with low amounts of standard error and bias. Additionally, the number of subsidiary branches had the most significant indirectly impact on seed yield performance via the pods' number per plant. Therefore, it is recommended that these two traits be prioritized in breeding programs aimed at increasing seed yield. Finally, SP, HSW, NPP, and SB can be beneficially utilized for selection in genetic improvement projects targeting chickpea yield enhancement.
Acta Biol Szeged 68(1):1-8 (2024)

KEY WORDS
direct effect
multiple regression
selection
simple correlation

ARTICLE INFORMATION
Submitted
11 June 2024
Accepted
28 October 2024
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INTRODUCTION

Chickpea, as a self-pollinating crop, holds the distinction of being the third most significant legume globally, cultivated across more than 50 countries. Approximately 95% of its harvested area and consumption are attributed to developing nations. With a crude protein content ranging from 18 to 30% of dry weight, chickpeas provide a crucial protein source, often 2 to 3 times more than that found in cereals (Sofi et al. 2020). They are a staple in the diets of people in these countries, playing a vital role in meeting their protein needs. In the 2022 crop year, global chickpea production reached around 18.1 million tons, with average production varying from 285 kg ha^{-1} in Libya to 5500 kg ha^{-1} in China (FAOSTAT 2022). In Iran, chickpeas are cultivated across approximately 430 thousand hectares, yielding around 176 thousand tons, marking its prominence among legumes. Although chickpea ranks third globally in terms of cultivated area among legumes, it holds primary importance in Iran, considered one of its origins. Consequently, it is grown extensively throughout the country, except in the northern humid regions. However, despite its widespread cultivation, its average yield performance remains relatively low, standing at about 400 kg ha^{-1} (FAOSTAT 2022).

Correlation and path analysis of yield components serve as valuable tools for identifying promising genotypes. Correlations between traits hold particular significance in plant breeding as they elucidate the strength and nature of relationships among various traits (Janmohammadi et al. 2014). Understanding the correlation among different traits, especially between yield and its components, and investigating their cause-and-effect relationships empowers plant breeders to select the most favorable combination of components conducive to higher yield performance. While simple linear correlation coefficients provide insight into trait relationships, they do not reveal the underlying cause-and-effect dynamics, necessitating the use of path analysis (Nayebi-Aghbolag et al. 2019).

Path analysis dissects correlation coefficients to direct effects as well as indirect impacts of causal characters on the target. Given the pivotal role of understanding trait relationships in enhancing yield, path analysis enables the recognition of direct effects as well as indirect impacts of characters influencing yield performance (Mohebodini et al. 2018). Consequently, most plant breeders utilize path analysis as a valuable tool to ascertain the significance of influential traits in yield performance.

Chickpea yield, being a quantitative trait, is influenced by numerous genetic and environmental factors. Therefore, its selection forms the cornerstone of enhancing performance in breeding programs, with plant characteristics playing a pivotal role. Direct selection based solely on seed yield often proves ineffective. Instead, indirect selection through related traits with high heritability yields more practical results (Salgotra 2016). The complexity of chickpea yield performance entails correlations with various other traits. While correlation coefficients among traits indicate linear relationships, path analysis elucidates the contribution of each trait by delineating their interrelationships. By determining direct effects as well as indirect impacts on performance, path analysis aids breeders in trait selection and prioritization. Studies by Güler et al. (2001) revealed that hundred-seed weight, number of seeds and pods as well as plant height had the large directly influences on yield performance, while the days to maturity indicated a negatively non-significant direct effect. Similarly, research conducted by Saleem et al. (2002) on 20 chickpea cultivars demonstrated remarkable positively association between seed yield and the days to flowering, plant dry weight, pods' number per plant, and hundred-seed weight. Conversely, a negatively significant association was observed between the secondary branches and yield performance. The study highlighted the direct impact of pods' number per plant and hundred-seed weight on seed yield, suggesting these traits as key targets for enhancing chickpea yield. Padi (2003) emphasized the importance of biomass, harvest index, and pods' number per plant as pivotal traits directly influencing seed yield, recommending their prioritization in breeding programs. Furthermore, the study identified pod growth rate as exerting a direct and negative effect on chickpea seed yield. Similarly, research by Çiftçi et al.

