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Phenotypic associations reveal sesame genotypes with high yield and shattering tolerance

Fenotipik ilişkiler, yüksek verim ve dökülmeye dayanıklılığa sahip susam genotiplerini ortaya koyar

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ABSTRACT

Sesame production is significantly hindered by seed shattering, which causes substantial yield loss. Breeding programs increasingly prioritize developing shatter-resistant cultivars, but success depends on understanding the relationship between shattering and key agronomic traits. This study investigated the correlations between shattering and various morphological and yield-related characteristics in 64 sesame genotypes, arranged in an 8 x 8 simple lattice design. The analysis revealed a significant positive correlation between shattering and both the duration from capsule opening to maturity and the length of capsule cracking. Conversely, shattering was negatively correlated with seed yield traits such as plant height and number of branches, indicating that taller, more branched plants are more shatter-resistant. Overall, shattering-related traits showed a strong negative association with yield-related morphological traits. Principal Component Analysis (PCA) of the data provided critical insights, with the first four principal components accounting for 72.90% of the total variation. Seed yield and its related traits were the primary contributors to PC1, while capsule length, shattering percentage, and days to maturity loaded heavily on PC2, confirming distinct genotypic differences. This analysis helped identify promising high-yielding, low-shattering varieties, such as AsARC-acc-SG-013. Furthermore, cluster analysis segregated the 64 genotypes into two distinct groups. Cluster I (40.62% of genotypes) was superior for desirable traits, including greater plant height, more branches and capsules, a longer capsule-bearing zone, higher seed yield, and lower shattering. These findings advocate for selecting genotypes from Cluster I, which combine reduced shattering with high-yield potential, to guide future sesame breeding programs.

Key Words: Capsule-opening; correlation coefficient; cluster analysis; principal component analysis; seed retention

ÖZ

Susam üretimi, kapsüllerin olgunluk döneminde tohumlarını kolayca dökmesi (shattering) nedeniyle önemli ölçüde sınırlanmakta ve bu durum ciddi verim kayıplarına yol açmaktadır. Bu nedenle ıslah programlarında dökülmeye dayanıklı çeşitlerin geliştirilmesi giderek daha fazla önem kazanmakta olup, bu hedefe ulaşılabilmesi dökülme özelliği ile temel agronomik karakterler arasındaki ilişkilerin ortaya konulmasına bağlıdır. Bu çalışmada, 8 × 8 basit kafes deneme deseninde düzenlenen 64 susam genotipinde dökülme ile çeşitli morfolojik ve verim unsurları arasındaki ilişkiler incelenmiştir. Yapılan korelasyon analizleri, dökülme ile kapsül açılmasından fizyolojik olgunluğa kadar geçen süre ve kapsül çatlama uzunluğu arasında pozitif ve anlamlı bir ilişki bulunduğunu göstermiştir. Buna karşılık dökülme, bitki boyu ve dal sayısı gibi verimle ilişkili bazı özelliklerle negatif korelasyon göstermiştir. Bu durum, daha uzun boylu ve daha fazla dallanan bitkilerin dökülmeye karşı daha dayanıklı olabileceğini ortaya koymaktadır.

Genel olarak, dökülme ile ilişkili özelliklerin verimle bağlantılı morfolojik karakterlerle güçlü bir negatif ilişki sergilediği belirlenmiştir.
Verilere uygulanan Temel Bileşenler Analizi (Principal Component Analysis, PCA) sonucunda ilk dört temel bileşenin toplam varyasyonun %72,90'ını açıkladığı belirlenmiştir. Tohum verimi ve buna bağlı özellikler birinci temel bileşene (PC1) en yüksek katkıyı sağlarken, kapsül uzunluğu, dökülme oranı ve olgunlaşma süresi ikinci temel bileşen (PC2) üzerinde yüksek yük değerleri göstermiştir. Bu sonuçlar, incelenen genotipler arasında belirgin farklılıkların bulunduğunu doğrulamaktadır. Analizler sonucunda AsARC-acc-SG-013 genotipi, yüksek verim ve düşük dökülme özelliğini birlikte taşıyan ümitvar bir materyal olarak öne çıkmıştır. Ayrıca gerçekleştirilen kümeleme analizi, 64 genotipi iki ana gruba ayırmıştır. Genotiplerin %40,62'sini içeren I. küme; daha yüksek bitki boyu, daha fazla dal ve kapsül sayısı, daha uzun kapsül taşıyan bölge, daha yüksek tohum verimi ve daha düşük dökülme oranı gibi arzu edilen özellikler bakımından üstün bulunmuştur. Elde edilen bulgular, yüksek verim potansiyeli ile düşük dökülme özelliğini bir arada bulunduran I. kümede yer alan genotiplerin seçiminin, gelecekte yürütülecek susam ıslah programlarına önemli katkılar sağlayabileceğini göstermektedir.

Anahtar Kelimeler: *Kapsül açılması, korelasyon katsayısı, kümeleme analizi, temel bileşenler analizi, tohum tutma yeteneği*

Introduction

Sesame (*Sesamum indicum L.*, 2n=26) is an important oilseed crop whose cultivation is constrained by various genetic and environmental factors. A major genetic limitation to yield is seed shattering, where mature capsules dehisce, releasing seeds and causing significant pre- and post-harvest losses. These losses range from 50–90% in shattering cultivars to 30–50% in non-shattering types (Qureshi et al. ,2022), with shattering alone capable of reducing yield by up to 50% (Ahmed et al., 2023). This phenomenon, governed by genetic, environmental, and agronomic factors [Ahmed et al., 2023; Mainty et al., 2021), adversely affects farmer income and threatens food security.

Addressing this yield loss requires integrated strategies, including the development of shatter-resistant cultivars through targeted breeding, optimized harvest timing, and improved agronomic practices like paclobutrazol application [Ahmed et al., 2023; Mahmood et al., 2021). Sesame breeders are consequently focused on developing varieties with reduced shattering as a key breeding objective (Qureshi et al., 2022). However, sesame improvement for shattering resistance should not be in the sacrifice of seed yield. A critical step in this process is understanding the morphological traits associated with shattering, which allows breeders to precisely select for or modify these characteristics. Effective breeding programs must therefore not only aim for a low shattering degree but also for high yield, necessitating the selection of genotypes with a favorable combination of traits that positively influence both.

