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RESEARCH ARTICLE

Unlocking the potential of black cumin (*Nigella sativa* L.) by evaluating improved varieties for enhanced yield in the Wolaita zone, Southern Ethiopia

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Abstract

Black cumin (*Nigella sativa* L.), a spice crop with significant medicinal properties, holds immense potential as a high-value export commodity. This study aimed to identify superior black cumin genotypes exhibiting desirable traits such as high yield, adaptability to local conditions and disease tolerance. Field experiments were conducted at two locations in the Wolaita zone, southern Ethiopia, Dalbo and Taba, during the 2020/21 cropping season. Eight black cumin varieties were evaluated using a randomized complete block design with three replications. Data on various vegetative growth, yield and quality parameters were collected and subjected to analysis of variance. Results revealed significant variability ($p<0.05$) among varieties for key agronomic traits, indicating a promising degree of genetic diversity within the tested germplasm. The performance of varieties was significantly influenced by location, highlighting the importance of genotype-by-environment interactions. Notably, Dalbo consistently outperformed Taba in terms of seed yield across all varieties. Genetic parameter estimates provided valuable insights into the inheritance of these traits, informing future breeding strategies. Based on overall performance, varieties Darbera, Silingo and Dershaye emerged as top performers at Dalbo, while Dershaye, Darbera and Kenna excelled at Taba. Crucially, Darbera and Dershaye demonstrated superior adaptability, consistently producing high yields and exhibiting commendable disease tolerance across both locations. These findings suggest that Darbera and Dershaye hold substantial promise for cultivation in the study area and similar agroecological zones. Further research focusing on these promising varieties could involve multi-environment trials, seed production and value chain development to fully harness their economic potential.

Keywords: black cumin; Ethiopia; *Nigella sativa;* variety evaluation; yield performance

Introduction

Black cumin (*Nigella sativa*), a member of the *Ranunculaceae* family, stands out as a prominent spice and medicinal crop, often hailed as the "miracle herb of the century" (1). This annual herb, native to a region spanning the Mediterranean, West Asia and Northern India, holds significant economic and medicinal value (2). Black cumin seeds are a rich source of oil and bioactive compounds, making them attractive for culinary use, traditional medicine and emerging applications such as biodiesel production (3).

The notable properties of black cumin seeds stem from their complex chemical composition, rich in essential oils, fatty acids and bioactive compounds. Thymoquinone, a phytochemical found abundantly in black cumin oil, has garnered significant scientific attention for its diverse pharmacological activities (4). Studies have demonstrated Thymoquinone (TQ) potent antioxidant, anti-inflammatory and anticancer properties (5). Its ability to modulate various signaling pathways involved in inflammation, oxidative stress and tumorigenesis makes it a promising candidate for developing innovative therapeutic interventions (6). In addition to its medicinal value, black cumin is a key ingredient in culinary traditions around the globe. Its pungent, slightly bitter flavor imparts a distinctive character to a variety of dishes, from savory curries and stews to aromatic breads and pastries. Furthermore, the versatility of black cumin extends well beyond the kitchen; its high oil content, rich in unsaturated fatty acids, makes it a valuable source for biodiesel production (7). This sustainable application highlights not only the culinary potential but also the economic significance of this remarkable plant.

Ethiopia, with its diverse agroecological zones, recognizes black cumin as a high-value cash crop, second only to ginger in export revenue. Despite a significant 12 % share in the global market, a notable 99 % of Ethiopia's black cumin production is consumed domestically, highlighting a substantial untapped export potential (8). The crop's versatility is evident in its various applications - as a flavoring agent in whole grain and powdered forms, as an oleoresin extract and as a key ingredient in traditional remedies. Despite wide cultivation, production faces multiple constraints. These include the use of farmer-saved seeds with low genetic potential, a lack of awareness regarding improved crop management practices and limited access to high-yielding and disease-resistant varieties (9). These challenges are particularly pronounced in the highlands, including the Wolaita zone, where research on black cumin cultivation and varietal performance remains limited.

Hence, this knowledge gap presents a significant barrier to optimizing black cumin production and unlocking its full economic potential in this area. This study addresses this critical gap by evaluating the adaptability and performance of improved black cumin varieties in the Wolaita zone. By identifying superior genotypes suited to the local environment, this research aims to enhance productivity, diversify crop production and ultimately contribute to the economic empowerment of farmers in the region. Therefore, the objectives of this study were to: i) assess the genetic variability among a diverse collection of black cumin genotypes for key agronomic traits, including yield and yield components, growth and phenology and disease resistance, ii) evaluate the adaptation of these genotypes to the specific environmental conditions of the Wolaita zone, considering factors such as altitude and soil type, iii) identify superior black cumin varieties that exhibit high yield potential, disease resistance and broad adaptation to the local environment.

