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REGRESSION ANALYSIS OF YIELD-RELATED TRAITS IN CHICKPEA (*CICER ARIETINUM* L.)

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SUMMARY

Chickpea (*Cicer arietinum* L.) is one of the crucial legume crops and a primary source of protein for human beings worldwide. The genetically diverse accessions are valuable sources for further improvement in chickpeas through breeding. In the presented study, the 36 chickpea lines from the Chickpea International Elite Nursery-Winter, International Center for Agricultural Research in the Dry Areas (ICARDA), bore assessment for yield-related traits. Determining the effects of various quantitative and yield-attributing traits on the seed yield used linear regression. Simple linear regression models ran separate evaluations for each studied parameter, including plant height, the height of the first pod, the number of secondary branches, the number of pods, the number of seeds per plant, and 100-seed weight. According to analysis for high seed productivity in chickpea cultivation under organic production conditions, the approximate model ensures a high yield as follows: The plant height ranged from 68 to −78 cm, height to the first pod (26–31 cm), number of secondary branches (8–14), number of pods (52–79), number of seeds (64–95), and 100-seed weight (25–45 g). In determining the seed productivity of chickpea genotypes, a direct positive and significant correlation occurred between the 100-seed weight and the number of seeds per plant. These parameters can serve as effective selection criteria for enhancing the chickpea yield.

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Keywords: Chickpea (*Cicer arietinum* L.), regression analyses, correlation coefficient, quantitative traits, yield-related traits, crop productivity

Key findings: In chickpeas, the seed weight per plant emerged as the pivotal trait influencing seed yield, helping formulate a predictive theoretical model. Additionally, traits like the number of secondary branches and a 100-seed weight demonstrated a substantial positive correlation with seed yield, providing crucial selection criteria for effective breeding programs.

INTRODUCTION

Chickpea (*Cicer arietinum* L.) is the second most consumed legume crop, cultivated in more than 50 countries worldwide (Koul *et al*., 2022). Chickpea is also one of the foremost crops that enhance soil fertility due to its nitrogen-fixing root nodulation capacity. It has a widespread and deep-root system, allowing low water utilization and adaptation to adverse weather conditions. Extreme variations in weather and climatic conditions, including prolonged droughts, excessive rainfall, and temperature fluctuations, are crucial in influencing chickpeas' growth patterns, development stages, and overall yield (Singh *et al*., 2022). These environmental factors can lead to significant challenges in cultivating and producing this essential legume crop, affecting its quality and quantity (Khrisanapant *et al*., 2022). The manifestation of phenotypic traits often occurs by interacting genotypes with existing environmental conditions (Murthy *et al*., 2017). Traits, such as seed yield per plant and 100-seed weight, showing high heritability and genetic advance, are the key for selection criteria (Miohariya *et al*., 2023).

Worldwide, the average chickpea yield was approximately 850 kg/ha, although yields are generally lower in developing areas. Nevertheless, several developing regions have outperformed developed nations in this respect. Between 2008 and 2017, Asia accounted for 83% of worldwide chickpea production (FAO, 2019). According to FAO, chickpea yields in Central Asian countries, including Kazakhstan and Uzbekistan, comprised 600 kg/ha and 2200 kg/ha, respectively.

Weather conditions influenced the cultivation of chickpea varieties in the dry lands of Uzbekistan. The optimal planting time for chickpeas in dryland conditions is the first 10-day period of March. However, when anticipating high spring rainfall, recommendations for better planting are during the 20th and 30th days of March (Nakhalbaev and Khamdamov*,* 2020). In the harsh agroecological conditions of southern Uzbekistan, chickpea varieties inoculation with rhizobium and azotobacter strains resulted in increased plant growth and grain yield (Abdiev *et al*., 2019). Additionally, after sowing chickpea plants in the Mirzachol region of Uzbekistan, an increase in mobile phosphorus content in the soil was evident versus its initial state (Turdimetov *et al.,* 2020).

