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Correlation and path analysis of morphologic characters associated with yield performance in black cumin

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Abstract

Developing improved black cumin (*Nigella sativa* L.) cultivars requires robust tools to manage trait relationships within breeding programs. This study utilized path analysis to examine associations of yield performance and nineteen morphological characters in 27 black cumin genotypes. Correlation analysis indicated that yield had a meaningfully positive association with most characters, except for leaf width, seed width, and thousand-seed weight. Path analysis identified thousand-seed weight and dry shoot weight as the primary contributors to yield. Additionally, the follicles of the plant, main stem internodes, seed width, and seed length directly influenced seed yield as first-order characters. To ensure reliable results, characters with high collinearity, like the follicles of plant, seed length, and seed width, were excluded from the first-order character group. Assessment of seed yield components highlighted the path seeds of follicle → stem diameter → follicles of plant → dry shoot weight as the most significant and positively correlated pathway influencing seed yield in black cumin. Therefore, efforts to enhance the seeds of follicles, stem diameter, follicles of plant, and dry shoot weight could significantly improve yield performance. The characters identified as influencing seed yield suggest that, while maintaining other characters constantly, improving these specific characteristics will enhance the yield of black cumin, so the characters should be prioritized in future genetic improvement programs.

Keywords: Collinearity, Multiple regression, Yield components

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Introduction

Native to West Asia, black cumin (*Nigella sativa* L.) is believed to have originated in the Middle East and the Indian subcontinent and is widely cultivated in India and several Middle Eastern countries. Black cumin is an herbaceous annual plant from the Ranunculaceae family, characterized by its grayish-green leaves and capsule-shaped fruit, which is divided into five parts. The seeds are typically small and dark gray or black (Hossain et al., 2021). The seeds of black cumin possess a wide range of medicinal properties, including promoting lactation, alleviating flatulence, acting as a laxative, providing antiparasitic and antiepileptic effects, and offering antiviral, antibacterial, antitumor, analgesic, and blood sugar-regulating benefits. They also improve blood circulation and relieve kidney discomfort, migraines, diarrhea, and smooth muscle spasms (Hannan et al., 2021).

Additionally, black cumin seeds are known to stimulate the immune system. Genotype, environmental factors, and interactions influence the performance of medicinal plants like black cumin. Given the economic importance of medicinal plants and the increasing demand for their cultivation, understanding the genetic potential of existing genotypes is crucial. Thus, evaluating and analyzing various agronomic characteristics, particularly those that affect seed yield, is essential for breeding programs to improve crop performance.

A comprehensive evaluation of black cumin traits enables more precise planning for future improvements. Seed yield, a complex trait influenced by multiple factors, exhibits low heritability and is strongly affected by environmental conditions. Therefore, identifying the characteristics that influence seed yield is crucial. Understanding the relationships and the degree of simple and multiple correlations among various traits in black cumin genotypes is essential for selecting appropriate cultivars for specific regions (Gebremedin et al., 2024). This knowledge forms the foundation for genetic and agronomic research to increase seed yield. Path analysis is a highly effective for analyzing these correlations and determining direct and indirect factors influencing yield. By studying the morphological traits of black cumin and quantifying their contributions to seed yield, it becomes possible to identify and recommend high-yielding cultivars for cultivation with greater precision and efficiency. The genetic diversity within native black cumin populations offers a valuable resource for breeding efforts and understanding the relationships among yield components (Gashaw, 2020). Therefore, thoroughly examining these native populations is essential for planning future breeding programs and ensuring sustainable improvements in black cumin cultivation.