Materials and Methods

Description of experimental site

The field experiments of the 2020/21 cropping season were conducted at two distinct locations. The first location, Dalbo (latitude 06°52' N and longitude 37°48' E), sits at an altitude of 2162 m above sea level. Dalbo experiences a temperate climate with a maximum temperature of 21 °C and a minimum of 11.5 °C. The average annual rainfall is 1271 mm. The soil in Dalbo is classified as clay loam with a slightly acidic pH of 5.36. The second location, Taba (latitude 06°83' N and longitude 37°73' E), is situated at a lower altitude of 1907 meters above sea level. Taba shares a similar temperature range to Dalbo with a maximum of 21 °C and a minimum of 11.5 °C. However, it receives slightly less rainfall with an annual average of 1250 mm. The soil in Taba is classified as sandy loam and has a slightly alkaline pH of 7.6 (10).

Planting materials, treatment and experimental design

Eight commercially available black cumin varieties were sourced from Sinana, Deberizeit and Kulimisa Agricultural Research Centers for this study. Field experiments were conducted during the 2020/21 cropping season. To ensure optimal planting conditions, the experimental fields underwent thorough preparation, including plowing, pulverization and leveling. The experiment followed a Randomized Complete Block Design (RCBD) with three replications to evaluate the eight black cumin varieties. Each experimental plot measured 1.8 meters wide and 2 meters long, resulting in a total gross area of 3.6 square meters. Planting was carried out manually, placing two seeds per hole at a row spacing of 30 cm and a plant spacing of 10 cm. To support healthy plant growth, a recommended fertilizer application was implemented. This included 20 kg/ha of phosphorus applied as diammonium phosphate at planting and 55 kg/ha of nitrogen applied as urea. Following emergence, thinning was conducted to maintain the desired plant density within each plot. Throughout the growing season, meticulous crop management practices were employed, including regular hoeing and weeding. Additionally, vigilant monitoring for diseases such as powdery mildew, downy mildew and root rot were also monitored closely, as they could significantly affect crop health and yield and common pests such as aphids, cutworms and flea beetles' outbreaks were conducted through regular visual inspections.

Data collection and measurements

The study meticulously recorded a comprehensive set of agronomic traits. Days to flowering, a key developmental stage, was determined by calculating the number of days from planting to the point at which 50 % of the plants within each plot-initiated flowering. Similarly, days to maturity were estimated by counting the number of days from planting to the stage where a visible color change in the capsules, from green to lemon yellow, was observed in 90 % of the plants within each plot. Upon reaching maturity, plant height was measured from the ground to the apex for five randomly selected plants within each plot. Branching, a crucial determinant of yield potential, was assessed by meticulously counting the number of branches originating from the main stem of five randomly chosen plants per plot at maturity. The number of capsules per plant, a direct indicator of reproductive success, was carefully counted on five randomly selected plants within each plot upon maturity. To assess seed production, the number of seeds per capsule was determined at the maturity stage. This involved counting seeds from a predetermined number of capsules from five randomly selected plants per plot and calculating an average. Seed yield, the ultimate measure of productivity, was determined by manually harvesting the mature seeds from each net plot area and extrapolating the harvested seed weight to a per hectare basis (kg/ha). Finally, the oil content of seed samples carefully collected from each plot was analyzed using the established hydro-distillation method as described earlier (11).

Following data collection, a comprehensive statistical analysis was conducted. The collected data were subjected to analysis using the general linear model employing GenStat 15th edition (12). The interpretation of the results adhered to the procedures outlined previously (13). In instances where treatment effects exhibited statistically significant differences, further analysis was conducted using the least significant differences test at a significant level of 5% to discern specific differences between treatment means.

The study employed established statistical methods to dissect the contributions of genetics and environment to observed variations in agronomic traits. Variance components due to phenotype (σ2p), genotype (σ2p) and the environment (σ2e) were calculated by adopting the following formula as suggested elsewhere (14).