Crop yield enhancement with good quality is one of the main objectives of breeding programs (Ayubov *et al*., 2021; Bakhtiyorova *et al*., 2024; Umedova *et al*., 2024). Analyzing the relationship between seed yield and yield-related traits allows the emphasis on those components for the maximum influence on seed yield. Therefore, these components help researchers understand the basics of increased crop yield. The path coefficient analysis allows the dissection of correlation coefficients into their direct influences, originating from various traits toward the dependent variables (Wright, 1921). This approach also assists in evaluating causality and optimizing selection processes.

A linear regression equation is a widely used method focusing more on specific valuable traits to enhance crop productivity. Past studies developed the optimal model for the fodder pea using this method and should be between 60–70 cm plant height, with 8–10 beans, 30–40 seeds per plant, and 160 to 260 g 1000-seed weight (Kosev, 2015). Predicting the yield capacity of crops is a complex task, as the final yield depends on various factors throughout the growing season (Niedbala *et* *al*., 2019; Turaev *et al*., 2023; Baboeva *et al*., 2023). Crop productivity level influences come from several factors, i.e., the soil's biological nutrients, pH, soil type, and weather conditions (daily temperature and precipitation), with genotypes as considered primary factors (Niedbala *et al*., 2019).

Secondary factors include fertilization with organic and mineral fertilizers, disease control, weed and pest management, and crop species (Abrougui *et al*., 2019; Suleimanova *et al*., 2022, 2023). Mathematical models, such as linear and nonlinear regression models, are traditional approaches for studying crop productivity. Regression analysis estimates the relationship between two or more variables. It explains how the typical values of dependent variables change by altering any independent variable by keeping other independent variables constant. Linear regression is one of the most widely used predictive modeling techniques. Frequent employment of regression models envisages the yield and study of the relationship between independent and dependent variables. The multiple linear regression (MLR) method helps forecast crop productivity, accounting for the variability determined by numerous independent variables (Matsumura *et al*., 2015).

The linear regression model permits evaluating each parameter as a time variable. Multivariate analysis also provides additional insights compared with univariate analysis. Principal component analysis (PCA) relies on the performance of linear comparisons of the original variables, depending upon the linear comparisons of the original variables. PCA is a multivariate analysis method that reduces dataset complexity while preserving data covariance. Regression analysis assesses the strength of the correlation between related (*Y*) and unrelated (*X1, X2, and X3*) parameters (Claudia, 2019). Correlation analysis between the traits that affect productivity is typical in various selection processes. Correlation analysis quantifies the degree of association between the variables and shows the strength of their correlation (Biabani *et al*., 2021). Therefore, based on the above facts, the relevant study aimed to determine the impact of quantitative traits on seed yield by constructing a regression model. The model is also essential for selecting chickpea lines under organic production conditions. It involves the regression analysis of quantitative traits in chickpea genotypes.

MATERIALS AND METHODS

Plant material and procedure

In the presented study, the 36 chickpea accessions were samples procured from the Chickpea International Elite Nursery-Winter, provided by The International Center for Agricultural Research in the Dry Areas (ICARDA) (Table 1). The effect of the yield-related traits on the seed yield in the chickpea genotypes underwent comparative investigation.

The experiments ran in 2021–2022 at the Durmon Field Experimental Plot, Institute of Genetics and Plant Experimental Biology, Academy of Sciences, Uzbekistan (with geographical coordinates: Latitude 41°31′N, Longitude 69°24′E). The randomized complete block design (RCBD) with three replications aided the assessment of chickpea lines. Growing all chickpea genotypes transpired in four-row plots with a 4-m length and 60-cm spacing. The subplot size was 0.6 m in width and 4 m long, resulting in a total area of 2.4 m^2. The sowing of chickpea accession seeds commenced on October 20, 2021, and harvesting was on June 20-25, 2022. In addition, no application of mineral fertilizers and pesticides ensued in the chickpea experiment. The climate of the experimental area is semi-arid and continental, characterized by significant annual and daily temperature fluctuations. The average annual air temperature ranges from 16.5 °C to 17.0 °C, with a yearly precipitation of 400 mm. The experimental plot soil is clay with a humus horizon thickness of 15–18 cm. In the arable layer, the humus content reaches up to 1.4%, the gross nitrogen content ranges from 0.08% to 0.22%, the amount of hydrolyzed nitrogen is between 44.8 and 71.5 mg/kg, mobile phosphorus levels range from 80.3 to 82.5 mg/kg, and exchangeable potassium levels are between 373 and 380 mg/kg.