Studies on yield and its components have reported significant variability in characters such as biomass, seeds of capsule, seed yield performance, and thousand-seed weight. Faravani et al., (2006) found that the capsule seeds had the highest influence on yield performance. According to path coefficient analysis by Ghamarnia et al., (2010), biomass and the follicle seeds had the primary direct influence on yield performance, with positive correlations observed between yield, biomass yield, and the seeds of the follicle and in a study on the agronomic diversity of black cumin genotypes, Salamati and Zeinali (2013) identified plant dry matter and harvesting ratio with the highest heritability, while yield performance indicated a high positive association with biomass, plant height and the number of branches per plant. These characters collectively explained 95% of seed yield variation. The positive association of yield performance with the follicles of plant, biological yield, weight of follicle, branches number, and harvest index were observed. At the same time, the path analysis indicated that plant capsules followed by seed weight had the main direct effects on yield, and the indirect effect of plant capsules was from biological yield. Hence, the capsules of plant and seed weight had major contributions to yield, and their selection can lead to an increase in the yield of black cumin. Ghorbanzadeh-Neghab and Zare-Mehrjerdi (2018). Gashaw et al., (2020) found a negative and significant correlation between seed yield and plant capsules, while the harvest index indicated a positive correlation with seed yield performance. Verma et al., (2024) reported a negative and positive relation between seed yield and the lateral branches, with the strongest correlation for the capsules of the plant and the lateral branches. Given the importance of increasing black cumin yield and identifying characters that contribute to it, the present study aimed to evaluate the seed yield of native landraces, examine the relationships for yield and its related characters, analyze association coefficients among characters, and identify the most critical characters affecting black cumin yield.

Materials and Methods

To investigate the correlation coefficients and analyze the path relationships among characters influencing seed yield, a study was conducted on 27 native black cumin (*Nigella sativa L.*) landraces collected from diverse regions (Table 1).

Table 1. Name of the 27 black cumin genotypes and coordinates (longitude/latitude) of the collected region.

#	Name	Coordinates	#	Name	Coordinates
G1	Ardabil-I	38°15′N 48°17′E	G15	Shiraz	29°36′N 52°32′E
G2	Ardabil-II	38°15′N 48°17′E	G16	Qazvin	36°17′N 50°00′E
G3	Amlash	37°05′N 50°11′E	G17	Karaj	35°49′N 50°56′E
G4	Ahwaz	31°18′N 48°40′E	G18	Lordegan	31°30′N 50°50′E
G5	Arak	34°05′N 49°41′E	G19	Lorestan	32°28′N 46°49′E
G6	Isfahan-I	32°39′N 51°40′E	G20	Kashan	33°58′N 51°25′E
G7	Isfahan-II	32°39′N 51°40′E	G21	Kashmar	35°14′N 58°27′E
G8	Borujen	31°58′N 51°17′E	G22	Kordestan	35°19′N 47°22′E
G9	Birjand	33°05′N 59°10′E	G23	Mashhad-I	36°19′N 59°32′E
G10	Piranshahr	36°41′N 45°08′E	G24	Mashhad-II	36°19′N 59°32′E
G11	TorbatHeydariye	35°17′N 59°13′E	G25	Marivan	35°31′N 46°10′E
G12	Takestan	36°04′N 49°41′E	G26	Miandoab	36°57′N 46°06′E
G13	Semirom	31°24′N 51°34′E	G27	Neyshabur	36°12′N 58°47′E
G14	Sarbisheh	32°34′N 59°47′E			

The trial was performed as a randomized complete block scheme with four replicates in Ardabil (38°15′N, 48°17′E) with loam-sand soil texture, mean annual temperature of 8.5 ºC, average humidity of 70%, and annual rainfall of 430 mm. Ten seeds from each genotype were sown in pots with a 25 cm diameter in greenhouse conditions. Once the plants were established, the number of plants per pot was reduced to five to optimize growth conditions and maintain uniformity across the trial. Standard agronomic practices, including irrigation and manual weed control, were implemented throughout the growing period. Irrigation was scheduled every two days to ensure optimal moisture levels. At the 50% flowering stage, a comprehensive set of morphological characters was measured to assess the performance of each genotype. Plant height (PH), length of flowering stem (LFS), length of internodes (LI), leaf width (LW), leaf length (LL), follicle width (FW), and follicle length (FL) were recorded by lab scaler. Stem diameter (SD), seed width (SW), and seed length (SL) were measured by a clipper. SPAD assesses chlorophyll content (CC), and leaf area (LA) is recorded by a leaf area meter. Internodes of the main stem (IMS), number of seeds per follicle (NSF), internodes to the first flower (IFF), and number of follicles per plant (NFP) were counted. Capsule weight (CW), thousand-seed weight (TSW), seed yield (SY), and dry weight of shoot (DWS) were measured by a sensitive weighing scale.

The data normality for the measured characters was evaluated using the Ryan-Joiner test in Minitab 17.0 (Minitab, Pennsylvania, USA). This method assesses the correlation between the dataset and expected standard scores to determine impact on yield, ensuring that the findings were credible and robust for the study's objectives.