Genotypic Variance, $\sigma^2_g = (MSg - MSe)/r$, where MSg = mean square of genotype, square of error and r = number of replications (Eqn.1)

Phenotypic variance ($\sigma 2p$) = $\sigma 2g + \sigma 2e$ (Eqn. 2)

Environmental variance ($\sigma 2e$) = Error mean square (Eqn. 3)

According to the previous study (15), the phenotypic and genotypic coefficients of variances were expressed as:

$$PVC = \frac{\sqrt{\text{Phenotypic variance}}}{\text{Population mean for trait}} \quad \text{or} \quad PVC = \frac{\sigma 2P}{X} \times 100 \qquad \text{(Eqn. 4)}$$

Where PVC = Phenotypic coefficient of variation

$$GVC = \frac{\sqrt{\text{Genotypic variance}}}{\text{Population mean for trait}} \quad \text{or} \quad GVC = \frac{\sigma 2g}{X} \times 100 \qquad \text{(Eqn. 5)}$$

Where GVC = Genotypic coefficient of variation

X = the grand mean of a character

Heritability in a broad sense was calculated for each trait by using the formula (16):

$$H^2 (\%) = \frac{\sigma\, 2g}{\sigma\, 2p} \times 100 \qquad \text{(Eqn. 6)}$$

Where H = Heritability in broad sense, $\sigma^2 g$ = genotypic variance and σ^2_p = Phenotypic variance

Genetic Advance (GA) under selection, assuming the selection intensity of 5 % was calculated as proposed previously (14):

$$GA = K \sqrt{\sigma 2p}. \frac{\sigma 2g}{\sigma 2p} = KH^* \sqrt{\sigma 2p}. \qquad \text{(Eqn. 7)}$$

Where: GA = Expected genetic advance

K = The selection differential (K= 2.056 at 5% selection intensity)

Genetic advance as a percentage of the mean was calculated to compare the extent of predicted advances of different traits under selection, using the formula given elsewhere (17):

$$GAM = \frac{GA}{X} \times 100 \qquad \text{(Eqn. 8)}$$

GAM = Genetic advance as a percentage of the mean, GA = Genetic advance under selection and X = Mean value

Results

Days to Flowering

An analysis of variance was conducted to assess the variation in days to flowering among the evaluated genotypes. The results indicated significant ($p<0.05$) differences among genotypes, suggesting a genotypic influence on this trait (Table 1). Although other traits showed significant genotype × environment interactions, days to flowering remained relatively consistent across environments. However, notable differences in flowering time were observed among genotypes across different locations. Specifically, the longest time to flowering (92.67 days) was recorded for the variety Darbera at the Dalbo site, while the shortest duration (78.33 days) was observed for the variety Sooreso at the Taba site.

Days to maturity

The analysis of variance revealed significant variation in days to maturity ($p<0.05$), indicating the genotypic influence on this trait (Table 1, Fig. 1). Furthermore, the varieties exhibited differential responses to location, highlighting the role of environmental factors in shaping this trait. At the Dalbo site, days to maturity ranged from 126.7 to 146, with a difference of 18.33 days between the earliest and latest maturing varieties. In contrast, at the Taba site, the range narrowed to 117.33 to 123.67 days, with a difference of 6.34 days between the extremes. This suggests that, overall, varieties reached maturity faster at the Taba site compared to the Dalbo site. Among the tested varieties, Derashaye exhibited the longest time to maturity (146 days) at the Dalbo site, followed by Qeneni (140.67 days). Conversely, Qeneni reached maturity the fastest (117.33 days) at the Taba site.

Plant height (cm)

The analysis of variance revealed significant ($p<0.05$) differences in plant height among the black cumin varieties, indicating that plant height is a genetically influenced trait in this species (Table 1). Plant height exhibited considerable variation, ranging from 28.60 cm for the variety Dershaye at the Taba site to 47.47 cm for the variety Darbara at the Dalbo site. Among the tested varieties, Darbera emerged as the tallest (47.47 cm), followed by Dershaye (44 cm). Conversely, Aden exhibited the shortest statues, 28.60 cm.