Table 1. The pedigree codes and donors for the 50 chickpea genotypes used in the study

Code	Pedigree-Code	Donor	Code	Pedigree-Code	Donor
1	FLIP09-320C	ICARDA	26	TDS-Maragheh90-373	Turkey
2	TDS-Maragheh90-229	Turkey	27	TDS-Maragheh90-266	Turkey
3	FLIP09-228C	ICARDA	28	FLIP09-441C	ICARDA
4	TDS-Maragheh90-155	Turkey	29	TDS-Maragheh90-112	Turkey
5	TDS-Maragheh90-213	Turkey	30	FLIP09-53C	ICARDA
6	TDS-Maragheh90-216	Turkey	31	TDS-Maragheh90-205	Turkey
7	TDS-Maragheh90-4	Turkey	32	FLIP09-267C	ICARDA
8	AZAD	Iran	33	TDS-Maragheh90-423	Turkey
9	TDS-Maragheh90-352	Turkey	34	TDS-Maragheh90-221	Turkey
10	TDS-Maragheh90-145	Turkey	35	TDS-Maragheh90-162	Turkey
11	FLIP09-318C	ICARDA	36	TDS-Maragheh90-92	Turkey
12	FLIP09-423C	ICARDA	37	TDS-Maragheh90-137	Turkey
13	TDS-Maragheh90-357	Turkey	38	TDS-Maragheh90-143	Turkey
14	TDS-Maragheh90-204	Turkey	39	FLIP09-279C	ICARDA
15	TDS-Maragheh90-325	Turkey	40	TDS-Maragheh90-250	Turkey
16	TDS-Maragheh90-333	Turkey	41	TDS-Maragheh90-434	Turkey
17	TDS-Maragheh90-46	Turkey	42	FLIP09-242C	ICARDA
18	TDS-Maragheh90-210	Turkey	43	TDS-Maragheh90-61	Turkey
19	FLIP09-239C	ICARDA	44	TDS-Maragheh90-87	Turkey
20	TDS-Maragheh90-400	Turkey	45	FLIP09-249C	ICARDA
21	TDS-Maragheh90-305	Turkey	46	TDS-Maragheh90-235	Turkey
22	TDS-Maragheh90-90	Turkey	47	FLIP09-397C	ICARDA
23	TDS-Maragheh90-150	Turkey	48	FLIP88-85C-X85	ICARDA
24	TDS-Maragheh90-30	Turkey	49	TDS-Maragheh90-152	Turkey
25	TDS-Maragheh90-445	Turkey	50	TDS-Maragheh90-208	Turkey

(2004) on 14 chickpea varieties underscored the positive and substantial direct effects of biomass, and pods' number per plant on yield performance.

Toker (2004) categorized phenotypic correlations of traits into three groups based on their direct influences on yield performance: the first group comprised biological yield and pods' number, the second group included days to flowering and duration of the flowering period, while the third group consisted of plant height and height of the first pod. Notably, Toker (2004) emphasized that hundred-seed weight should be evaluated separately from these traits, suggesting it be considered independently by breeders during the selection process. In a study involving 15 chickpea genotypes over two years, a positively relationship was discovered between yield performance and height of the first pod from the ground, total pods' number, filled pods' number, and seeds' number per plant (Yücel et al. 2006). Path analysis results indicated that all traits, except for days to flowering, the first pod height, and total number of pods, exerted the highest direct influences on yield performance. Consequently, they were identified as key targets for enhancing seed yield in chickpea. The objective of resent investigation was to explore the associations between yield performance and morphological traits of chickpea genotypes through correlation and path analysis. This aimed to identify the direct effects as well as indirect impacts of chickpea characters on yield and leverage this knowledge for indirect selection in chickpea breeding programs.