Results

The simple correlation coefficients (Table 2) revealed positive associations between yield and nearly all characters, excluding leaf width (LW), seed width (SW), and thousand-seed weight (TSW). As shown in Table 2, TSW was negatively and significantly correlated with most characters, except LW, length of flowering stem (LFS), and seed length (SL). However, a negative association was seen between thousand-seed weight and most characters, particularly seed yield and its components. On the other hand, the other yield-related characters, such as the seeds of the follicle (NSF) and the follicles of the plant (NFP), showed strong positive associations with all characters, excluding seed width (Table 2). Path coefficient analysis was conducted better to understand the direct and indirect relationships with seed yield. This statistical method allows for the distinction between direct and indirect correlations among characters. The results of the standardized coefficients, which represent the directly influencing factors of characters on yield, are shown in Table 3, with yield performance as the target character and other characters considered as first-order characters. The collinearity indices, including Tol. and VIF, are also provided in Table 3. The results indicated inconsistent relationships among some characters and high collinearity for certain variables, such as stem diameter (SD), seed length (SL), seed width (SW), and capsule weight (CW). The path coefficient analysis excluded these characters as first-orders to address the collinearity issue.

the adherence of the data to a normal distribution. Following this, the relationships between characters were examined by calculating simple correlation coefficients using IBM-SPSS 25.0 (IBM-SPSS, Chicago, USA). Path analysis was employed to better understand the connections between characters and pinpoint those most influencing yield performance. This analysis began by applying a stepwise regression model, where seed yield was designated as the target character, and all other characters were treated as predictor characters. This step helped identify the key characters that best explained the observed variations in yield performance. Subsequently, path analysis was computed to determine the direct and indirect influencing factors on seed yield. Initially, yield performance served as the target character, and other dependent characters were gradually incorporated into subsequent steps to refine the analysis. To validate the robustness of the results, a bootstrapping procedure with 1,000 resamples was conducted. This method provided averages from the resampled datasets, assessed the bias between these averages and the original path coefficients, and calculated standard deviations to ensure accuracy. Differences between the original coefficients and bootstrapped results were critically evaluated to ensure reliability. The tolerance (Tol.) values and variance inflation factors (VIF) were computed using IBM-SPSS 25.0 to address potential multicollinearity issues further. Additionally, path diagrams were constructed using AMOS 21.0 (Thakkar & Thakkar, 2020), offering a visual representation of the relationships between characters. This thorough analytical strategy enabled a comprehensive understanding of the interdependencies among characters and their

Table 2. Simple correlation coefficients among measured characters of black cumin genotypes.

Characters†	PH	LI	LFS	SD	IMS	IFF	LW	LL	LA	CC	FW	FL	NSF	SL	SW	NFP	CW	DWS	TSW
LI	0.83‡																		
LFS	0.62	0.54																	
SD	0.96	0.77	0.55																
IMS	0.97	0.80	0.48	0.93															
IFF	0.95	0.80	0.45	0.92	0.99														
LW	0.71	0.51	0.46	0.68	0.68	0.66													
LL	0.80	0.56	0.45	0.79	0.76	0.76	0.77												
LA	0.74	0.53	0.34	0.73	0.67	0.67	0.78	0.79											
CC	0.64	0.60	0.23	0.68	0.65	0.67	0.27	0.44	0.45										
FW	0.62	0.58	0.73	0.54	0.52	0.47	0.42	0.41	0.34	0.22									
FL	0.82	0.74	0.63	0.86	0.77	0.75	0.59	0.63	0.58	0.45	0.56								
NSF	0.90	0.72	0.66	0.93	0.85	0.82	0.69	0.71	0.71	0.50	0.63	0.89							
SL	0.54	0.51	0.83	0.50	0.42	0.40	0.54	0.40	0.36	0.23	0.50	0.65	0.64						
SW	-0.14	-0.10	0.40	-0.19	-0.24	-0.25	0.15	-0.13	-0.01	-0.13	0.08	0.03	-0.03	0.68					
NFP	0.96	0.76	0.60	0.98	0.91	0.89	0.71	0.77	0.75	0.61	0.60	0.86	0.96	0.57	-0.11				
CW	0.84	0.75	0.69	0.85	0.81	0.78	0.55	0.56	0.48	0.48	0.65	0.88	0.90	0.71	0.08	0.88			
DWS	0.94	0.72	0.62	0.97	0.89	0.87	0.67	0.75	0.71	0.62	0.65	0.85	0.95	0.55	-0.11	0.99	0.88		
TSW	-0.72	-0.61	-0.26	-0.75	-0.75	-0.74	-0.33	-0.58	-0.39	-0.42	-0.39	-0.57	-0.66	-0.03	0.71	-0.70	-0.58	-0.69	
SY	0.58	0.42	0.60	0.62	0.45	0.43	0.37	0.48	0.53	0.45	0.46	0.63	0.63	0.64	0.34	0.64	0.65	0.66	-0.15