Branches per plant

Significant ($P<0.05$) differences in the number of branches per plant were observed among the black cumin varieties, indicating a genotypic influence on this trait (Table 1). Notably, plants grown at the Dalbo site tended to produce a higher number of branches compared to those grown at the Taba site, suggesting an environmental effect on branch development. Across all varieties and locations, the number of branches per plant ranged from 10.00 to 28.17. The highest branch number (28.17) was recorded for the variety Darbera at

Table 1. Mean performance of black cumin varieties for phenological and growth parameters

Location	Varieties	Days to flowering	Days to maturity	Plant height (cm)	Branch number
Dalbo	Silingo	83.00	136.33a-c	43.37a-c	22.03a-e
	Dershaye	83.67	146.00a	44.00ab	26.63a
	Aden	86.67	134.67a-d	40.53a-d	24.37a-c
	Darbera	92.67	135.67a-c	47.47a	28.17a
	Kenna	91.67	139.00ab	43.60a-c	24.90a-c
	Qeneni	90.33	140.67ab	31.87c-e	25.57ab
	Gemmachis	91.67	140.00ab	38.07a-e	23.27a-d
	Sooressa	88.00	127.67b-e	40.37a-e	26.47a
Taba	Silingo	82.33	119.33e	31.20de	14.10c-f
	Dershaye	76.33	120.00de	31.50de	14.37b-f
	Aden	80.00	123.67c-e	28.60e	10.93ef
	Darbera	86.00	123.67c-e	32.20c-e	11.50ef
	Kenna	87.00	122.67c-e	31.20de	12.23d-f
	Qeneni	85.67	117.33e	30.23de	10.00f
	Gemechis	86.33	119.33e	29.87de	11.30ef
	Sooressa	78.33	123.67c-e	32.86b-e	12.20d-f
	LSD	NS	15.29	11.77	11.39
	CV (%)	12.89	7.09	19.58	36.02

*= significant at 5 %, NS= not significant

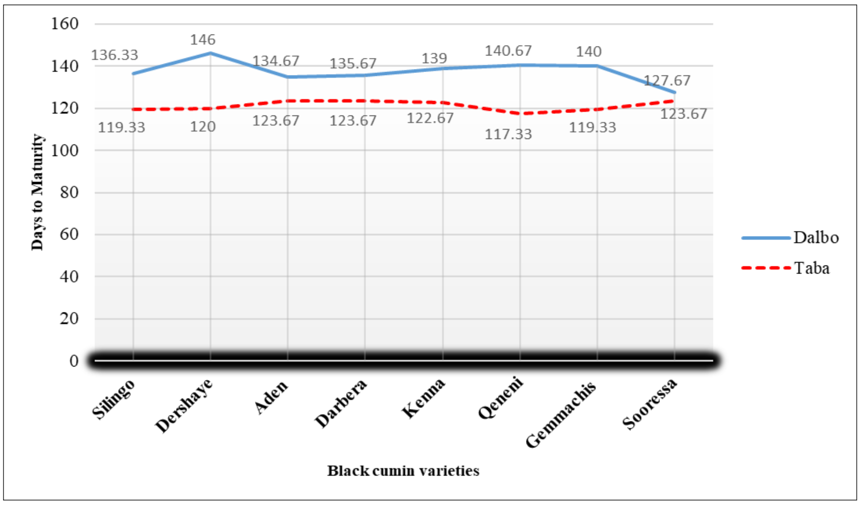

Fig 1. Effect of genotypes on Days to Maturity.

the Dalbo site, closely followed by Dershaye with 26.63 branches per plant. In contrast, the lowest branch number (10) was observed for the variety Qeneni at the Taba site. Remarkably, while Dershaye, Darbera and Sooressa exhibited superior branching at the Dalbo site, Silingo, Dershaye and Sooressa were the top performers in terms of branch production at the Taba site.

Capsules per plant

A significant interaction effect between location and variety was observed for the number of capsules per plant, indicating that the performance of varieties in terms of capsule production is influenced by the environment (Table 2). Across all varieties and locations, the number of capsules per plant ranged from 10.60 to 30.27. At the Dalbo site, capsule production was generally higher, ranging from 25.63 to 30.27 capsules per plant. In contrast, at the Taba site, the range narrowed to 10.60 to 19.23 capsules per plant. This suggests that the environmental conditions at the Dalbo site were more conducive to capsule development in black cumin. Varietal responses also varied across locations. At Dalbo, Darbera, Aden and Sooressa exhibited higher capsule production, while Gemechis, Kenna and Dershaye were the top performers at Taba. The highest capsule count (30.27) was recorded for Darbera at Dalbo, followed by Aden with 27.83 capsules per plant. Conversely, Aden produced the fewest capsules (10.60) at the Taba site.