MATERIALS AND METHODS

Trial

To explore the associations between yield performance and its constituent components via path analysis, a total of 49 foreign lines of chickpea (Table 1) were obtained from ICARDA (International Center for Agricultural Research in the Dry Areas). These lines were cultivated alongside a control variety named Azad, following a randomized complete block design with three repetitions. Prior to commencing the trial plan, all necessary preparatory operations for seedbed establishment, such as plowing, leveling, and bordering, were meticulously carried out using a tractor in Gavshaleh, Saqqez, Iran. Positioned at coordinates 36°19′54″N and 47°19′07″E, the area is specified as a semi-arid cool upland area. Each plot was designated with a size of 1 m^2, and the varieties were randomly planted according to the experimental plan. Planting was arranged in four rows, each 1 m in length, with a line spacing of 25 cm and a plant spacing of 8 cm within each row. Planting operations were conducted in March, aligning with the customary practices of the region, which typically involve spring and rainy season cultivation. Manual planting was carried out, and weeding activities were performed three times throughout the growing season to combat weed infestations. Prior to sowing, seeds underwent disinfection using Benomyl fungicide.

The field conditions mirrored those of a cold steppe region, characterized by an average annual rainfall ranging between 300-450 mm, followed by a dry season. To tackle pest challenges, efforts were made to address *Agrotis ipsilon* during seed germination through two spray treatments across the entire field. Additionally, post-flowering, the farm received treatment against the *Heliothis viriplaca* pest. Throughout the growing season and upon maturity, various traits were meticulously recorded. These included days to flower initiation (DF), canopy width (CW), and days to maturity (DM). Following maturity, a sample of 10 random plants was selected from each plot for trait assessment. Measurements were taken for the first pod height from the ground (FPH), chlorophyll content (CHL), plant height (PH), number of subsidiary branches (SB), number of pods per plant (NPP), pod weight (PW), shuck weight per plant (SW), plant dry weight (PDW), number of seeds per pod (SP), hundred-seed weight (HSW), protein percentage (PP), and seed yield (SY).

Statistical analysis

For the statistical analysis, we initially assessed the normality of the data for various traits using Minitab software version 14.0 (Minitab 2005). This was accomplished via the Ryan-Joiner statistic, which evaluates the correlation strength between the original data and the normal scores of the data. Subsequently, Pearson correlation coefficients between the studied traits were computed using SPSS software version 23.0 (IBM-SPSS 2015). To gain deeper insights into the relationships between traits and identify those with the most significant impact on seed yield, we employed path coefficient analysis. Initially, we utilized correlation coefficients and stepwise regression analysis, treating seed yield performance as the target variable and the other characters as independents. This enabled us to identify the variables that best accounted for variations in seed yield. Subsequently, employing path analysis, we computed the direct and indirect influences of the selected traits on final crop performance in the initial step and other dependent variables in subsequent steps.

To ensure the validity and reliability, the bootstrapping resampling method with 2000 samples was employed. This allowed us to obtain bias and standard deviation values, thereby assessing any differences between the bootstrapping results and the conventional method. Additionally, to mitigate the multicollinearity phenomenon, we computed tolerance and variance inflation factor (VIF)

Table 2. The simple correlation coefficients of chickpea traits

	PH	DF	DM	CHL	SB	FPH	NPP	PW	SW	SP	HSW	PDW	CW	PP
DF	-0.29													
DM	-0.04	0.57												
CHL	0.05	-0.38	-0.58											
SB	0.40	-0.02	-0.02	-0.16										
FPH	0.43	-0.04	0.06	-0.08	0.04									
NPP	0.29	-0.36	-0.44	0.30	0.43	0.15								
PW	0.11	0.12	0.45	-0.46	-0.05	0.12	-0.38							
SW	0.05	0.31	0.36	-0.25	-0.08	0.08	-0.16	0.43						
SP	0.24	-0.33	-0.44	0.29	0.43	0.12	0.99	-0.41	-0.16					
HSW	0.02	0.08	0.40	-0.41	-0.13	0.07	-0.30	0.76	0.41	-0.33				
PDW	0.76	-0.25	-0.11	0.13	0.23	0.42	0.33	0.08	0.04	0.30	-0.04			
CW	0.53	-0.09	0.09	-0.39	0.58	0.18	0.18	0.18	-0.05	0.15	0.22	0.28		
PP	0.10	-0.34	-0.39	0.81	-0.16	-0.07	0.15	-0.30	-0.19	0.13	-0.21	0.13	-0.26	
SY	0.19	-0.31	-0.37	0.21	0.39	0.11	0.94	-0.27	-0.01	0.96	-0.08	0.26	0.16	0.08