†For abbreviations, refer to text. † Significant correlations are 0.38 and 0.49, for P < 0.05 and P < 0.01 (degrees of freedom= 25), respectively

Table 3. Unstandardized coefficients of multiple regression model (b), their standard error (SE), the standardized coefficients of multiple regression model (β), and two collinearity indices (Tol. and VIF) for predictors on the seed yield of 27 black cumin genotypes.

Characters	b	SE	β	Tol.†	VIF‡
PH	0.48	1.90	0.47	0.01	163.2
LI	-11.26	13.70	-0.40	0.09	10.8
LFS	-0.35	4.31	-0.04	0.10	10.2
SD	45.18	31.95	2.32	0.01	126.6
IMS	-4.73	8.60	-1.07	0.01	177.5
IFF	1.17	6.64	0.26	0.01	104.8
LW	-1.39	0.93	-0.55	0.16	6.2
LL	0.03	0.44	0.03	0.14	7.0
LA	0.02	0.02	0.59	0.07	13.5
CC	-8.40	20.81	-0.15	0.15	6.6
FW	1.23	2.44	0.25	0.09	11.1
FL	-1.33	3.82	-0.16	0.10	9.9
NSF	-3.16	3.10	-0.93	0.03	38.8
SL	133.2	168.61	1.59	0.01	189.2
SW	-342.4	495.13	-1.72	0.00	289.4
NFP	-1.37	5.98	-0.52	0.00	240.8
CW	68.08	65.60	0.67	0.05	19.5
DWS	-0.67	11.87	-0.10	0.14	6.7
TSW	7.85	75.99	0.67	0.10	11.0

†Tol. Tolerance; ‡VIF, variance inflation factor

interval estimators, which reflect the variability in point estimators within a confident range for the actual magnitude of the statistical index. As a resampling method, Bootstrapping is particularly useful for estimating standard errors. In this study, the average of the standardized coefficients, calculated from 1,500 resamples, showed strong agreement with the computed values for the black cumin characters (Table 5). The minimum standard error of the computed coefficients and the minimal bias further demonstrate the robustness of the statistical procedure used. A t-test using the standard errors obtained through bootstrapping confirmed that all standardized coefficients were statistically significant (results not shown).

After addressing the collinearity issue (Table 4), the estimation of standardized coefficients involved classifying characters into first, second, third, and fourth-order categories, with yield performance as the target variable. The newly computed collinearity indices provided valuable insights into the relationships among the characters and their contributions to yield performance. The magnitudes of Tol. and VIF for the predictors showed a significant reduction in collinearity, which helped identify the true contributions of the predictors with minimal confounded and interference impacts. Therefore, applying this strategy proved highly effective in obtaining the most reliable and favorable results. Plant breeders aim to obtain both point and

Table 4. The standardized coefficients of multiple stepwise regression model (β), coefficient of determination (R^2), and two collinearity indices (Tol. and VIF) for identified predictors on the first-, second-, third-, and fourth-order characters of 27 black cumin genotypes.

Y†	X‡	β	R^2	Tol.¶	VIF§	Y	X	β	R^2	Tol.	VIF
SY	DWS	1.06	0.61	0.52	1.91	SD	CC	0.28		0.75	1.33
	TSW	0.58		0.52	1.91		NSF	0.79	0.92	0.75	1.33
DWS	NFP	0.99	0.97	1.00	1.00	IFF	NSF	0.30	0.78	0.34	2.91
							LI	0.40		0.47	2.12
TSW	IMS	-0.07	0.98	0.30	3.30		LL	0.32		0.49	2.02
	SW	1.28		0.20	5.05						
	SL	-0.87		0.17	5.80	PH	NSF	0.45	0.91	0.34	2.91
							LI	0.34		0.47	2.12
NFP	SD	0.98	0.97	1.00	1.00		LL	0.29		0.49	2.02
IMS	IFF	0.99	0.96	1.00	1.00	LW	LL	0.40		0.38	2.63
							LA	0.46	0.64	0.38	2.63
SW	LFS	0.78	0.46	0.62	1.62						
	PH	-0.96		0.39	2.59	LFS	FW	0.47	0.58	0.57	1.74
	LW	0.48		0.49	2.04		CW	0.38		0.57	1.74
SL	LFS	0.83	0.68	1.00	1.00						