Seeds per capsules

The interaction between location and variety had a significant ($p<0.05$) impact on the number of seeds per capsule, as revealed by an analysis of variance (Table 2). Compared to Taba, Dalbo had a higher seed count per capsule. The number of seeds per capsule ranged from 76.33 to 92.67 in Dalbo and 57 to 70.53 in Taba. *When examining the number of seeds per capsule,* specific varieties exhibited superior performance at each location. At Dalbo, the standout varieties were Silingo, Gemechis and Deshaye, while at Taba, Dershaye, Qeneni and Darbera demonstrated superior performance. Notably, Silingo exhibited the highest seed count per capsule (92.67), followed closely by Gemechis with a mean of 91.03 seeds per capsule at the Dalbo location. Conversely, Gemechis recorded the lowest number of seeds per capsule (57) at the Taba location.

Seed yield

The analysis of variance showed that the interaction between location and variety significantly ($p<0.05$) influenced seed yield. Dalbo consistently exhibited higher seed yields compared to Taba (Table 2). The inferior performance of varieties at the Taba location could be attributed to unfavorable growing conditions, such as soil type and climatic factors, which negatively impacted crop performance. Among the tested varieties, Darbera, Silingo and Dershaye demonstrated superior seed yield at the Dalbo location. Conversely, at the Taba location, Dershaye, Darbera and Kenna exhibited higher seed yields. Notably, Darbera and Dershaye displayed consistent seed yield stability across both locations, indicating their adaptability to varying environmental conditions. Overall, Darbera achieved the highest seed yield, reaching 1137 kg/ha, followed closely by Silingo with a mean seed yield of 1130 kg/ha at the Dalbo location. In contrast, Gemechis recorded the lowest seed yield of 377 kg/ha at the Taba location.

Oil content

Analysis of variance indicated a significant ($p<0.05$) interaction effect between location and variety on oil content (Table 2). Oil content was higher in Dalbo compared to Taba. The interaction between location and variety resulted in oil content ranging from 22 % to 33 %. At Dalbo, the varieties Qeneni,

Table 2. Mean performance of black cumin varieties for yield components, seed yield and oil content

Location	Varieties	Pods per plant	Seeds per pod	Seed yield (kg/ha)	Oil content (%)
Dalbo	Silingo	27.27ab	92.67a	1130a	27.50a-c
	Dershaye	25.87a-c	89.43a	1083ab	31.80ab
	Aden	27.83ab	82.27a-c	800a-e	24.90a-c
	Darbera	30.27a	81.93a-c	1137a	23.00bc
	Kenna	26.30a-c	81.07a-d	1080ab	25.10a-c
	Qeneni	26.97a-c	76.33a-e	663a-e	33.00a
	Gemechis	26.97a-c	91.03a	1057a-c	32.67a
	Sooressa	25.63a-c	86.70ab	960a-d	26.43a-c
Taba	Silingo	12.27d	62.73d-f	433de	22.00c
	Dershaye	14.33d	70.53b-f	530b-e	31.00a-c
	Aden	10.60d	63.97c-f	433de	27.90a-c
	Darbera	12.00d	68.20b-f	490c-e	25.97a-c
	Kenna	17.33cd	62.13ef	477de	26.77a-c
	Qeneni	14.77d	70.47b-f	437de	28.80a-c
	Gemechis	19.23b-d	57.00f	377e	31.53ab
	Sooressa	13.60d	61.67ef	400de	26.33a-c
	LSD	10.32	18.79	573	9.03
	CV (%)	20.75	15.05	17.95	19.50

*= significant at 5 %, NS= not significant

Gemechis and Dershaye exhibited superior oil content, with Qeneni demonstrating the highest yield at 33 %. In contrast, at the Taba location, Gemechis excelled, achieving a mean oil content of 32.67 %. This shows that the combination of the Qeneni variety at Dalbo produced the maximum oil content, while the Taba location with the Silingo variety recorded the lowest oil content of 22 %. Overall, Qeneni, Gemechis and Dershaye displayed relatively stable oil contents across both locations, but it was the specific combination of Qeneni at Dalbo that represented the highest extreme and Silingo at Taba that represented the lowest.