Multivariate statistical methods are powerful tools for identifying trait associations and selecting key characteristics for crop improvement (Visioni et al., 2013; Almeida et al., 2014). For instance, correlation analysis has been used to identify traits for frost tolerance in barley (Visioni et al., 2013) and to elucidate yield-related trait relationships in maize (Almeida et al., 2014). In sesame, morphological traits such as capsules per plant, capsule-bearing zone length, and plant height are known to contribute to seed yield (Wang et al., 2024). Breeding for these traits could simultaneously enhance yield and minimize shattering. Furthermore, Principal Component Analysis (PCA) is widely used to reduce data dimensionality by transforming original variables into uncorrelated principal components (Jolliffe, 2002; Shlens, 2014). In plant breeding, PCA is applied to evaluate genetic diversity (Singh et al., 2016) and select yield-related traits (Gedifew, 2022). Cluster analysis is also employed to classify germplasm based on key traits to identify superior genotypes.

Therefore, this study was conducted to: (i) to determine the relationships between seed shattering and seed yield-related morphological traits; (ii) identify key traits for shattering resistance; and (iii) classify genotypes through multivariate analysis to highlight candidates for breeding programs.

Material and Methods

Plant Materials and Experimental Design

The study utilized 64 sesame genotypes (Table 1) as plant material. The experiment was conducted at the Pawe Agricultural Research Center (PARC) during the 2019 cropping season. A simple lattice design (8 x 8) was employed, and all recommended agronomic practices were followed.

Data Collected

Data were collected from both non-destructive and destructive sampling at plot, plant, and capsule bases. On a plot basis, the Days to 90% maturity (DM) and the days to the first capsule opening (DFCO) were recorded. Capsule ripening uniformity was assessed by calculating DM–DFCO, the interval between first capsule opening and 90% maturity. The following agronomic traits were measured from five randomly selected plants per plot: plant height (PH), height to the first branch (PHFB), length of the capsule-bearing zone (LCBZ), number of branches per plant (BPP), number of capsules on the main stem (NCMS), total number of capsules per plant (CPP), and the number of opened capsules per plant (OCPP). The percentage of opened capsules per plant (POCPP) was derived using the formula:

$$POCPP = \left(\frac{OCPP}{CPP}\right)100$$

Capsule morphology was assessed by measuring the length (CL) and width (CW) of five randomly chosen unopened capsules from the middle of the main stem. For opened capsules, the length of the opened capsule (LOC) and the length of the capsule cracking (LCOC) were recorded on five capsules. The percentage of cracking on opened capsules (PCOC) was then calculated as:

$$PCOC = \left(\frac{LCOC}{LOC}\right)100$$

Seed yield per plant (SYPP) was determined as the average seed yield from the five randomly selected plants.

Data from destructive sampling included quantifying seed shattering from opened capsules. The number of seeds dropped per opened capsule (SDPOC) was determined by counting the empty seed holes in five opened capsules. Furthermore, the number of seeds released upon inverting the capsule downward (SDPOCI) and the number of seeds still retained within it (SRPOC) were counted. The percentage of shattering (Sh) per opened capsule was subsequently calculated using the following formula:

$$Sh = \left(\frac{SDPOC + SDPOCI}{SDPOC + SDPOCI + SRPOC}\right)100$$

Table 1. List of the plant materials employed in the experiment.

GenNo	Genotype	GenNo	Genotype	GenNo	Genotype	GenNo	Genotype
1	EBI17697	17	EBI28320	33	AsARC-acc-SA-017	49	KG-012 (2)
2	EBI17702	18	EBI202514	34	AsARC-acc-SA-019	50	MG-012 (1)
3	EBI17703	19	EBI207957	35	AsARC-acc-SA-020	51	MG-012 (2)
4	EBI17704	20	Abasena	36	AsARC-acc-SA-022	52	MT-023 (1)
5	EBI17708	21	AsARC-acc-S-001	37	AsARC-acc-SG-005	53	MT-075 (1)
6	EBI23548	22	AsARC-acc-S-003	38	AsARC-acc-SG-013	54	Setit-1
7	EBI23565	23	AsARC-acc-S-004	39	AsARC-acc-SG-018	55	Setit-2
8	EBI28301	24	AsARC-acc-S-006	40	GK-012 (1)	56	TM-023 (2)
9	EBI28302	25	AsARC-acc-S-010	41	GK-012 (2)	57	TZ-013 (1)
10	EBI28303	26	AsARC-acc-S-022	42	GM-012 (1)	58	TZ-013 (2)
11	EBI28304	27	AsARC-acc-SA-002	43	GM-012 (2)	59	TZ-054 (1)
12	EBI28306	28	AsARC-acc-SA-007	44	Gondar-1	60	TZ-054 (2)
13	EBI28308	29	AsARC-acc-SA-008	45	HM-012 (1)	61	ZT-013 (1)
14	EBI28309	30	AsARC-acc-SA-009	46	HM-012 (2)	62	ZT-013 (2)
15	EBI28316	31	AsARC-acc-SA-011	47	Humera-1	63	ZT-054 (1)
16	EBI28318	32	AsARC-acc-SA-016	48	KG-012 (1)	64	ZT-054 (2)

Statistical Analysis

Genotype means for all traits were subjected to Pearson correlation analysis using the metan R package (Oliveto and Lucio , 2020) in R software version 4.2.2 (R Core Team, 2022). The relationships between traits were visualized with scatter plots generated by the ggpubr package (Kassambara, 2023). A correlation heatmap was constructed to depict the associations among seed yield-related morphological traits, shattering, and shattering-related traits using the 'plot' function applied to a 'corr_coef' object.

