Modern Biology and Genetics
(International scientific journal)

2026

№2

(16)

CONTENTS

UDC 633.853.74; 581.1; 581.19

OIL, PROTEIN, AND PHOTOSYNTHETIC PIGMENT VARIATION IN FOREIGHN SESAME

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Summary. Sesame (*Sesamum indicum* L.) is a major oilseed crop valued for both its high oil content and nutritional protein. The present study evaluated variation in seed oil content, crude protein, and photosynthetic pigment composition (chlorophylls *a*, *b* and carotenoids) among 11 foreighn accessions and a local control variety Tashkentskiy-122. Oil was determined by Soxhlet extraction (GOST 10857-64), protein by the Kjeldahl method (factor 6.25), and pigments by spectrophotometry in 96% ethanol at three phenological phases. One-way ANOVA, Pearson correlation, principal component analysis (PCA), and a Combined Productivity Index (CPI) were applied. Oil content ranged from 43.76% K-598 (China) to 53.23% K-9549 (India); protein from 18.33% K-98 (Armenia) to 20.95% Tashkentskiy-122. Total chlorophyll varied from 1.48 to 1.98 mg g^{-1} f.w. All traits showed highly significant genotypic differences ($p < 0.001$). PCA revealed that pigment variation (PC1+PC2 = 73.5%) is structurally independent from seed oil-protein variation (PC3 = 15.3%), indicating that leaf photosynthetic indices cannot predict seed biochemical composition. K-1185 (Tajikistan) and K-1396 (Kenya) showed the highest CPI among foreighn accessions. The results provide a basis for targeted selection of sesame germplasm for nutritional quality improvement.

Keywords: *sesame; oil content; crude protein; photosynthetic pigments; genotypic variation; PCA; Combined productivity index.*

СОДЕРЖАНИЕ МАСЛА, БЕЛКА И ФОТОСИНТЕТИЧЕСКИХ ПИГМЕНТОВ В ЗАРУБЕЖНЫХ ОБРАЗЦАХ КУНЖУТА

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Аннотация. Кунжут (*Sesamum indicum* L.) - важная масличная культура, ценная как по содержанию масла, так и по питательному белку. В настоящей работе изучена изменчивость содержания масла, сырого белка и фотосинтетических пигментов (хлорофилл *a*, *b* и каротиноиды) у 11 зарубежных образцов и местного контрольного сорта Ташкентский-122. Масличность определяли методом Сокслета (ГОСТ 10857-64), содержание белка - методом Кьельдаля (коэффициент 6,25), пигменты - спектрофотометрически в 96% этаноле на трёх фенологических фазах. Применялись однофакторный дисперсионный анализ, корреляционный анализ Пирсона, метод главных компонент (МГК) и комплексный индекс продуктивности (КИП). Масличность варьировала от 43,76% К-598 (Китай) до 53,23% К-9549 (Индия); содержание белка - от 18,33% К-98 (Армения) до 20,95% Ташкентский-122. Сумма хлорофиллов изменялась от 1,48 до 1,98 мг/г сырой массы. Все показатели демонстрировали достоверные генотипические различия ($p < 0,001$). МГК выявил структурную независимость пигментной изменчивости (ГК1+ГК2 = 73,5%) от изменчивости биохимического состава семян (ГК3 = 15,3%). Образцы К-1185 (Таджикистан) и К-1396 (Кения) показали наибольший КИП среди зарубежных форм. Результаты создают основу для направленного отбора образцов кунжута по показателям питательной ценности.

Ключевые слова: *кунжут; масличность; сырой белок; фотосинтетические пигменты; генотипическая изменчивость; МГК; комплексный индекс продуктивности;*

INTRODUCTION

Sesame (*Sesamum indicum* L.) ranks among the oldest cultivated oilseed crops and is widely grown in tropical and subtropical regions for its high oil and protein content (Gharby et al., 2015; Li et al., 2014; Anilakumar et al., 2010). The oil fraction (45-63%) is dominated by oleic and linoleic acids with remarkable oxidative stability conferred by lignans sesamin and sesamolin (Reshef et al., 2019). The protein fraction (17-25%) comprises mainly globulins and albumins of high biological value, relevant to both nutrition and food processing (Idowu et al., 2021; Sharma et al., 2016).