Phenotypic and genotypic variations

In this study, phenotypic variance among black cumin varieties varied from 45.14 for oil content to 1835.54 for the number of seeds per pod. Apart from oil content, which showed relatively low phenotypic variance (below 50), all other traits exhibited substantially higher phenotypic variance (≥ 100). Genotypic variance ranged from 15.78 to 1708.53, with all traits except oil content showing greater values compared to the genotypic variance of oil content. The number 45.14 being below 50 confirms its classification as low. For greater clarity, we could state that the other traits displayed significantly higher genotypic variance relative to oil content (Table 3). Moderate genotypic variance was observed only for oil content. Notably, no lower genotypic variance was found for any of the black cumin varieties. The phenotypic coefficient variation ranged from 18.19 % for flowering to 65.72 % for seeds per pod. Following the classification of PCV and genotypic coefficient of variation values as high (>20 %), medium (10-20 %) and low (<10 %), days to maturity, branches per plant, pods per plant, seeds per pod, seed yield and oil content exhibited high PCV (28). Conversely, only days to flowering showed moderate PCV, indicating a more pronounced environmental influence on the expression of the former traits. The genotypic coefficient of variation ranged from 7.09 % to 48.01 %. Branches per plant, pods per plant and seed yield displayed high GCV, while days to flowering, plant height, seeds per pod and oil content showed moderate GCV values. In contrast, days to maturity had a low GCV value below 10 %.

Broad-sense heritability and genetic advance

Broad-sense heritability (H^2) ranged from 34.96 % for oil content, the lowest value, to 94.59 % for pods per plant, the highest (Table 3). Following the classification by (14) (low: < 30 %, moderate: 30-60 %, high: > 60 %), days to maturity, plant height, branches per plant, pods per plant, seeds per pod and seed yield exhibited high H^2 estimates. In contrast, days to maturity and oil content showed relatively moderate H^2, likely due to the influence of environmental factors on the polygenic nature of these traits. Genetic advance as a percentage of the mean ranged from 4.65 % for days to maturity to 30.54 % for seed yield. Conversely, only days to maturity had low genetic advance. These results suggest that selecting the top 5 % of genotypes could lead to an improvement of 4.65 % to 30.54 % over the population mean for the respective traits (Table 3). Notably, total branches per plant, pods per plant and seed yield exhibited both high heritability and high genetic advance, indicating that these traits are primarily influenced by additive gene action, making selection effective in early generations. Plant height and seeds per pod showed high heritability coupled with moderate genetic advancement, suggesting that selection for these traits might be more effective in later generations. Days to flowering and oil content exhibited moderate heritability and moderate genetic advance, also pointing towards selection in later generations for these traits.

Correlations of traits

The correlations among agronomic traits are presented in Table 4. Correlation coefficient (r) values ranged from -0.29 to 0.94. Days of flowering showed a significant positive correlation with branches per plant, pods per plant and seed yield. Similarly, plant height was positively and significantly correlated with branches per plant, pods per plant, seeds per pod and seed yield. A positive and significant association was observed between branches per plant and pods per plant, seeds per pod and seed yield. Pods per plant exhibited a positive and significant correlation with both seeds per pod and seed yield. Furthermore, a positive and significant correlation was found between seeds per pod and seed yield. Days to maturity did not show strong and significant positive correlations with seed yield; all other agronomic traits did.

Table 3. Phenotypic and genotypic coefficient of variability, heritability and genetic advance for varieties

Trait	σ2p	σ2g	σ2e	PCV (%)	GCV (%)	H^2 (%)	GA	GA (%)
Days to flowering	242.54	120.73	121.81	18.19	12.89	49.78	15.97	18.66
Days to maturity	1152.60	1068.50	84.10	26.25	7.09	92.70	6.01	4.65
Plant height	473.47	423.62	49.85	60.34	19.58	89.47	4.10	11.37
Branch number	723.28	676.56	46.72	44.35	36.69	93.54	5.18	27.80
Pods per plant	709.33	670.98	38.35	28.35	29.84	94.59	5.19	25.01
Seeds per pod	1835.54	1708.53	127.01	65.72	15.05	93.08	8.21	10.96
Seed yield	128.43	116.58	11.85	58.06	48.01	90.77	21.19	30.54
Oil content	45.14	15.78	29.36	24.18	19.50	34.96	4.84	17.42

Table 4. Correlation of agronomic traits of black cumin varieties

Trait	DF	DM	PH	BN	PPP	SPP	SY	OC
Days to flowering (DF)	1.00	0.08^{NS}	0.47^{NS}	0.58*	0.69*	0..42^{NS}	0.53*	-0.04^{NS}
Days to maturity (DM)		1.00	-0.21^{NS}	-0.24^{NS}	-0.13^{NS}	-0.29^{NS}	-0.21^{NS}	-0.08^{NS}
Plant height (PH)			1.00	0.85*	0.83*	0.83*	0.94*	-0.24^{NS}
Branch number (BN)				1.00	0.92*	0.85*	0.90*	0.01^{NS}
Pods per plant (PPP)					1.00	0.81*	0.87*	0.11^{NS}
Seeds per pod (SPP)						1.00	0.93*	0.13^{NS}
Seed yield (SY)							1.00	-0.02^{NS}
Oil content (OC)								1.00

Notably, negative associations among the traits were not statistically significant.