Principal Component Analysis (PCA) was performed with the 'prcomp' function in R. The factoextra package (Kassambara and Mundt, 2016) was used to create a scree plot of eigenvalues, a biplot of individuals and variables, and to assess the contribution of individuals and variables to the principal components. Following Kaiser's rule (Kaiser, 1960), principal components with eigenvalues greater than 1 were retained.

For hierarchical clustering, a distance matrix was computed using squared Euclidean distance via the 'dist' function. Genotypes were clustered into distinct groups using the complete linkage method with the 'hclust' and 'plot' functions. The optimal number of clusters was determined by identifying the elbow point on a scree plot generated by the fviz_nbclust function from the factoextra package (Kassambara and Mundt, 2016). Finally, cluster means were calculated to characterize the genotypes in each group based on the studied traits.

Results and Discussion

Correlation Analysis

Shattering is a highly detrimental trait in sesame, leading to substantial yield losses both pre- and during harvest. The relationships between shattering and associated traits are illustrated in Figure 1. The analysis revealed a significant positive correlation between shattering (Sh) and the duration from the first capsule opening to maturity (DM-DFCO) (r = 0.30*) and with the length of cracking on opened capsules (PCOC) (r = 0.28*). A non-significant positive correlation was also found between shattering and the percentage of opened capsules per plant (POCPP) (r = 0.15^{ns}).

Among the shattering-related traits themselves, DM-DFCO showed non-significant positive correlations with both PCOC (r = 0.05^{ns}) and POCPP (r = 0.22^{ns}). Similarly, a non-significant positive correlation was observed between PCOC and POCPP (r = 0.20^{ns}). These findings indicate that a longer period between the first capsule opening and full maturity, as well as a greater crack length on capsules, are significant contributors to shattering. An extended maturation period causes seeds to drop from the lower capsules while waiting for the upper ones to mature. Therefore, to reduce losses, harvesting is recommended when the lower capsules are dry and begin to rupture, even if it means sacrificing some yield from the upper plant (Qureshi et al., 2022). Although the percentage of opened capsules per plant (POCPP) showed only a minor association with shattering in this study, it does not preclude significant overall yield loss. This is because shattering was quantified per opened capsule, not on a per-plant basis. In conclusion, breeding efforts should focus on developing sesame genotypes with a shorter capsule maturity period, reduced capsule cracking, and fewer opened capsules at maturity to effectively minimize yield loss from shattering.

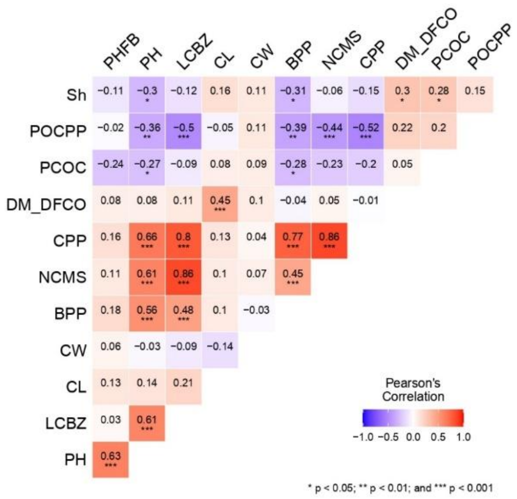

Figure 1. A correlation heatmap illustrating the relationships among seed yield-related morphological traits, shattering, and shattering-related traits.

Figure 2 shows the relationships between seed yield per plant (SYPP) and various morphological traits. SYPP showed highly significant positive correlations with plant height (r = 0.60***), length of the capsule-bearing zone (LCBZ) (r = 0.79***), number of branches per plant (BPP) (r = 0.69***), number of capsules on the main stem (NCMS) (r = 0.82***), and total capsules per plant (CPP) (r = 0.91***). In contrast, traits including plant height to first branch (PHFB) (r = 0.084^{ns}), capsule length (CL) (r = 0.21^{ns}), and capsule width (CW) (r = 0.081^{ns}) showed non-significant positive correlations with yield. These findings align with previous studies (Khairnar and Monpara, 2013; Abate et al., 2015; Abhijatha et al., 2017) that reported a significant correlation between capsule number and sesame yield. Similarly, strong positive phenotypic correlations have been observed between seed yield and traits like length of capsule bearing zone (LCBZ), number of capsules per plant (CPP), and number of branches per plant (BPP) (Teklu et al., 2017). Bulgarian breeding programs for mechanized harvesting also identified total capsules per plant and capsules on the main stem as the most critical traits for yield optimization (Georgiev et al., 2008). Therefore, indirect selection for PH, LCBZ, BPP, NCMS, and CPP is a viable strategy for enhancing sesame seed yield. However, when selecting for these high-yield traits, it is crucial to consider their association with undesirable characteristics like shattering.

A primary objective of this study was to investigate the relationship between shattering and seed yield-related traits (Figure 1). As Shattering (Sh) demonstrated a significant negative correlation with plant height (r = -0.30*) and BPP (r = 0.31*). Non-significant negative correlations were found between shattering and PHFB (r = -0.11^{ns}), LCBZ (r = -0.12^{ns}), NCMS (r = -0.06^{ns}), and CPP (r = -0.15^{ns}). A non-significant positive correlation was observed for capsule length (r = 0.16^{ns}) and width (r = 0.11^{ns}). Furthermore, key shattering-related traits showed significant negative correlations with high-yield morphological traits. The percentage of opened capsules per plant (POCPP) correlated negatively with PH (r = -0.36**), LCBZ (r = -0.50***), BPP (r = -0.39**), NCMS (r = -0.44***), and CPP (r = -0.52***).

The percentage of cracking on opened capsules (PCOC) exhibited a significant negative correlation with PH (r = -0.27*) and BPP (r = -0.28*), and non-significant negative correlations with PHFB (r = -0.24^{ns}), LCBZ (r = -0.09^{ns}), NCMS (r = -0.23^{ns}), and CPP (r = -0.20^{ns}).