Uzbekistan maintains a long tradition of sesame cultivation, with the variety Tashkentskiy-122 serving as the dominant cultivar. However, the available genetic base remains narrow, and yields are limited by soil salinity, heat stress, and water scarcity (Kalandarov & Amanova, 2023; Isabaev et al., 2024; Yusupov, 2025). Evaluating introduced germplasm accessions for biochemical quality traits is therefore a rational strategy for expanding the breeding pool (Amanova, 2012; Amanova & Rustamov, 2018).

The photosynthetic pigment apparatus - chlorophylls a and b, and carotenoids - determines the capacity for carbon fixation and photoprotection. The chlorophyll *a*/*b* ratio reflects the proportion of light-harvesting complex II (LHCII) relative to reaction centres and is a recognised indicator of light adaptation: high values characterise sun-type, low values shade-type genotypes (Boardman, 1977; Lichtenthaler & Wellburn, 1983). Carotenoids serve dual roles as accessory light-harvesting and photoprotective pigments (Demmig-Adams & Adams, 1992). Whether genotypic differences in the leaf pigment apparatus translate into variation in seed biochemical quality remains an open question in sesame, particularly across diverse introduced germplasm.

An important aspect of sesame seed composition is the well-documented inverse relationship between oil and protein content - a trade-off rooted in the competition for carbon skeletons and reductive equivalents during seed filling (Li et al., 2014). This constraint complicates simultaneous selection for both traits and underscores the need for comprehensive multi-trait evaluation frameworks. The present study aimed to (I) characterise genotypic variation in photosynthetic pigments across three phenological phases; (II) quantify seed oil and protein variation by ANOVA and LSD; (III) determine the multivariate relationship between pigment and seed quality traits by PCA; and (IV) rank accessions by a Combined Productivity Index (CPI) integrating oil and protein.

MATERIALS AND METHODS

Twelve sesame (*Sesamum indicum* L.) accessions were evaluated over three consecutive growing seasons (2023-2025) the local variety Tashkentskiy-122 (Uzbekistan) as control, and 11 introduced accessions from the gene bank of the Research institute of plant genetic resources (Kibray district, Tashkent region): K-66 (Afghanistan), K-98 (Armenia), K-119 (Iran), K-161 (Turkey), K-216 (Syria), K-221 (Israel), K-598 (China), K-1185 (Tajikistan), K-1396 (Kenya), K-9428 (Venezuela), and K-9549 (India). Field trials were conducted at the experimental station of the Research institute of plant genetic resources, Kibray district under furrow irrigation following established evaluation protocols for the world sesame collection in Uzbekistan (Amanova & Rustamov, 2018). A randomised complete block design with three replications was used. Sowing in early May, harvest in late August-early September.

Third fully expanded leaves were sampled from five representative plants per plot at budding, full flowering, and capsule formation (08:00-10:00 h). Extraction 96% ethanol (1:10 w/v, 24 h, 4°C, dark). Absorbances at 664, 649, and 470 nm. Pigment concentrations by Lichtenthaler and Wellburn (Lichtenthaler & Wellburn, 1983) equations:

$$Chl\ a = 13.36 \cdot A_{664} - 5.19 \cdot A_{649}$$
$$Chl\ b = 27.43 \cdot A_{649} - 8.12 \cdot A_{664}$$
$$Car = (1000 \cdot A_{470} - 2.13 \cdot Chl\ a - 97.64 \cdot Chl\ b) / 209$$

where A_{664}, A_{649}, A_{470} are absorbances at respective wavelengths; results expressed as mg g^{-1} fresh weight (f.w.). Chlorophyll a/b and Car/Chl (a+b) ratios were calculated as functional indices.

Oil content Soxhlet extraction with petroleum ether, expressed on dry weight basis (GOST 10857-64). Crude protein Kjeldahl method (Nielsen, 2017; GOST 13496.4-93), conversion factor 6.25. Three analytical replicates per plot, yielding nine observations per accession across three seasons.