Critical amounts P<0.05 and P<0.01 (with 48 degrees of freedom) are 0.36 and 0.28, respectively.

statistics. All statistical analyses were conducted using SPSS, and for visual representation of the path diagram, we utilized AMOS software version 20.0 (Arbuckle 2001). This comprehensive approach allowed us to thoroughly examine the relationships between traits and their collective impact on seed yield, ensuring robust and reliable results for our investigation.

RESULTS AND DISCUSSION

The Pearson's correlations presented in Table 2 unveil significant relationships among various traits. Plant height (PH) demonstrated positively significant associations with the first pod height from the ground (FPH), number of subsidiary branches (SB), number of pods per plant (NPP), plant fresh weight (PFW), and canopy width (CW). Conversely, it exhibited a negative correlation with days to flower initiation (DF). This aligns with findings from Güler et al. (2001), who demonstrated a positively association between plant height and the number of pods per plant, alongside a negative association with the number of days to maturity (DM). Furthermore, protein percentage (PP) showcased negative significant correlations with DM, DF, and PW, while displaying positive associations with chlorophyll content (CHL). Similarly, hundred-seed weight (HSW) revealed positive significant relationships with shuck weight per plant (SW), DM, and PW, but negative correlations with the SP, NPP, and CHL (Table 2). Moreover, the simple correlations in Table 2 highlight positive significant relations between yield performance (SY) and some characters such as the number of subsidiary branches (SB), number of seeds per pod (SP), and number of pods per plant (NPP), while displaying negative associations with days to flower initiation (DF), days to maturity (DM), and pod weight (PW). These findings corroborate with the research of Vaghela et al. (2009), who reported similar positive interrelationships between yield performance and the number of pods, seeds and branches, both at the genotypic and phenotypic levels. Hence, these identified traits emerge as influential factors impacting seed yield in chickpea, potentially serving as indicator traits for seed yield breeding programs. To unravel the

Table 3. Multicollinearity indices, tolerance and variance inflection factor (VIF) in Enter Model (I) and Stepwise Model (II)

	Tolerance		VIF	
	I	II	I	II
PH	0.25	0.91	4.07	1.09
DF	0.50	1.00	1.99	1.00
DM	0.41	1.00	2.42	1.00
CHL	0.19	0.94	5.31	1.07
SB	0.43	1.00	2.31	1.00
FPH	0.72	1.00	1.38	1.00
NPP	0.11	0.91	9.00	1.09
PW	0.30	1.00	3.36	1.00
SW	0.64	0.94	1.56	1.07
SP	0.11	0.89	8.83	1.12
HSW	0.34	0.89	2.93	1.12
PDW	0.36	0.92	2.74	1.09
CW	0.34	0.92	2.93	1.09
PP	0.29	1.00	3.44	1.00

Table 4. Direct effects and coefficient of determination (R2) of path analysis for target and independent traits model Stepwise Model (II)

Target	IT	Direct	R^2
SY	SP	1.04	0.97
	HSW	0.25	
SP	NPP	1.01	0.98
	PH	-0.05	
HSW	PW	0.76	0.56
NPP	DM	-0.44	0.35
	SB	0.42	
PH	PDW	0.66	0.67
	CW	0.34	
PW	CHL	-0.38	0.28
	SW	0.33	
DF	DM	0.57	0.31
PDW	FPH	0.42	0.16
CHL	PP	0.81	0.65
SW	DF	0.31	0.08

IT, independent trait

Table 5. Indirect effect of path analysis which are shown in outside of diagonal

		SP	HSW
SY	SP	1.04	-0.08
	HSW	-0.34	0.25
		NPP	PH
SP	NPP	1.01	-0.02
	PH	0.30	-0.05
		DM	SB
NPP	DM	-0.44	-0.01
	SB	0.01	0.42
		PDW	CW
PH	PDW	0.66	0.10
	CW	0.19	0.34
		CHL	SW
PW	CHL	-0.38	-0.08
	SW	0.10	0.33

most reliable structure of these interrelationships and determined the effects (directly or indirectly) of the characters on SY, a path analysis is warranted. This analytical approach will provide deeper insights into the intricate relationships among the traits and their collective impact on seed yield, facilitating informed decision-making in chickpea breeding endeavors.