This investigation established a significant negative correlation between shattering and both plant height and branch number, indicating that taller, more branched genotypes are less prone to shattering. While not statistically significant, negative trends were also observed between shattering and yield morphological traits, including the length of the capsule-bearing zone and the number of capsules per plant. Genotypes with minimal shattering (evidenced by a low proportion of opened capsules and minimal cracking length) were consistently associated with this high-yielding morphology. The consistent inverse relationship between yield traits and shattering suggests that selecting for low shattering in partially shattering populations does not negatively impact seed yield. This is a critical advantage over completely non-shattering, indehiscent lines, which were found to have lower yields and undesirable traits, making them less suitable for cultivation. The authors argue that the gene conferring indehiscence is likely linked to pleiotropic effects that reduce productivity (Qureshi et al., 2022).

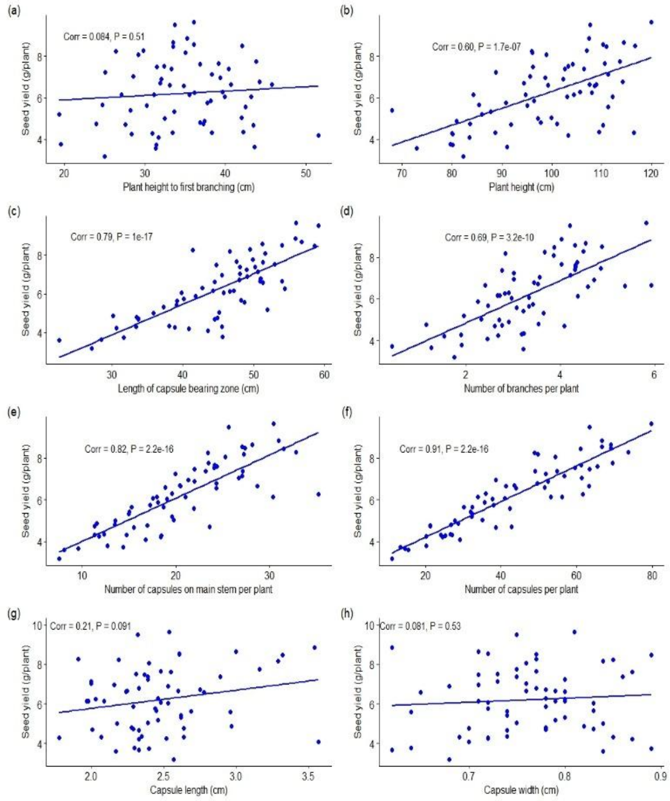

Figure 2. Relationships of yield and its related traits and their correlation coefficient values.

Principal Component Analysis

Principal Component Analysis (PCA) of 64 sesame genotypes reduced the data dimensionality to four principal components (eigenvalue >1), which collectively explained 72.9% of the total variation (Kaiser, 1960). PC1, accounting for 39% of the variance, was primarily defined by high negative loadings from key yield-related traits: number of capsules per plant (-0.42), seed yield per plant (-0.40), and other components like plant height and branch number (Table 2). This aligns with previous studies linking PC1 to plant architecture and yield (Gedifew, 2022; Ercan et al., 2002; Furat and Uzun, 2010; Mukhthambica et al., 2023). Conversely, PC2 was associated with shattering-related traits, including days to maturity (0.57), percent shattering (0.49), and capsule length (0.49). The PCA thus reinforces the correlation analysis by visually segregating high-yielding genotypes (associated with PC1's yield traits) from those with high shattering (associated with PC2), confirming their inverse relationship (Arriel et al., 2007).

Table 2. Eigenvalues and score load of original variables to the principal component

	Principal components			
	PC1	PC1	PC1	PC1
Eigenvalues	5.10	1.80	1.50	1.20
Variance Proportion (%)	39	13.70	11.30	8.90
Cumulative Variance (%)	39	52.70	64	72.90
Plant height	-0.35	-0.04	0.36	-0.07
Plant height to first branch	-0.12	-0.04	0.68	-0.18
Length of capsule bearing zone	-0.38	0.15	-0.18	0.09
Capsule length	-0.08	0.49	0.21	0.41
Capsule width	0.01	0.12	-0.04	-0.84
Number of branches per plant	-0.34	-0.11	0.05	0.01
Number of capsules on the main stem per plant	-0.39	0.11	-0.14	-0.12
Number of total capsules per plant	-0.42	0.04	-0.12	-0.08
Seed yield per plant	-0.40	0.10	-0.19	-0.07
Number of days from first capsule opening to maturity	0.00	0.57	0.27	0.03
Cracking on opened capsule (%)	0.13	0.31	-0.33	-0.08
Number of opened capsules per plant (%)	0.27	0.15	0.22	-0.19
Shattering (%)	0.12	0.49	-0.16	-0.12