†Y, target variable; ‡X predictor trait, variance inflation factor; ¶Tol. Tolerance, §VIF, variance inflation factor

Table 5. Bootstrapping for the standardized coefficients of multiple stepwise regression model reported as Mean.

†Y	X‡	Mean	Bias	SE¶	Y	X	Mean	Bias	SE
SY	DWS	1.064	-0.005	0.183	SD	CC	0.281	-0.014	0.086
	TSW	0.583	-0.006	0.163		NSF	0.793	-0.011	0.060
DWS	NFP	0.988	0.031	0.988	IFF	NSF	0.297	-0.002	0.167
						LI	0.404	-0.002	0.125
TSW	IMS	-0.073	0.003	0.035		LL	0.320	0.012	0.136
	SW	1.284	0.002	0.043					
	SL	-0.872	0.000	0.049	PH	NSF	0.448	-0.028	0.120
						LI	0.343	0.016	0.084
NFP	SD	0.981	0.001	0.062		LL	0.289	0.018	0.092
IMS	IFF	0.981	0.001	0.062	LW	LL	0.403	0.003	0.220
						LA	0.461	-0.034	0.332
SW	LFS	0.778	0.037	0.220					
	PH	-0.960	0.001	0.219	LFS	FW	0.474	0.095	0.309
	LW	0.476	-0.027	0.242		CW	0.384	-0.020	0.116
SL	LFS	0.834	0.032	0.157					

†Y, target variable; ‡X predictor trait; ¶SE, standard error

the indirect coefficient of DWS through TSW was moderate and negative (-0.40), while the indirect coefficient of TSW through DWS was relatively high and adverse (-0.73). Numerous studies have aimed to represent statistical outputs visually, and the path analysis diagram (Fig. 1) provides a clearer comprehension of the relationships among

The coefficients of determination (R^2) confirmed the significant impact of the dry weight of shoot (DWS) and thousand-seed weight (TSW) as first-order characters donating to yield, explaining 61% of the variability in yield (Table 5). However, DWS had a more significant impact (1.06) than TSW (0.58) on seed yield. According to Table 6, effects, together explaining over 98% of the variability. Additionally, the indirect coefficient of IMS via SW and SL was moderate and negative (-0.431 and -0.37, respectively), while the indirect coefficient of SW via SL was high and negative (-0.59). The indirect coefficient of SL via SW was high and positive (0.87), whereas its indirect coefficient via IMS was very low (-0.03).

characters and their contributions to yield performance. As the second-order characters were treated as independent characters and first-order characters as the target, the results showed that the follicles of the plant (NFP) positively affected DWS and explained more than 97% of its variability (Table 4). For TSW, seed width (SW) had a positive effect, while internodes of the main stem (IMS) and seed length (SL) had adverse

Table 6. Standardized and indirect coefficients for the predictors are ordered as the first-, second-, third--, and fourth-order characters in path analysis.

Y†		X‡			Y		X	
TSW		IMS	SW	SL	SY		DWS	TSW
	IMS	-0.07	-0.31	-0.37		DWS	1.06	-0.40
	SW	0.02	1.28	-0.59		TSW	-0.73	0.58
	SL	-0.03	0.87	-0.87				
SW		PH	LW	LFS	SD		CC	NSF
	PH	-0.96	0.34	0.48		CC	0.28	0.40
	LW	-0.68	0.48	0.36		NSF	0.14	0.79
	LFS	-0.59	0.22	0.78				
IFF		NSF	LI	LL	LW		LL	LA
	NSF	0.30	0.29	0.23		LL	0.40	0.36
	LI	0.21	0.40	0.18		LA	0.32	0.46
	LL	0.21	0.23	0.32				
PH		NSF	LI	LL	LFS		FW	CW
	NSF	0.45	0.25	0.20		FW	0.47	0.25
	LI	0.32	0.34	0.16		CW	0.31	0.38
	LL	0.32	0.19	0.29				