Table 1. List of chickpea genotypes used in the research.

Accession code	Plant samples	Accession code	Plant samples
11101	X07 TH 87/FLIP 03-110CXGhab4	11119	X07 TH 75/FLIP 03-113CXILC3279
11102	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)	11120	X07 TH 87/FLIP 03-110CXGhab4
11103	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)	11121	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)
11104	X07 TH 72/FLIP 03-97CXILC482	11122	X07 TH 77/FLIP 03-117CXILC191
11105	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)	11123	X07 TH 75/FLIP 03-113CXILC3279
11106	X07 TH 87/FLIP 03-110CXGhab4	11124	Malhotra (Local Check)
11107	X07 TH 77/FLIP 03-117CXILC191	11125	X07 TH 75/FLIP 03-113CXILC3279
11108	X07 TH 77/FLIP 03-117CXILC191	11126	X07 TH 87/FLIP 03-110CXGhab4
11109	X07 TH 68/FLIP 03-80CXILC191	11127	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)
11110	X07 TH 73/FLIP 03-110CXILC605	11128	X07 TH 72/FLIP 03-97CXILC482
11111	X07 TH 73/FLIP 03-110CXILC605	11129	X07 TH 72/FLIP 03-97CXILC482
11112	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)	11130	X07 TH 89/FLIP 03-113CXFLIP97-706C
11113	X79TH101/ILC 523 X ILC 183 (Improved check)	11131	X07 TH 77/FLIP 03-117CXILC191
11114	X89TH258/ (FLIP 85-122CXFLIP 82-150C)/FLIP 86-77C	11132	X07 TH 75/FLIP 03-113CXILC3279
11115	ILC482 (Long term check)	11133	X07 TH 87/FLIP 03-110CXGhab4
11116	X07 TH 77/FLIP 03-117CXILC191	11134	X07 TH 77/FLIP 03-117CXILC191
11117	X07 TH 90/FLIP 03-115CXInci (FLIP93-146C)	11135	X07 TH 72/FLIP 03-97CXILC482
11118	X85 TH143/ILC 629 x FLIP 82-144C	11136	X07 TH 69/FLIP 03-84CXILC200

Data collection and statistical analysis

Phenological observations of various traits, including seed weight, number of pods and seeds per plant, 100-seed weight, plant height, the height of the first pod, and number of secondary branches began during the plant's growth period. Random selection of five plants in each unit plot served for data collection.

The Statgraphics Centurion (Version 18) software helped conduct various statistical analyses. The regression and correlation analyses used the Multiple Regression function of the Multiple Factors analysis of the software. The influence of quantitative traits on seed yield determination engaged a linear regression equation. Simple linear regression models ran separate evaluations for each parameter, including plant height, height to the first pod, number of secondary branches, number of pods and seeds, and the 100-seed weight, analyzed according to the following equation:

$$Y = a + b \times X_1$$

Where:
Y: is a parameter, *a:* is the point of intersection, *b:* is a constant, and X_1: is a regression coefficient (time). Using the SAS version 7.0 with a significance level ($P < 0.05$) helped reject the null hypothesis.

RESULTS AND DISCUSSION

Regression analysis

Improving plant productivity and quality by developing new cultivars is the primary goal of breeding programs. Therefore, to achieve this, it is essential to evaluate the different accessions by analyzing the diverse traits of the crop plants and accurately assessing and selecting the breeding material. Employing correlation regression analysis is a common approach in processing the experimental data, contributing to this task.

Correlation and regression analyses are more appropriate for exploring the relationship among economically valuable traits, such as seed yield and yield-related traits. However, path analysis is the best unique approach to understanding the relationship between the characteristics (Dash *et al*., 2021). Regression analysis helps the breeder determine each factor's correlation coefficient that directly or indirectly affects the seed yield based on the different variables.