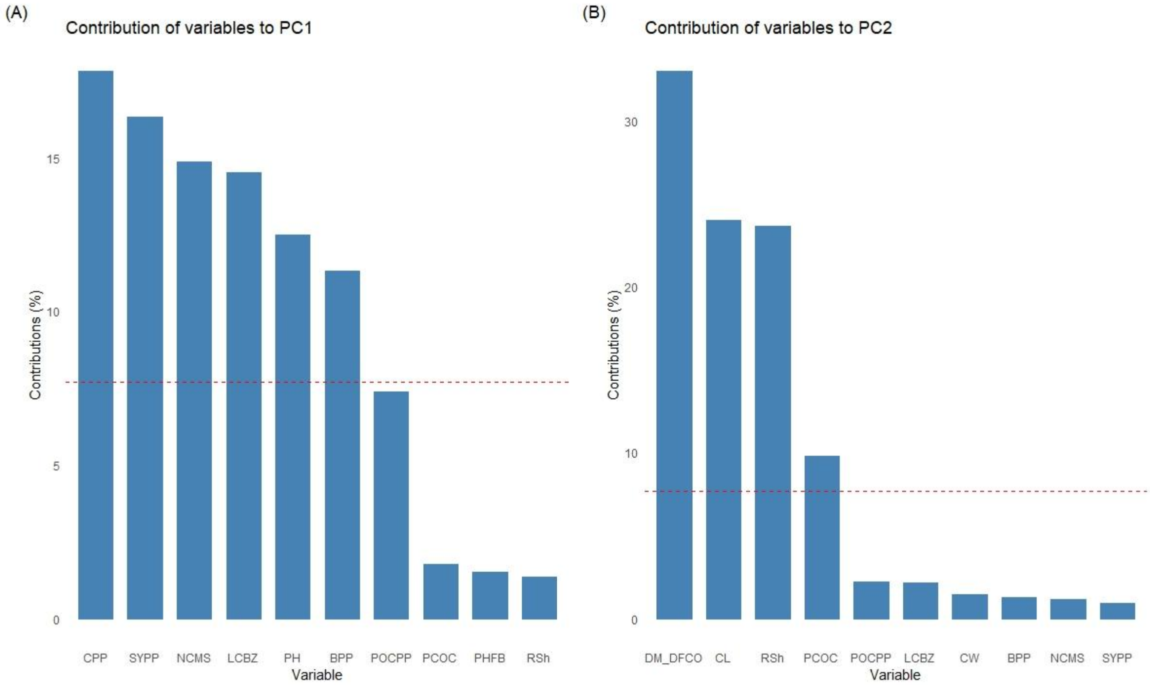

Figure 3. Graph anticipating the contributions of variables to PC1 (A) and PC2 (B)

The first principal component (PC1) clearly separated the sesame genotypes based on a key trade-off: high negative loadings for yield-related traits versus high positive loadings for shattering-related traits (e.g., percent cracking and opened capsules). This reinforces the inverse relationship between yield and shattering. Genotypes like KG-012(1) and Setit-2, with high positive PC1 scores, were high-shattering, low-yielding types. Conversely, genotypes such as AsARC-acc-SG-013 and Gondar-1, with high negative PC1 scores, were low-shattering and high-yielding (Figure 5). This clear separation demonstrates that selection based on PC1 loadings is an effective strategy for breeders to exploit variability and identify genotypes with desirable, coupled characteristics (Akbar et al., 2011; Mukhthambica et al., 2023).

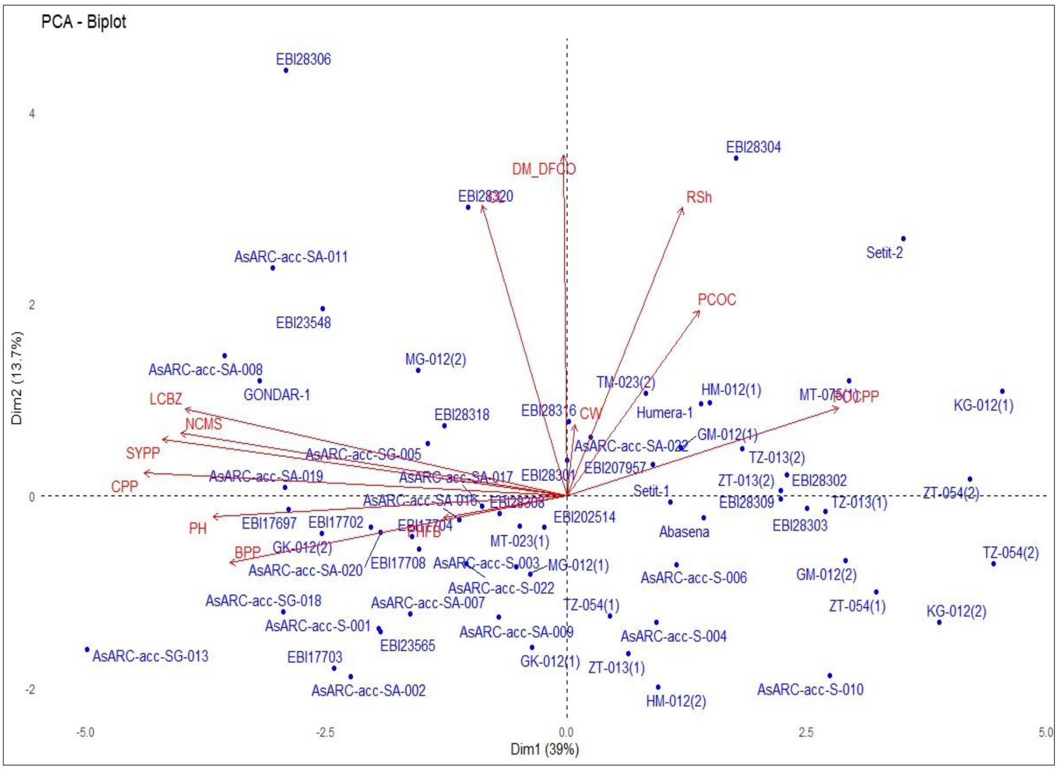

Figure 4. Principal component biplot of variables and sesame genotypes (PC1 vs PC2)

The analysis of genotype contributions to the principal components (Figure 5) identified key candidates for breeding. AsARC-acc-SG-013 was the foremost contributor to PC1, a component associated with high yield and low shattering, making it a premier candidate for selection. In contrast, genotypes EBI28306, EBI28304, and EBI28320 were the main contributors to PC2, which is related to other trait complexes. The significant phenotypic variation confirmed among the genotypes presents a valuable opportunity for genetic gain through strategic selection. These findings collectively underscore that elucidating the relationship between yield and shattering is fundamental for directing breeding efforts toward superior sesame varieties with improved seed yield and reduced losses.