†Y, target variable; ‡X predictor trait

that the seeds of the follicle (NSF) and chlorophyll content (CC) positively affected SD, explaining 92% of the variation (Table 4). Furthermore, NSF, length of internodes (LI), and leaf length (LL) positively influenced IFF and plant height (PH), accounting for 78% and 91% of the variability, respectively. LL and leaf area (LA) positively affected LW, explaining approximately 64% of the variation. Finally, follicle width (FW) and capsule weight (CW) positively influenced LFS, accounting for about 58% of the variability (Table 4).

The assessment of seed yield components revealed that the path NSF → SD → NFP → DWS → SY was the most significant and positively correlated path influencing seed yield

When third-order characters were considered independent and second-order characters as target characters, the results showed that stem diameter (SD) positively affected the number of follicles per plant (NFP), explaining 98% of its variability. Similarly, internodes to the first flower (IFF) positively affected the main stem (IMS) internodes, accounting for 99% of the variability. Additionally, the length of the flowering stem (LFS) and leaf width (LW) had a positive influence on seed width (SW), explaining 46% of the variation. In contrast, plant height (PH) negatively influenced SW. LFS also positively affected seed length (SL), explaining about 68% of its variability (Table 4). When fourth-order characters were treated as predictors and third-order characters as targets, the outputs indicated reproductive success, ultimately leading to higher seed yield in black cumin. The significant impact of the dry weight of shoot and thousand-seed weight was found as first-order characters donating to yield, similar to the report of Gashaw et al. (2020) in path analysis on 36 black cumin genotypes. In contrast, high standardized coefficients were found for the dry weight of shoot and harvest index, identifying them as the most influential characters on seed yield. The dry weight of the shoot and thousand-seed weight are key determinants of seed yield in black cumin due to their roles in biomass accumulation and resource allocation. A higher shoot dry weight indicates greater photosynthetic efficiency and biomass production, ensuring sufficient nutrients and carbohydrates for seed development.

Meanwhile, TSW reflects seed quality, with heavier seeds indicating better nutrient allocation and efficient source-to-sink transport. Together, a well-developed shoot system supports reproductive growth, while larger seeds enhance yield potential, making these traits crucial for determining seed yield in black cumin. A similar approach for evaluating character associations and conducting reliable path analysis regarding collinearity issue was applied by Mohebodini et al. (2018) in *Lepidium sativum L.* and Zavoshti et al. (2023) in *Onobrychis viciifolia Scop.* The advantages of this method in reducing collinearity and recognizing the real donations of each independent character are consistent with findings from studies on other crops, such as *Secale cereale L.* (Nayebi-Aghbolag et al., 2019) and *Cicer arietinum L.* (Sabaghnia & Janmohammadi, 2024). Ghorbanzadeh-Neghab and Zare-Mehrjerdi (2018) studied associations among 16 black cumin ecotypes and found that NFP, DWS, and TSW were the most significant characters influencing seed yield performance. In their analysis, SW had a greater impact (1.28) on TSW than IMS and SL. According to Bardideh et al. (2013), stem diameter, dry weight of shoot, plant capsules, branch number, and thousand-seed weight were identified as key characteristics influencing seed yield performance in black cumin.

performance in black cumin (Fig. 1). Therefore, increasing the seeds of the follicle, dry weight of shoot, stem diameter, and follicles of plant, could improve yield performance. In addition to this primary path, three other important paths were identified: CC → SD → NFP → DWS → SY as the second most influential path, FW → LFS → SW → TSW → SY as the third, and CW → LFS → SW → TSW → SY as the fourth. Additionally, two other paths were observed following the aforementioned ones: LA → LW → SW → TSW → SY and LL → LW → SW → TSW → SY (Fig. 1). It appears that the first path, involving dry weight of shoot, is the most effective due to its high coefficient values, while the other paths, except for the second one, are related to thousand-seed weight. Notably, the two main yield components, the seeds of the follicle and the follicles of the plant, are prominent in the first path, while thousand-seed weight influences the remaining paths.