To assess the importance of chickpea traits in relation to seed yield (SY), we employed a multiple regression model while considering multicollinearity indices (Table 3). Initially, all characters were treated as primary-orders (model I) with SY as the target trait. Subsequently, the direct effects were extracted using a stepwise regression model, constituting model II. Multicollinearity indices provided insights into the interrelationships among traits and their contributions to SY. Although there wasn't a significant decrease in the multicollinearity indices of the two models, the values decreased slightly in model II (Table 3). The corrected R^2 (coefficient of determination) highlighted the roles of SP and HSW as primary-order variables explaining the variation in SY (Table 4). Notably, SP exhibited a larger direct effect (1.04) compared to HSW. The indirect effect of HSW via SP was moderate and negative (-0.34), while the indirect effect of SP via HSW was low and negative (-0.08) (Table 5). Efforts were made to visually represent the results of the statistical analysis through a path analysis diagram (Figure 1). This diagram, generated via the default model of AMOS, underwent verification using three fit indices: the ratio of CMIN/df, GFI and RMSEA. All three indices were significant, confirming the accuracy of the fitted model. The positive impact of the seeds' number and hundred-seed weight on chickpea performance has been previously reported in path analyses (Singh et al. 2021; Tamatam and Pandey 2024). However, while other researchers identified the pods' number as another major character, we did not detect this trait as a primary-order variable.

When considering the primary-orders, with SP and HSW assumed as target variables, we observed that the NPP had a positively influence on SP, while plant height (PH) had a negative impact on SP. Together, these traits accounted for more than 98% of the variability (Table 4). Notably, NPP exhibited a larger direct effect (1.01) compared to PH, with a low and negative indirect effect of PH via NPP (-0.05), while the indirect effect of NPP via PH was positively moderate (0.30) (Table 5). The significance of the pods' number on chickpea performance has been previously noted by some researchers (Raju and Lal 2021; Jain et al. 2022). Additionally, only pod weight (PW) positively influenced HSW, explaining 56% of its variation with a relatively high direct effect of 0.76 (Table 4). To identify tertiary-orders, the secondary-orders (NPP, PH, and PW) were considered as targets separately. It was found that days to maturity (DM) negatively affected NPP, while the subsidiary branches (SB) had a positively impact on NPP, explaining approximately 35% of the variation. The indirect effect of both traits via each other was very low (Table 5). Moreover, plant dry weight (PDW) and canopy width (CW) positively impacted PH, describing about 67% of the variability (Table 4). The indirect effect of PDW via CW was 0.10, while the indirect effect of CW via PDW was 0.19 (Table 5). Furthermore, chlorophyll content (CHL) negatively influenced PW,

Table 6. Bootstrapping indices for path analysis for target and independent traits model Stepwise Model (II)

Target	IT	Direct	R^2	SD†
SY	SP	1.039	0.005	0.041
	HSW	0.254	0.001	0.030
SP	NPP	1.006	-0.003	0.023
	PH	-0.052	0.002	0.018
HSW	PW	0.063	0.260	0.145
NPP	DM	-0.436	0.003	0.114
	SB	0.425	-0.002	0.113
PH	PDW	0.659	-0.012	0.109
	CW	0.342	-0.001	0.080
PW	CHL	-0.377	-0.003	0.144
	SW	0.330	0.014	0.167
DF	DM	0.569	-0.002	0.117
PDW	FPH	0.421	-0.001	0.122
CHL	PP	0.813	-0.003	0.083
SW	DF	0.308	0.000	0.137

†SD, standard deviation

while the weight of shuck per plant (SW) had a positively influence on PW, explaining only 28% of the variation. The indirect effect of CHL via SW was low and negative (-0.08), while the indirect effect of SW via CHL was low and positive (Table 5). Previous investigations by Bhanu et al. (2017), Manikanteswara et al. (2019) and Jain et al. (2022) have reported similar findings, highlighting the positive direct effects of hundred-seed weight, number of branches and seeds, as well as plant height on chickpea seed yield. Our analysis, however, identified these traits as primary, secondary, and tertiary orders, underscoring their significant impact on yield performance. Thus, the seeds' number per pod and hundred-seed weight emerge as crucial factors influencing seed yield in chickpea and could serve as morphologic markers for breeding yield performance.