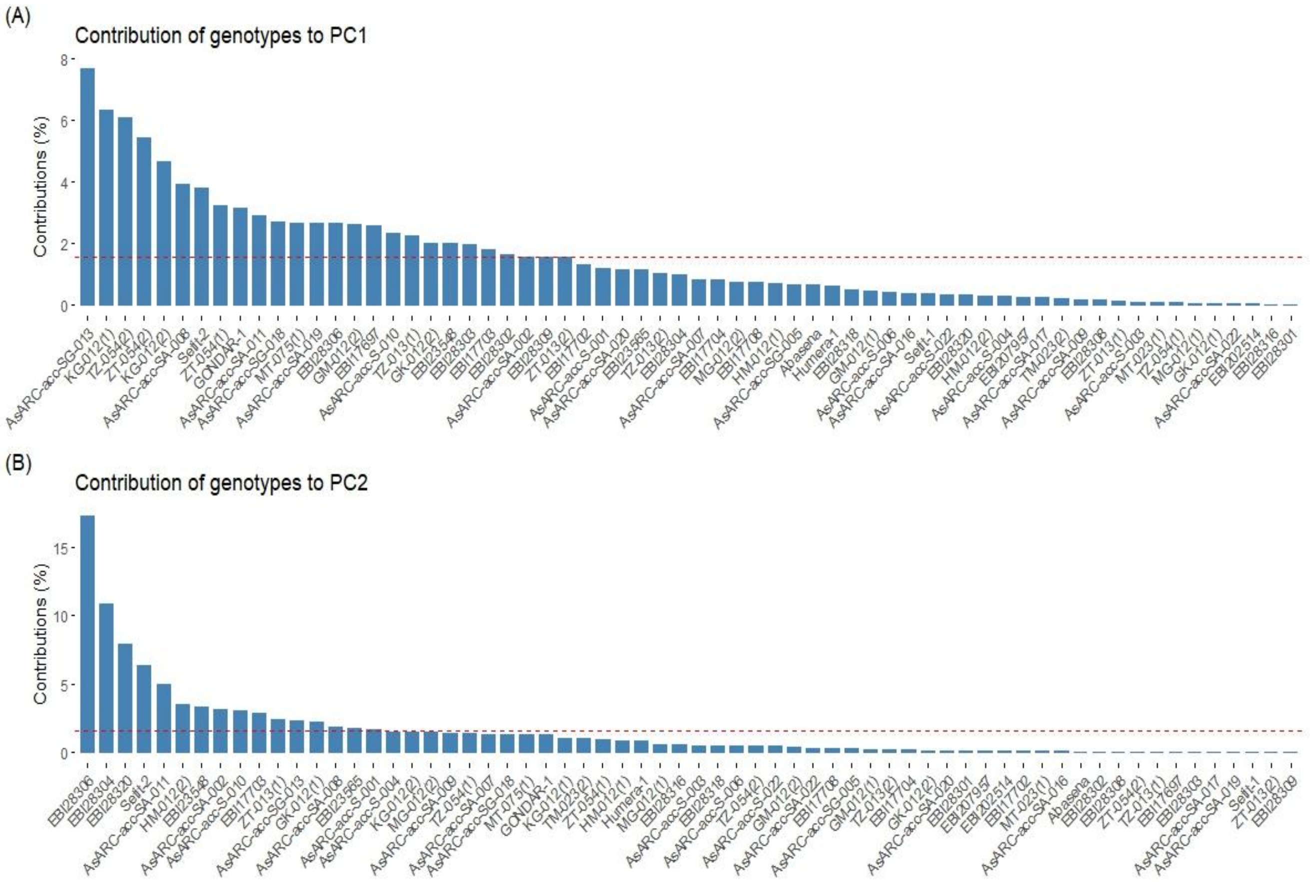

Figure 5. Graph anticipating the contributions of sesame genotypes to PC1 (A) and PC2 (B)

The cluster analysis indicated that the 64 sesame genotypes are best classified into two distinct clusters, a finding supported by the scree plot of within sum of squares. The circular dendrogram (Figure 6) and cluster membership (Table 3) show a relatively even distribution, with 40.62% of genotypes in Cluster I and 59.38% in Cluster II. This clear bifurcation suggests the existence of two primary patterns of trait variation within the population. The analysis provides a framework for understanding genetic relationships and dissimilarities, which is directly applicable to breeding. By identifying the traits that characterize each cluster, researchers can pursue more informed selection to combine desirable genes, thereby leveraging cluster analysis as a proven method for evaluating productivity enhancement (Bandila et al., 2011).

Table 3. Pattern of clustering of 64 sesame genotypes based on 13 quantitative traits grown at Pawe

Cluster	List of genotypes	Number of genotypes
I	EBI17697, EBI17702, EBI17703, EBI17704, EBI17708, EBI23548, EBI23565, EBI28306, EBI28318, AsARC-acc-S-001, AsARC-acc-S-003, AsARC-acc-S-022, AsARC-acc-SA-002, AsARC-acc-SA-007, AsARC-acc-SA-008, AsARC-acc-SA-009, AsARC-acc-SA-011, AsARC-acc-SA-017, AsARC-acc-SA-019, AsARC-acc-SA-020, AsARC-acc-SG-013, AsARC-acc-SG-018, GK-012(1), GK-012(2), Gondar-1, MG-012(2)	26
II	EBI202514, EBI207957, EBI28301, EBI28302, EBI28303, EBI28304, EBI28308, EBI28309, EBI28316, EBI28320, Abasena, AsARC-acc-S-004, AsARC-acc-S-006, AsARC-acc-S-010, AsARC-acc-SA-016, AsARC-acc-SA-022, AsARC-acc-SG-005, GM-012(1), GM-012(2), HM-012(1), HM-012(2), Humera-1, KG-012(1), KG-012(2), MG-012(1), MT-023(1), MT-075(1), Setit-1, Setit-2, TM-023(2), TZ-013(1), TZ-013(2), TZ-054(1), TZ-054(2), ZT-013(1), ZT-013(2), ZT-054(1), ZT-054(2)	38

Cluster analysis revealed two distinct groups of sesame genotypes defined by key quantitative traits (Table 4). Cluster I was characterized by superior agronomic performance, exhibiting significantly greater plant height, branch number, capsule production, and seed yield. Critically, this cluster also demonstrated better seed retention, with lower percentages of shattering, opened capsules, and capsule cracking. In contrast, Cluster II was defined by inferior traits, including dwarf stature, lower yield components, and higher seed shattering, which poses challenges for harvest efficiency. These results confirm that branch number, capsule count, and seed yield are key discriminators between sesame clusters (Gedifew, 2022; Abate et al., 2015). For breeding, genotypes in Cluster I represent ideal candidates for selection to develop more productive and shattering-resistant varieties.