According to the regression analysis of the yield-related and quantitative traits in chickpea genotypes, the seed weight per plant was the choice as the main trait determining the seed yield. After a comprehensive study of all the quantitative traits, the developed theoretical model of the chickpea plant showed productivity depending on the values of the quantitative traits. It also permits statistical representation of the direction of change of the attributes that donate to enhance productivity at the expense of seed weight per plant.

The analysis results revealed that the regression of seed productivity was almost significant in the studied traits (Table 2). The multiple linear regression model described the relationship between Y and X variables. The general model of the theoretical regression equation represents the impact of each studied trait on seed productivity, as given below.

$$Y = -29.488 + 0.01X_1 + 0.345X_2 + 0.893X_3 - 0.011X_4 - 0.007X_5 + 0.028X_6$$

Where:
Y : is seed weight per plant (seed yield), X_1 : is number of pods per plant, X_2 : is number of seeds per plant, X_3 : is 100-seed weight, X_4 : is plant height, X_5 : is height of the first pod, X_6 : is number of secondary branches.

Based on the attained results of the regression analysis, the 100-seed weight (R = 0.893) and the number of seeds per plant (R = 0.345) significantly influenced the formation of the seed weight per plant. These results were consistent with the findings of Dawane *et al*. (2020) and Raju and Lal (2021), who reported that various characteristics (except seed yield per plant and plant height) positively influence seed productivity. However, the number of secondary branches forming the main pods (R = -0.028) and the number of pods per plant (R = -0.01) enunciated an insignificant influence (Table 3).

The regression analysis of the parameters, such as plant height (R = -0.011) and the height to the first pod (R = -0.007), showed a weak negative correlation with the seed weight per plant, determining seed productivity. The lack of plant tolerance to lodging due to greater plant height could result in lower yield. The present observations align with the findings by Georgieva and Kosev (2020a), who reported a negative relationship between plant height and seed yield in leguminous crops. These studies highlighted the close relationships between morphological and physiological parameters and significant correlation coefficients. Additionally, past studies also demonstrated the existence

Table 2. Analysis of variance (ANOVA) on seed productivity per plant with other traits.

ANOVA	Df	SS	MS	F	Significance F
Regression	6	3954.03	564.86	1107.69	0.0000
Residual	65	32.63	0.51		
Total	71	3986.67			

Table 3. Analysis of variance on seed productivity per plant with other traits.

Traits	Coeff. (R)	St. Error	t. Stat	P-Value
Constant	-29.488	1.320	-22.595	0.0000
Number of pods	0.01	0.012	0.724	0.471
Number of seeds	0.345	0.009	35.782	0.0001
100-seed weight	0.893	0.027	35.735	0.0001
Plant height	-0.011	0.011	-0.903	0.369
Height to the first pod	-0.007	0.016	-0.430	0.668
Number of secondary branches	0.028	0.0302	0.946	0.347

of a correlation between valuable economic traits and physiological indicators in wheat (Adylova *et al*., 2018; Amangeldikyzy *et al*., 2023; Meliev *et al*., 2023; Bakhadirov *et al*., 2024), upland cotton (Matniyazova *et al*., 2022; Kushanov *et al*., 2022; Khidirov *et al*., 2023), and peas (Suleimanova *et al*., 2022).

Relationship between seed yield and yield-related traits

The seed weight is an influential parameter that considerably affects productivity. The graphical representation of the relationship between the various quantitative traits related to the seed weight per plant provides a precious opportunity to drive critical statistical insights and establish the main relationships among these quantitative traits (Figures 1 to 3). A positive correlation was also evident between the seed productivity, the number of secondary branches, and the 100-seed weight. This correlation is crucial in increasing chickpea yield, as also observed in studying the association between grain yield and morphological traits of the chickpea genotypes (Parhe *et al*., 2014).