Plant breeders often seek both point estimation and interval estimation for various statistics to ensure robust results. Resampling strategies such as bootstrapping prove invaluable in this regard, providing reliable estimations for standard error (SD) and bias for direct effects. Utilizing 2000 resamples (Table 6), the exceedingly small standard error and bias magnitudes for the direct effects underscore the statistical robustness of path analysis and affirm the reliability of the results obtained. This suggests that path analysis is unlikely to lead to multicollinearity issues among traits, particularly those with high associa-

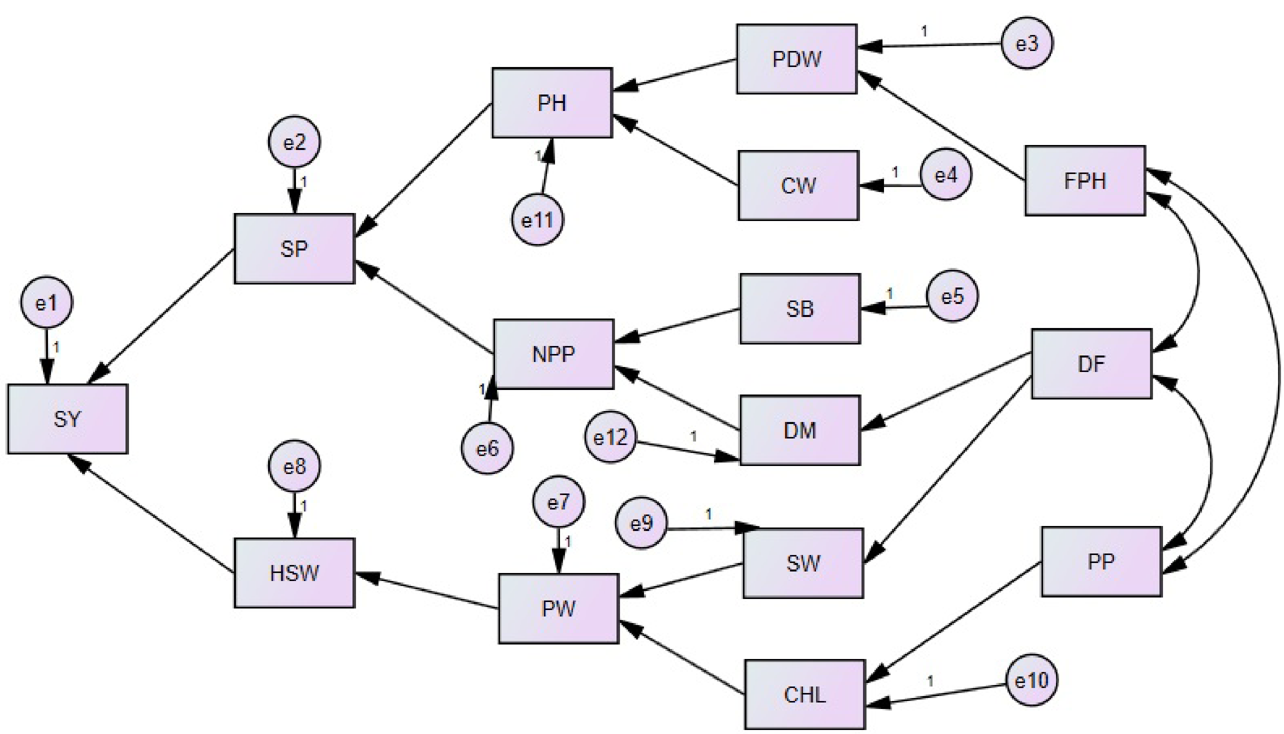

Figure 1. Path diagram of 18 traits of 50 chickpea genotypes which showing the direct effects