Table 4. Cluster means for seed yield-related morphological traits, shattering, and shattering-related traits

Trait	Cluster	
	I	II
Plant height (cm)	106.22	93.54
Plant height to first branching (cm)	35.34	34.18
Length of capsule bearing zone (cm)	50.67	40.63
Capsule length (cm)	2.50	2.45
Capsule width (cm)	0.77	0.76
Branches per plant	4.13	2.79
Number of capsules on the main stem	26.08	16.78
Capsule per plant	60.23	31.60
Seed yield per plant (g)	7.68	5.19
Days from first capsule opening to days to 90% maturity	3.19	3.62
Percentage of cracking on opened capsule (%)	27.86	32.10
Percentage of opened capsules per plant (%)	11.01	23.50
Shattering (%)	47.99	53.43

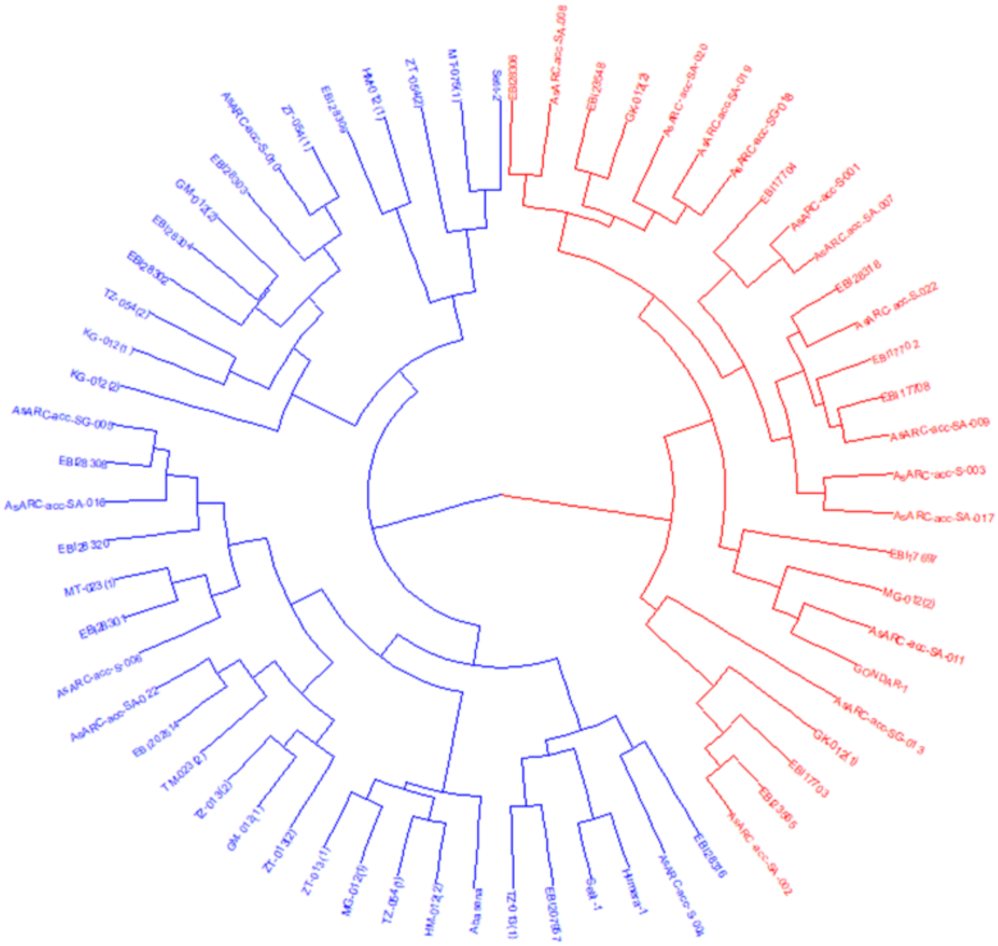

Figure 6. Agglomerative hierarchical clustering of 64 sesame genotypes based on 13 quantitative traits of sesame: Red-colored (Cluster I) & blue-colored (Cluster II)

Conclusion

The study concludes that mitigating seed shattering is crucial for reducing yield losses in sesame. A central finding was the consistent inverse relationship between shattering and yield potential, revealed through multiple analyses. Genotypes with low shattering were consistently those with high-yielding characteristics: tall plant height, numerous branches, and a high number of capsules. The PCA visualized this trade-off, with PC1 clearly separating high-shattering/poor-yield genotypes (KG-012(1)) from low-shattering/high-yield genotypes (AsARC-acc-SG-013). This was validated by cluster analysis, which grouped genotypes with superior yield architecture and better seed retention together. Therefore, selection for these complementary agronomic traits offers a viable strategy for developing high-yielding, shatter-resistant sesame varieties. In general, these findings indicate that breeding programs should focus on multi-trait selection strategies, integrating shattering resistance with agronomic performance to accelerate the development of resilient, high-yielding sesame cultivars.

However, the results of this study should be validated through molecular trait profiling of the genotypes and by further examining the associations between shattering and yield-related traits.

Declaration of competing interest

The authors have declared no competing interests.

Authors' Contribution

Sintayehu Gedifew was responsible for selection of the research topic, conducting an experiment, data collection and analysis, writing and submitting the manuscript. Askalech Bekele wrote the revised manuscript.

References

Abate, M., Mekbib, F., Ayana, A., & Nigussie, M. (2015). Genetic variability and association of traits in mid-altitude sesame (Sesamum indicum L.) germplasm of Ethiopia. American Journal of Experimental Agriculture, 9(3), 1-14.

Abhijatha A, Arya K, Madhukar K, Gogineni S (2017) Evaluation of sesame (Sesamum indicum L.) genotypes to the shaded uplands of southern region. International Journal of Current Microbiology and Applied Science 6, pp 332-339.