Discussion

Positive associations were observed between seed yield and most of the measured characters of black cumin. This is similar to Asadoorian and Abaszadeh (2022), which found the primary components influencing seed yield in black cumin as the seeds of the follicle, follicles of the plant, and thousand-seed weight. The positive associations between seed yield and various traits in black cumin can be explained by their physiological roles in growth, reproduction, and resource allocation. Plant height, leaf area, and chlorophyll content enhance photosynthesis, increasing biomass and energy availability for seed formation. Strong structural traits, such as stem diameter and internode length, support efficient water and nutrient transport, ensuring optimal growth. Flowering-related traits, including the number of follicles, capsule weight, and follicle size, directly influence seed production by improving reproductive efficiency.

Additionally, seed-specific traits like seed width, length, and thousand-seed weight indicate better nutrient allocation, resulting in larger, more viable seeds. These interconnected traits enhance photosynthetic efficiency, structural stability, and particularly when strong associations exist among traits. A path analysis approach that accounts for collinearity was employed to address this, recognizing that the assumption of predictor independence is often unrealistic in real-world conditions, where yield-related traits are highly interdependent (Pallavi et al., 2024). As demonstrated in previous studies, ranking traits based on their interrelationships were applied here and has been widely used in various crops, including wheat (Janmohammadi et al., 2014). For genetic improvement programs to enhance black cumin seed yield under upland semi-arid conditions, selection should prioritize traits such as the number of seeds per follicle, stem diameter, and shoot dry weight. Additionally, traits like thousand-seed weight, chlorophyll content, follicle width, length of the flowering stem, seed width, and capsule weight should be considered in subsequent selection stages.

Based on the insights, the following recommendations can be made for black cumin breeders. Breeding efforts should prioritize traits that have a direct and significant influence on seed yield. According to the path analysis, the most impactful are key traits such as the number of seeds per follicle, stem diameter, and shoot dry weight. Selecting these characteristics can help maximize seed yield in black cumin. Additionally, collinearity among traits can obscure true relationships and lead to inaccurate conclusions in breeding decisions. To mitigate this, breeders should employ path analysis that accounts for collinearity, ensuring that the selected traits are genuinely independent and contribute effectively to yield improvement. This approach has proven beneficial in other crops, such as garden cress (Mohebodini et al., 2018) and camelina (Göre et al., 2023), and should be integrated into black cumin breeding programs.

For future genetic improvement projects on black cumin, assessing the available variability in yield-related characters is essential. A deeper understanding of how these traits influence seed yield can be achieved through path analysis, which involves examining standardized coefficients and categorizing them into different orders. The advantage of path analysis lies in its ability to identify the key traits affecting yield while determining their indirect effects through other variables (Hinson et al., 2022). Previous studies have demonstrated that path analysis provides more comprehensive insights into trait relationships than simple correlation analysis (Sabaghnia & Janmohammadi, 2024). This method is particularly useful for detecting compensation phenomena among yield-related traits when two or more characteristics interact inversely. The present study observed significant positive associations between seed yield and most of the examined traits, except for thousand-seed weight, another key yield component. Conversely, other yield-related traits, such as the number of seeds per follicle, stem diameter, and number of follicles per plant, positively influenced yield. Similar findings have been reported by Gashaw et al. (2020), while Bardideh et al. (2013) specifically emphasized the importance of thousand-seed weight in determining yield.

A path diagram was constructed to better organize the characters according to their developmental roles and visualize the relationships among traits. The contribution of each trait to yield performance is influenced by multiple factors through various pathways. Misinterpreting a trait’s contribution due to incorrect path assignments can mislead breeding efforts, thereby reducing the effectiveness of selecting the most favorable genotypes. Additionally, standard path analysis can be affected by collinearity issues,