Discussion

The results in Table 1 underscore the complex interactions between genotype and environment regarding phenological and growth traits in black cumin. The observation that there are no significant differences in days to flowering among varieties implies that flowering time might be predominantly regulated by environmental factors rather than genetic differences within this specific germplasm. This raises an intriguing contradiction to previous studies that suggested a stronger genetic influence on flowering time. While the data indicates a lack of significant variation, it's important to note that minor differences can still exist due to slight genetic diversities, micro-environmental conditions, or experimental error. Even if these variations are not statistically significant, they may still bear biological relevance and could indicate potential for future breeding. Regarding the comparison with earlier findings, particularly those outlined in reference (18), it's critical to highlight how differing experimental conditions or methodologies may have influenced the results. For instance, variations in soil composition, climate conditions, or measurement techniques utilized in both studies could account for the discrepancies observed in flowering times. This complexity illustrates the necessity of considering both genetic and environmental interactions in evaluating phenological traits thoroughly.

However, the significant variation in days to maturity indicates that this trait is influenced by both genotype and environment. The shorter time to maturity in Taba compared to Dalbo suggests that environmental conditions in Taba may have accelerated plant development. These findings underscore the considerable phenotypic variability presented within the tested varieties for this key phenological trait. The observed variation in days to maturity aligns with previous reports (19), who also documented variations in this trait among black cumin genotypes. Further investigation using stability analysis methods like AMMI or GGE biplot analysis (20) could provide valuable insights into the genotype-by-environment interaction and help identify ideal varieties for specific locations.

The variations in plant height and branch number between varieties and locations further emphasize the genotype-by-environment interaction. The generally lower plant height and branch number in Taba compared to Dalbo suggest that environmental conditions in Taba may have been less favorable for vegetative growth. The observed variation in plant height is likely attributable to the inherent genetic differences among the varieties. This observation aligns with the understanding that plant height is primarily determined by the genetic makeup of a genotype, although environmental factors can also exert modifying influences (21). This could also be due to factors such as water availability, nutrient levels, or temperature. The phenotypic variation observed in cowpea germplasm (22) demonstrates the influence of environmental factors on plant growth, although in a different species.

The observed variations in growth and phenological traits have implications for black cumin production. Early maturing varieties may be advantageous in environments with shorter growing seasons, while taller plants with more branches may contribute to higher yields in favorable conditions. Understanding the interplay between genotype, environment and these traits is crucial for optimizing black cumin production in different environments. These findings highlight the potential for genotype-by-environment interactions to influence branch development in black cumin.

The results presented in Table 2 reveal significant genotype-by-environment interactions for yield components, seed yield and oil content in black cumin. The lower seed yield, pods per plant and seeds per pod in Taba compared to Dalbo suggest that environmental conditions in Taba were less favorable for black cumin production. These findings are consistent with previous research (23, 24), which observed similar trends in seed yield per capsule across different black cumin varieties and geographical locations. For instance, studies highlighted the impact of environmental factors on seed yield (23, 24) . Similarly, (23, 25) also reported significant variations in growth characteristics among black cumin varieties, attributing these differences to factors such as temperature, rainfall, soil fertility and other environmental factors between the two locations. Furthermore, the influence of sowing dates and methods on the growth and seed yield of black cumin has been documented (26), suggesting that optimizing these practices could potentially improve yields in different environments.

The variations in yield components and seed yield among varieties within each location highlight the genetic diversity within the black cumin germplasm. 'Silingo' and 'Darbera' showed promising performance in Dalbo, while 'Dershaye' performed relatively well in Taba. These findings suggest that specific varieties may be better adapted to environments. Breeding programs can utilize this information to select and develop varieties with improved yield potential for different growing conditions. Genetic diversity analysis and character associations in black cumin (27) can provide valuable insights for such breeding efforts.