High crop productivity relies on the number of pods per plant and seeds within each pod. Evaluating plant productivity necessitates investigating the number of pods and seeds per plant, as also emphasized in the research by studying the adaptability of chickpea genotypes in the southern forest-steppe of Western Siberia (Kazydub *et al*., 2015). The regression equation reveals that seed weight per plant, with the number of pods and seeds as the chief components, has a significant positive impact on chickpea productivity (Figure 1). The seed weight per pod, the number of seeds formed in a pod, and the increase in number of seeds per plant are the crucial indicators of grain yield per plant. However, when the number of pods per plant ranges from 52 to 79, and the number of seeds falls within the range of 64–95, a prominent increase in the seed weight per plant occurs.

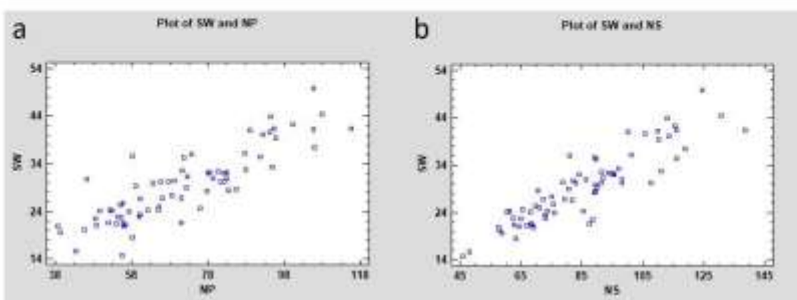

Figure 1. Relationship of seed weight (SW) per plant with (a) number of pods (NP) per plant and (b) number of seeds (NS) per plant in chickpea plants.

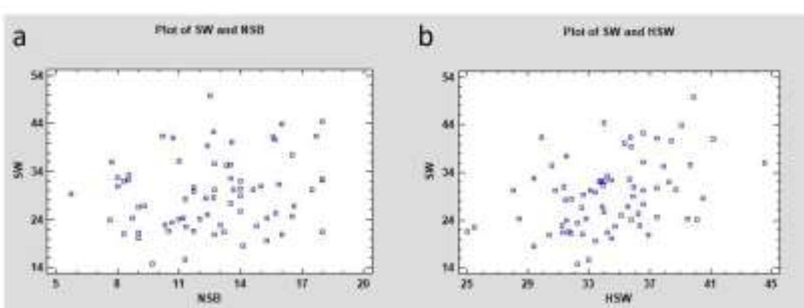

Figure 2. Relationship of seed weight (SW) per plant with (a) number of secondary branches (NSB) per plant and (b) 100-seed weight (HSW) in chickpea plants.

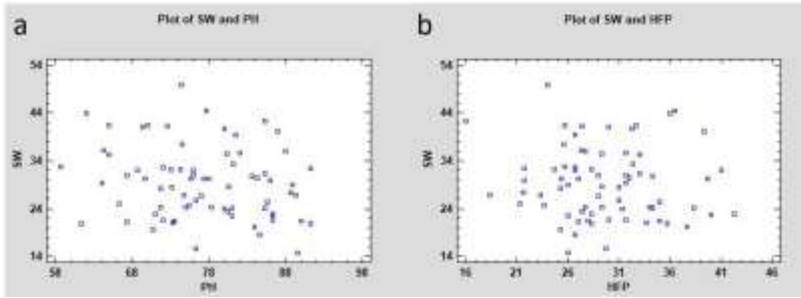

Figure 3. Relationship of seed weight (SW) per plant with (a) plant height (PH) and (b) the height to the first pod (HFP) in chickpea plants.

Consequently, productivity indicators positively influenced seed productivity.

In leguminous crops, the presence of productive branches is crucial for enhancing grain yield. For chickpea genotypes, having 8–14 secondary branches per plant exerts a positive impact on crop productivity (Figure 2a). Suboptimal branching can lead to a significant reduction in grain yield, while an increase in branching beyond the optimal range can have a favorable effect on chickpea yield. Plant branching not only contributes to increasing crop productivity, as observed in the previous study of chickpeas (Petrova, 2021). However, it also aids in boosting seed productivity per plant. Notably, environmental factors can also influence the expression of these quantitative traits. The superiority of chickpeas refers to their cold tolerance, disease resistance, improved productivity in temperate regions, and a larger 100-seed weight than spring peas (Ozdemir and Karadavut, 2003). Despite their high grain yield, chickpeas typically have a moderate seed size, with 100-seed weights ranging from 22.7 to 41.1 g (Qulmamatova, 2023).