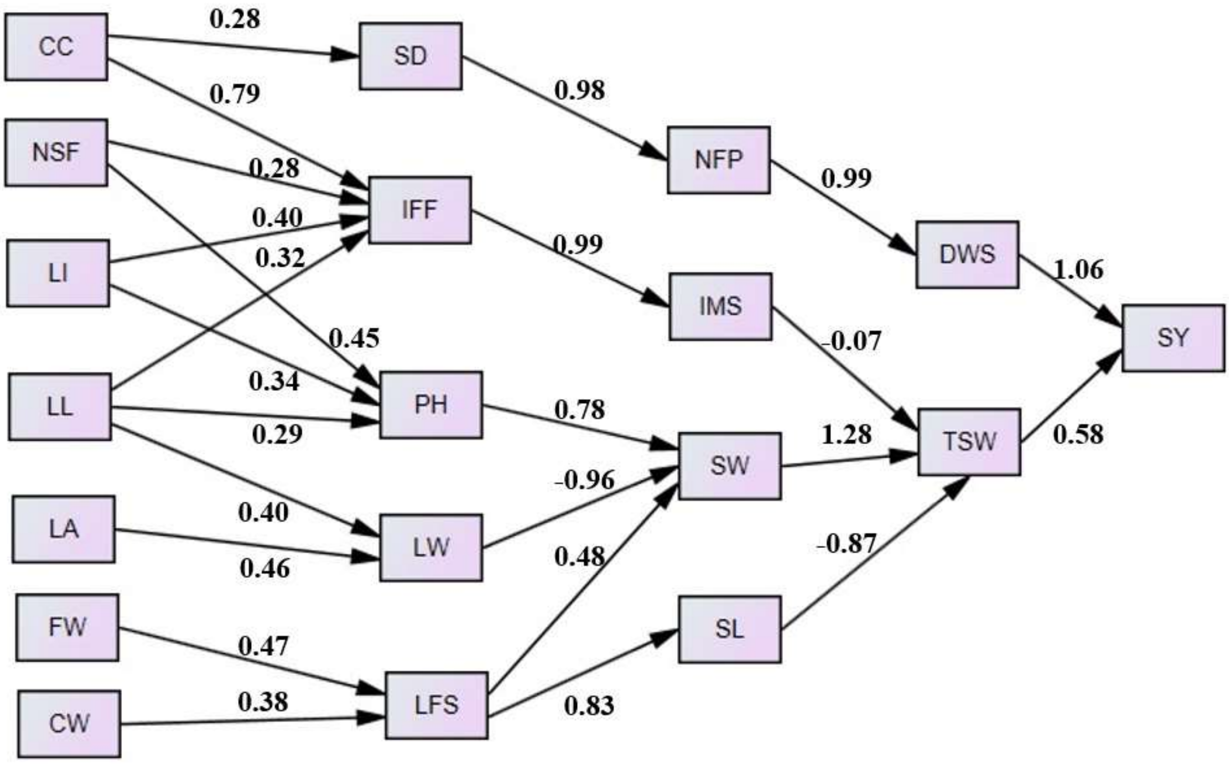

Figure 1. Path diagram indicating the deeper associations among characters contributing to black cumin's seed yield (SY). For abbreviations, refer to text.

significantly influence seed yield continuously. Maintaining flexibility in breeding goals based on new data will enhance the long-term effectiveness of breeding programs. By incorporating these strategies, black cumin breeders can optimize their selection processes, improve seed yield, and develop cultivars well-suited to current and future agricultural challenges.

Conclusions

The study emphasized path analysis to reveal the direct and indirect relationships between yield-related characters, which offers a more nuanced understanding than simple correlation coefficients. The research highlights characteristics like the seeds of the follicle, stem diameter, and dry weight of the shoot, which have the most significant impact on seed yield performance, making them critical targets for selection in breeding efforts. Addressing collinearity between characters is crucial to avoid misinterpreting the relationships and ensuring more effective breeding strategies. Finally, focusing on characters that directly impact seed yield while considering the role of second-order While certain traits, such as thousand-seed weight and chlorophyll content, are considered secondary, they still contribute to overall yield performance. Breeders should adopt a balanced selection strategy that integrates multiple traits rather than focusing solely on one or two high-impact characteristics. This comprehensive approach ensures sustainable yield improvement. Given the environmental context of the breeding efforts, specifically upland semi-arid conditions, breeders should prioritize genotypes that are not only high-yielding but also well-adapted to drought stress. This may involve selecting traits that confer drought tolerance alongside the key yield-related traits identified in the study. The path analysis framework provides valuable insights into the interrelationships among traits, helping breeders integrate multiple characteristics into their selection programs. By focusing on pathways with the strongest influence on seed yield, they can ensure that selected traits align with breeding objectives and are genetically linked to high productivity. As genetic variation and environmental conditions evolve, it is essential to reassess the traits that most enhancing black cumin yields, particularly under upland semi-arid conditions.

characters can improve the efficiency and accuracy of breeding programs aimed at

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