Ahmed, J., Qadir, G., Ansar, M., Wattoo, F. M., Javed, T., Ali, B., ... & Rahimi, M. (2023). Shattering and yield expression of sesame (Sesamum indicum L) genotypes influenced by paclobutrazol concentration under rainfed conditions of Pothwar. BMC Plant Biology, 23(1), 1-13. DOI: https://doi.org/10.1186/s12870-023-04145-7.

Akbar, F., Rabbani, M. A., Shinwari, Z. K., & Khan, S. J. (2011). Genetic divergence in sesame (Sesamum indicum L.) landraces based on qualitative and quantitative traits. Pak. J. Bot, 43(6), 2737-2744.

Almeida, G. D., Nair, S., Borém, A., Cairns, J., Trachsel, S., Ribaut, J. M., ... & Babu, R. (2014). Molecular mapping across three populations reveals a QTL hotspot region on chromosome 3 for secondary traits associated with drought tolerance in tropical maize. Molecular breeding, 34, 701-715.

Arriel, N. H. C., Di Mauro, A. O., Arriel, E. F., Unêda-Trevisoli, S. H., Costa, M. M., Bárbaro, I. M., & Muniz, F. R. S. (2007). Genetic divergence in sesame based on morphological and agronomic traits. Crop Breeding and Applied Biotechnology, 253-261.

Bandila, S., Ghanta, A., Natarajan, S., & SUBRAMONIAM, S. (2011). Determination of genetic variation in Indian sesame (Sesamum indicum) genotypes for agro-morphological traits. Journal of Research in Agricultural Science, 7 (2): 88-99.

Ercan, A. G., Taskin, K. M., Turgut, K., Bilgen, M., & Firat, M. Z. (2002). Characterization of Turkish sesame (Sesamum indicum L.) landraces using agronomic and morphologic descriptors. Ziraat Fakultesi Dergisi Akdeniz universitesi, 15(2), 45-52.

Furat, S., & Uzun, B. (2010). The Use of Agro-morphological Characters for the Assessment of Genetic Diversity in Sesame ('Sesamum indicum'L). Plant Omics, 3(3), 85-91.

Jolliffe, I. T. (2002). Principal component analysis for special types of data (pp. 338-372). Springer New York.

Gedifew, S. (2022). Characterization and evaluation of sesame (Sesamum indicum L.) accessions. International Journal of Agricultural and Natural Sciences, 15(3): 226-239.

Georgiev S, Stamatov S, Deshev M (2008) Requirements to sesame (Sesamum indicum L.) cultivars breeding for mechanized harvesting. Bulgarian Journal of Agricultural Sciences 14, pp 616-620.

Kassambara, A. (2023). ggpubr: 'ggplot2' Based Publication Ready Plots. R package version 0.6.0. URL: https://CRAN.R-project.org/package=ggpubr.

Kassambara, A, Mundt, F, (2016). Factoextra: Extract and Visualize the Results of Multivariate Data Analyses, R package version 1 (2016). https://rpkgs.datanovia.com/factoextra/index.html.

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. Educational and psychological measurement, 20(1), 141-151.

Khairnar, S. S., & Monpara, B. A. (2013). Identification of potential traits and selection criteria for yield improvement in sesame (Sesamum indicum L.) genotypes under rainfed conditions. Iranian Journal of Genetics and Plant Breeding, 2(2), 1-8.

Maity, A., Lamichaney, A., Joshi, D. C., Bajwa, A., Subramanian, N., Walsh, M., & Bagavathiannan, M. (2021). Seed shattering: a trait of evolutionary importance in plants. Frontiers in Plant Science, 12, 657773. DOI: 10.3389/fpls.2021.657773.

Mehmood, M. Z., Qadir, G., Afzal, O., Din, A. M. U., Raza, M. A., Khan, I., ... & Ahmed, M. (2021). Paclobutrazol improves sesame yield by increasing dry matter accumulation and reducing seed shattering under rainfed conditions. International journal of plant production. DOI: https://doi.org/10.1007/s42106-021-00132-w.

Mukhthambica, K., Bisen, R. and Ramya, K. T. (2023). Principal Component Analysis for Yield and Yield Related Traits in Sesame (Sesamum indicum L.). Biological Forum – An International Journal, 15(3): 227-232.

Olivoto, T., & Lúcio, A. D. C. (2020). metan: An R package for multi-environment trial analysis. Methods in Ecology and Evolution, 11(6), 783-789. DOI: https://doi.org/10.1111/2041-210X.13384.

Qureshi, M., Langham, D. R., Lucas, S. J., Uzun, B., & Yol, E. (2022). Breeding history for shattering trait in sesame: classic to genomic approach. Molecular Biology Reports, 49(7), 7185-7194. DOI: https://doi.org/10.1007/s11033-022-07636-2

R Core Team (2022) R software version 4.2.2: A language and environment for statistical computing, R foundation for statistical computing, Vienna, Austria. URL: http:// www.R-project.org.

Shlens, J. (2014). A tutorial on principal component analysis. arXiv preprint arXiv:1404.1100.

Singh, A., Ganapathysubramanian, B., Singh, A. K., & Sarkar, S. (2016). Machine learning for high-throughput stress phenotyping in plants. Trends in plant science, 21(2), 110-124.

Teklu DH, Kebede SA, Gebremichael DE (2017) Assessment of genetic variability, genetic advance, correlation and path analysis for morphological traits in sesame genotypes. International Journal of Novel Research in Life Sciences 4, pp 34-44.

Visioni, A., Tondelli, A., Francia, E., Pswarayi, A., Malosetti, M., Russell, J., ... & Comadran, J. (2013). Genome-wide association mapping of frost tolerance in barley (Hordeum vulgare L.). BMC genomics, 14, 1-13.

Wang, C., Niu, J., Miao, H., Li, C., Duan, Y., Ju, M., ... & Zhang, H. (2024). Genetic variation, correlation, and association mapping of seed yield and its component traits in sesame. Genetic Resources and Crop Evolution, 71(2), 603-619.