Table 7. The three fit indices for fitted model in path analysis

Model	CMIN†	df	P	CMIN/df
Default model	175.72	87	0.000	2.020
Independence model	787.02	105	0.000	7.495
	RMR	GFI	AGFI	PGFI
Default model	1623.09	0.725	0.620	0.525
Independence model	232.36	0.383	0.295	0.335
	RMSEA	LO 90	HI 90	P_{CLOSE}
Default model	0.144	0.113	0.175	0.000
Independence model	0.364	0.341	0.388	0.000

†CMIN, Chi-square minimum; df, degrees of freedom; P, probability level; RMR, root mean square residual; GFI, goodness-of-fit; AGFI, Adjusted GFI; PGFI, probability of GFI; RMSEA, root mean square error of approximation; LO 90 and HI 90, the lower and upper limit of a 90%confidence interval for RMSEA; P_{CLOSE}, the p-value of the null hypothesis

tions. It appears that employing the stepwise multiple regression model helps in circumventing the influence of multicollinearity in path analysis. The fundamental requirement for conducting a multiple regression model is that predictor traits are not interdependent at each step. In reality, however, variables are often intricately correlated, leading to multicollinearity. By categorizing traits into primary, secondary, and tertiary orders, this problem can be alleviated. This strategy has been effectively applied by Mohebodini et al. (2018) in their investigation on garden cress and by Nayebi-Aghbolag et al. (2019) in their research on rye. This approach facilitates a more nuanced understanding of trait interrelationships and enhances the reliability of the analysis results.

The number of subsidiary branches, seeds, and pods emerge as promising candidates for inclusion in genetic improvement projects wanted to enhance seed yield. Their suitability is underscored by the presence of phenotypic diversity, ease of selection, and significant positive correlations with yield performance. Studies by Usman-Saeed et al. (2012) and Banik et al. (2017) have further substantiated the existence of diversity and the positively correlation between yield performance and these traits. The outcomes of both multiple regression analysis and path analysis enabled a comprehensive examination of each trait's independent effect on yield performance. It was observed that an increase in the seeds' number per pod and hundred-seed weight directly led to an increase in yield performance. Additionally, the pods' number per plant directly influenced the seeds' number per pod. Moreover, the subsidiary branches exhibited the most indirect effect on yield performance through its influence on the pods' number per plant. Hence, it is recommended to prioritize these two traits in breeding programs aimed at enhancing seed yield. However, it is advised against increasing seed yield solely by enhancing pod weight and earliness properties like days to flowering and maturity. This recommendation stems from the negative correlation observed between the mentioned characters and yield performance. In summary, the findings from phenotypic correlations, multiple linear regression, and path analysis underscore the importance of the seeds' number, hundred seed weight, and pods' number as key determinants of yield performance in chickpea. Breeding efforts aimed at augmenting these traits hold the potential to significantly enhance seed yield in a favorable manner.

CONCLUSION

In conclusion, the results of path analysis have been validated through the bootstrapping method, affirming significant relationships between seed yield and various agro-morphologic characteristics. Notably, days to flowering and maturity as well as plant height emerged as the first-order variables, indicating their direct impact on yield performance. Furthermore, the number of seeds and hundred seed weight were identified as secondary-order variables, highlighting their significant influence on seed yield. Moreover, the pods' number, plant height, and pod weight were categorized as tertiary-order variables associated with seed yield. Our findings prepare good knowledge for genetic improvement projects wanted to enhance chickpea yield under cool upland semi-arid conditions. By leveraging this knowledge, breeders can strategically select traits to prioritize in breeding programs, with the overarching goal of augmenting chickpea yield. The identified primary, secondary, and tertiary-order variables serve as valuable indicators for guiding breeding efforts and maximizing yield potential in chickpea cultivation within such specific environmental conditions.

ACKNOWLEDGMENTS

We are grateful to local government officers who provided information and assisted during our field work.

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