One-way ANOVA separately for oil and protein; least significant difference $LSD_{0.05} = t(\alpha/2, df\_within) \times \sqrt{2 \cdot MSE/n}$. Pearson correlation coefficients among eight traits (Oil, Protein, Chl a, Chl b, Chl a+b, Car, Chl a/b, Car/Chl) computed on accession means (n = 12). PCA performed on standardised (z-score) data. A Combined Productivity Index (CPI) was computed as:

$$CPI = 0.6 \times Oil\_norm + 0.4 \times Protein\_norm$$

where Oil_norm and Protein_norm are min-max normalised values (range 0-1); weights 0.6 and 0.4 reflect the relative economic value of oil and protein in oilseed sesame. Coefficient of variation (CV%) within accessions and between year means assessed repeatability and interannual stability. Analyses performed in Python 3.11 (SciPy, scikit-learn).

RESULTS

Mean pigment values averaged across all three phenological phases are presented in Table 1 and Figure 1. Total chlorophyll [Chl (*a+b*)] varied from 1.48 mg g^{-1} f.w. in K-98 (Armenia) to 1.98 mg g^{-1} f.w. in K-161 (Turkey), with the control TASHKENTSKIY-122 at 1.86 mg g^{-1} f.w. K-98 and K-9549 (India) fell below the control by 20.4% and 15.1% respectively; K-161, K-66, and K-119 exceeded it by 6.5%, 4.8%, and 3.2%.

The Chl a/b ratio ranged from 1.60 (K-119, Iran) to 2.39 (K-9549, India), reflecting divergent light-adaptation strategies among accessions of different geographic origin. Carotenoid content ranged from 0.20 (K-119) to 0.29 mg g^{-1} f.w. (K-9428, K-161, K-9549), with Car/Chl ratio of 0.13-0.18.

Table 1

Photosynthetic pigment content in sesame accessions (mean ± SE, mg g⁻¹ f.w.), averaged across three phenological phases

Genotype	Country	Chl a	Chl b	Chl (a+b)	Car	Chl a/b	Car/Chl
Tashkentskiy-122	Uzbekistan	1.09±0.02	0.76±0.01	1.86±0.03	0.27±0.01	1.79	0.16
K-161	Turkey	1.30±0.03	0.68±0.02	1.98±0.04	0.29±0.01	1.97	0.15
K-66	Afghanistan	1.25±0.02	0.70±0.01	1.95±0.02	0.28±0.01	1.92	0.15
K-119	Iran	1.12±0.03	0.79±0.02	1.92±0.04	0.20±0.01	1.60	0.13
K-9428	Venezuela	1.23±0.02	0.64±0.01	1.88±0.03	0.29±0.01	2.03	0.16
K-1396	Kenya	1.20±0.03	0.60±0.01	1.81±0.04	0.27±0.01	2.13	0.16
K-598	China	1.10±0.02	0.52±0.01	1.64±0.03	0.27±0.01	2.26	0.17
K-221	Israel	1.07±0.03	0.56±0.01	1.64±0.04	0.23±0.01	2.04	0.15
K-1185	Tajikistan	1.07±0.02	0.53±0.01	1.60±0.03	0.28±0.01	2.17	0.18
K-9549	India	1.11±0.02	0.47±0.01	1.58±0.03	0.29±0.01	2.39	0.18
K-98	Armenia	1.01±0.01	0.46±0.01	1.48±0.02	0.25±0.01	2.19	0.16
K-216	Syria	1.03±0.02	0.53±0.01	1.57±0.03	0.23±0.01	1.96	0.15
$LSD_{0.05}$	**-**	**0.12**	**0.07**	**0.15**	**0.04**	**0.39**	**0.05**

$LSD_{0.05}$ values shown in the last row.

Phenological phase dynamics (Figure 4) showed two distinct patterns. Most accessions demonstrated a biphasic trajectory slight decline from budding to full flowering, followed by recovery at capsule formation - consistent with re-synthesis of chloroplasts in source leaves to sustain photosynthate supply to developing seeds.