In chickpeas, the indicator of 100-seed weight is generally stable; however, it may exhibit slight variations during ripening and grain filling. The 100-seed weight is dependent on the size of chickpea seeds. Figure 2b illustrates the influence of 100-seed weight on the number of seeds per plant in the regression model, showing a significant impact of 100-seed weight on seed productivity. These observations align with past findings of Georgieva and Kosev (2020b), who reported a positive influence of 100-seed weight on seed productivity of leguminous crops. Correlation analysis provides valuable insights into relationships among plant traits that contribute to seed yield and can be effective as selection criteria for yield improvement, especially given the complexity and often-low heritability of the grain yield. Yucel *et al*. (2006) reported the highest genetic diversity in 100-seed weight and the number of seeds per plant and their significant positive correlation with grain yield. Regression analysis further revealed that the optimal range for 100-seed weight was between 25 and 45 g in chickpea genotypes. The deviation from this range decreases to 32–38 g, resulting in lower productivity.

Among the studied traits, plant height and height of the first pod exhibited a negative influence on grain yield. However, when the plant height is lower than 50 cm or above 80 cm, it has a detrimental effect on productivity. Excessively tall leguminous plants tend to lodge, negatively affecting grain yield, prolonging the ripening period, and causing difficulties in harvesting. Therefore, medium-sized plants are mostly preferred for their resistance to lodging (Kosev, 2015). The relationship between seed weight per plant and plant height and the height of the first pod appears in Figure 3. Regression analysis showed that the selected chickpea genotypes had plant heights ranging from 58 to 92 cm, with an average of 77.3 cm for these traits. Deviation from the optimal plant height (68–78 cm) leads to reduced grain yield (R = -0.011; P < 0.36), with plant height above 80–90 cm potentially decreasing productivity (Figure 3).

However, the regression coefficient indicated that the height of the first pod was not significant (R =-0.007; P < 0.66). In the presented study, the optimal range for the height of the first pod emerged to be 26–31 cm, with an average trait value of 29.74 cm among the genotypes. However, this trait showed an association with adaptability to mechanized harvesting, and it does not significantly contribute to grain yield, according to the results. In leguminous crops, such as *Pisum sativum* L. and *Vicia faba* L., the plant height has occurred to affect yield components negatively (Georgieva and Kosev, 2020a, b).

The number of pods in chickpea accessions varied from 48 to 100, averaging 69.59. The Malhotra variety (accession code 11124) produced an average of 71.8 pods. The accession 11101 showed the highest yield with 100.8 pods, while the accession 11135 had the lowest yield at 52.3 pods. The genotype of the accessions and external environmental factors influenced the pod production potential. In accession 11101, which exhibited relatively little branching (9.1 pods), the potential for pod formation on secondary branches was 40.39% higher than that of the local Malhotra variety. For accession 11117, this potential appeared to be 27.86% higher than the local variety. The number of seeds per plant ranged from 42 to 145, averaging 83.90. The Malhotra variety averaged 80.7 seeds, but 18 samples surpassed this, indicating a potential for higher yields. This variability, from 44 to 145 seeds per plant, underscores the significant genetic diversity within the population. Research on germplasm accessions showed polymorphism in seed numbers and weights, revealing high heritability and genetic potential across various traits.

CONCLUSIONS

According to the results, the approximate model for getting high productivity in chickpeas under organic production conditions ensures that developing an ideal model for chickpea cultivation during the breeding process can be quite challenging. The potential to achieve high productivity depends on identifying the yield components and the complex relationship among them. The study highlights the importance of the 100-seed weight and seeds per plant as key factors for enhancing chickpea yield, suggesting these are crucial criteria for future breeding programs. Future research should focus on integrating molecular marker technologies to identify and select these yield-contributing traits more efficiently. Developing climate-resilient chickpea varieties that can thrive under varying environmental conditions will also be essential for sustaining productivity advancements.

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