The observed variations in oil content across varieties and locations further emphasize the influence of genotype and environment on this trait. While 'Qeneni' had the highest oil content in Dalbo, 'Gemechis' had the highest oil content in Taba. This suggests that oil content is not solely determined by genetic factors but is also influenced by environmental conditions. These findings are consistent with early results (28), reported that both genotype and environment influence the oil content of black cumin. Further research is needed to understand the complex interplay between genotype, environment and oil content in black cumin.

Phenotypic and genotypic coefficients of variation are essential for estimating the variability within a population (29, 30). The high PCV and GCV values observed for several traits indicate substantial phenotypic and genotypic variability within the black cumin germplasm. This variability provides a basis for selection and breeding programs aimed at improving these traits. The high heritability estimates for most traits suggest that selection would be effective in achieving genetic gain. This is further supported by the moderate to high GAM values, which indicate the potential for genetic improvement through selection.

The high heritability and GAM for seed yield are particularly encouraging, as this is a key trait for black cumin production. Selection for increased seed yield, along with other desirable traits such as plant height and branch number, could lead to significant improvements in overall productivity. However, the relatively low heritability of oil content suggests that selection for this trait may be less effective. Environmental factors may play a greater role in determining oil content and strategies for optimizing growing conditions may be necessary to improve this trait. Based on the classification (17) (low: 0-10 %, moderate: 10-20 %, high: > 20 %), branches per plant, pods per plant and seed yield showed high genetic advance, while days to flowering, plant height, seeds per pod and oil content exhibited moderate genetic advance. Correlation and path coefficient analysis in black cumin accessions could provide further insights into the relationships between yield and yield-related components, aiding in the development of effective breeding strategies (31) .

The observed correlations between different agronomic traits provide insights into the relationships between these traits and their potential influence on seed yield. The correlation between days to flowering and seed yield indicates that early-flowering varieties may be associated with higher seed yields. However, it's important to note that if early flowering leads to an increase in yield, it would suggest a negative correlation numerically and this relationship should be examined with care. This could be attributed to a longer growing season, allowing for greater biomass accumulation and seed production. The correlation studies in the yield components of black cumin (32). The strong positive correlations between plant height, branch number, pods per plant, seeds per pod and seed yield indicate that these traits are closely related and contribute to overall seed production. These findings are consistent with the research of, which established a positive correlation between black cumin seed yield and several plant characteristics, including plant height, the number of capsules per plant, the number of primary branches per plant and the number of seeds per capsule (33). Taller plants with more branches tend to have more pods and seeds, ultimately leading to higher seed yields. These findings suggest that selection of these traits could be an effective strategy for improving seed yield in black cumin. The genetic parameters of variation for seed yield and its component traits in black gram (34, 35). While not directly related to black cumin, this study may offer insights into the genetic basis of yield components in related legume species. The lack of correlation between oil content and other measured traits suggests that oil content is independently regulated and may not be directly influenced by factors affecting plant growth and seed production. This implies that breeding efforts focused on improving oil content may need to consider specific selection criteria independent of yield-related traits.

Conclusion

This study revealed significant variability in agronomic traits and genetic parameters among black cumin varieties, highlighting their inherent genetic diversity. Since variability serves as a valuable resource for future breeding programs focused on crop improvement. Notably, seed yield was consistently higher in Dalbo than in Taba across all varieties. The estimation of genetic components provided valuable insights into the genetic diversity present, further emphasizing its potential for crop improvement. Most agronomic traits examined showed a significant positive correlation with seed yield, underscoring their importance in determining yield potential. Among the varieties evaluated, Darbera, Silingo and Dershaye demonstrated superior seed yield in Dalbo, whereas Dershaye, Darbera and Kenna excelled in Taba. Notably, Darbera and Dershaye emerged as high-yielding and adaptable varieties, with consistent performance across both locations. Therefore, these two varieties hold strong potential for wider cultivation in Dalbo and Taba and other similar agroecological zones within the Wolaita zone. Furthermore, the study underscores the importance of understanding the interplay between varietal performance and environmental factors for optimizing black cumin production in different agroecological zones. Future research should focus on evaluating the long-term performance and adaptability of these promising varieties under diverse environmental conditions and management practices.

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Authors' contributions

AN and DM contributed to the design of the research proposal, fieldwork, data collection, analysis and interpretation of the data using SAS software version 9.20 and writing the manuscript. GL and AS assisted in the analysis and interpretation of the data and also in writing the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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