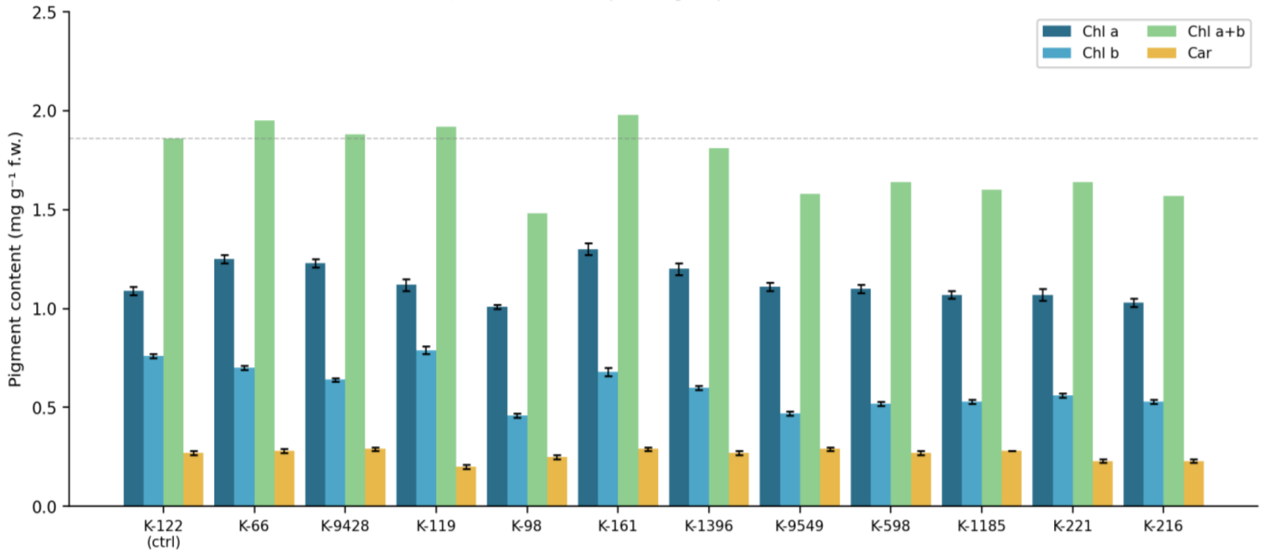


Fig. 1. Photosynthetic pigment content in sesame accessions

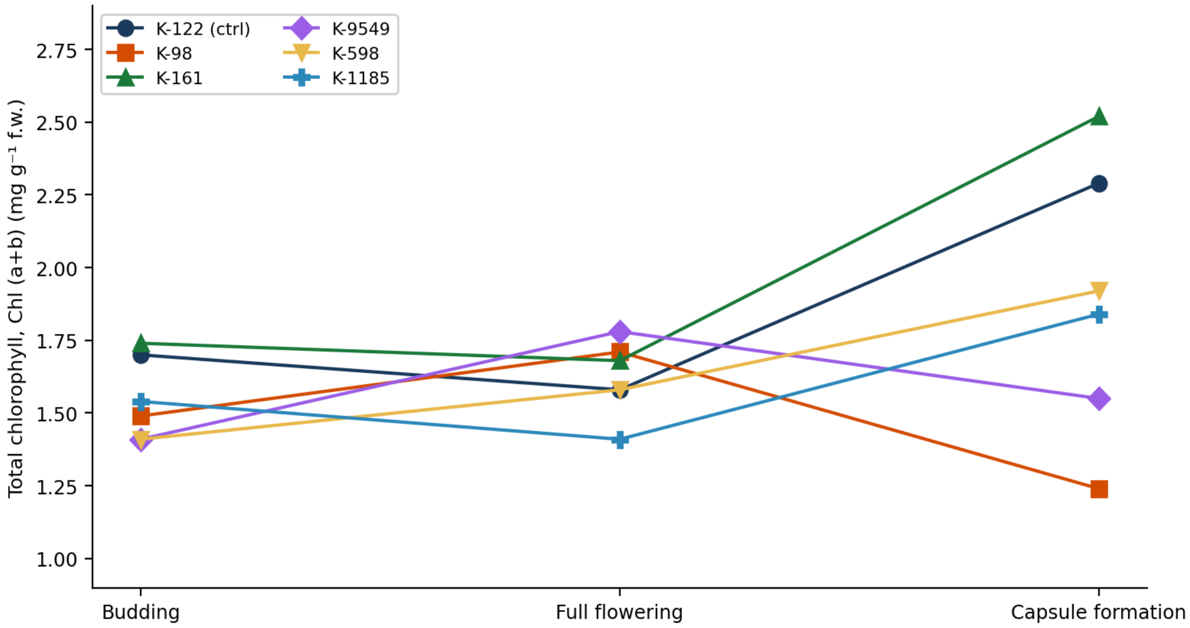


Fig. 4. Dynamics of total chlorophyll [Chl (a+b)] across phenological phases in selected sesame accessions.

K-98 (Armenia) showed a progressive monotonic decline across all three phases (1.49 → 1.71 → 1.24 mg g^{-1} f.w.), with a pronounced collapse at capsule formation, suggesting early photosynthetic senescence and accelerated nitrogen remobilisation.

Seed oil content. One-way ANOVA yielded F = 4207.7 (df = 11, 96; p < 0.001); $LSD_{0.05}$ = 0.105% (Table 2, Figure 2). Oil content ranged from 43.76±0.04% in K-598 (China) to 53.23±0.02% in K-9549 (India). K-598 was a clear outlier, departing from all other accessions by a minimum of 5.3 percentage points. Among the remaining accessions, K-9549 (+2.27%), K-1185 (+1.60%), K-1396 (+0.96%), and K-98 (+0.92%) significantly exceeded the control (50.96%). Three accessions fell significantly below K-221 (−1.90%), K-119 (−0.63%), and K-598 (−7.20%). Interannual stability was exceptional: CV between year means ranged from 0.03% (K-9549) to 0.10% (control).

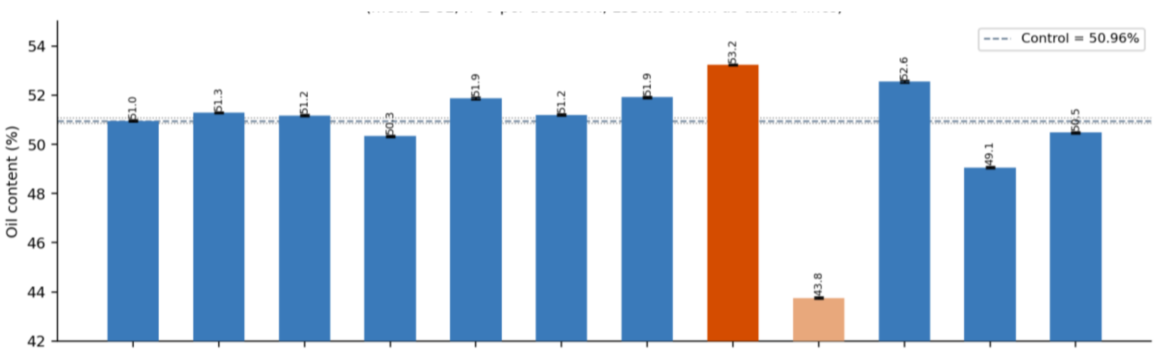
Seed protein content. ANOVA F = 323.6 (df = 11, 96; p < 0.001); $LSD_{0.05}$ = 0.129%. Protein ranged from 18.33±0.07% (K-98, Armenia) to 20.95±0.01% (control). Among introduced accessions, the highest values were recorded in K-1396 (Kenya) and K-598 (China) (both 20.37%), followed by K-1185 (Tajikistan) (20.11%). These results are consistent with crude protein variability reported for the same accession collection (Pirnazarov et al., 2026). A directional oil-protein antagonism was evident: K-9549 (highest oil, lowest protein at 18.98%); K-598 (lowest oil, joint-highest introduced protein). The oil-protein trade-off was not statistically significant at n = 12 (r = −0.21, p = 0.51), but its direction aligns with previously documented competition for carbon skeletons during seed filling (Li et al., 2014).

Table 2.

Oil and protein content in sesame accessions

Genotype	Country	Oil content, M±SE (%)	CV (%)	Protein content, M±SE (%)	CV (%)
Tashkentskiy-122	Uzbekistan	50.96±0.04	0.22	20.95±0.01	0.20
K-9549	India	53.23±0.02	0.14	18.98±0.05	0.76
K-1185	Tajikistan	52.56±0.05	0.26	20.11±0.04	0.52
K-1396	Kenya	51.92±0.04	0.20	20.37±0.04	0.56
K-98	Armenia	51.88±0.04	0.25	18.33±0.07	1.20
K-161	Turkey	51.20±0.03	0.19	19.22±0.07	1.05
K-9428	Venezuela	51.18±0.04	0.23	19.60±0.03	0.45
K-66	Afghanistan	51.29±0.04	0.21	19.16±0.03	0.53
K-216	Syria	50.48±0.04	0.23	18.61±0.08	1.24
K-119	Iran	50.33±0.04	0.22	19.52±0.03	0.38
K-221	Israel	49.06±0.04	0.22	18.55±0.02	0.33
K-598	China	43.76±0.04	0.27	20.37±0.04	0.56
$LSD_{0.05}$	-	**0.105%**	-	**0.129%**	-
F-value	-	**4207.7*****	-	**323.6*****	-

*** $p < 0.001$. $LSD_{0.05}$: *oil = 0.105%; protein = 0.129%.*



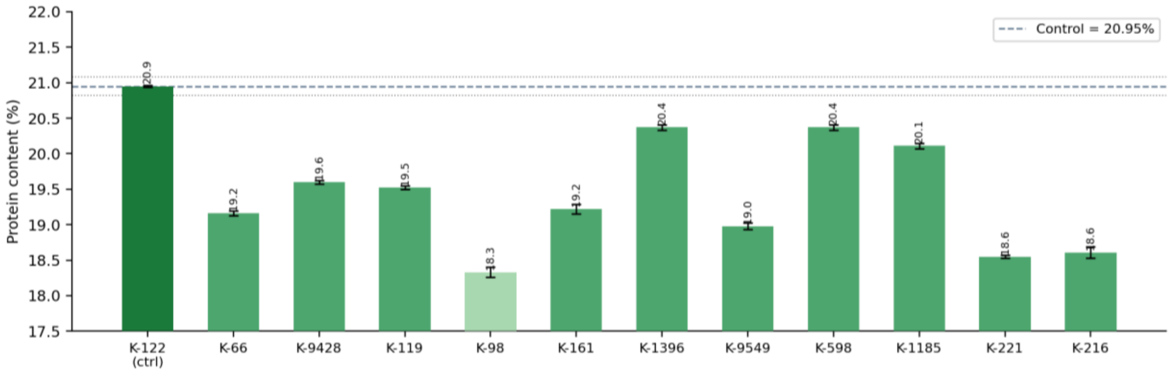


Fig. 2. (A) Oil content and (B) protein content in sesame accessions (M ± SE, n = 9). Dashed lines: control mean; dotted lines: $LSD_{0.05}$ bounds.

Multivariate analysis and Combined Productivity Index. Pearson correlation analysis revealed no statistically significant relationships between oil or protein and any pigment parameter (all $p > 0.25$). Within the pigment block, strong positive correlations were observed between Chl b and Chl (a+b) (r = +0.898) and between Chl a and Chl (a+b) (r = +0.835); the Chl a/b ratio correlated negatively with Chl b (r = −0.885), as expected arithmetically.

PCA on all eight standardised traits explained PC1 = 45.5% (Chl b and Chl a+b positive; Chl a/b and Car/Chl negative - antenna size axis); PC2 = 28.0% (Car and Chl a dominant - carotenoid axis); PC3 = 15.3% (Oil positive, Protein negative - oil-protein trade-off axis). Crucially, PC3 is structurally orthogonal to PC1 and PC2 leaf pigment traits and seed composition traits occupy independent dimensions of the total phenotypic space (Figure 3).

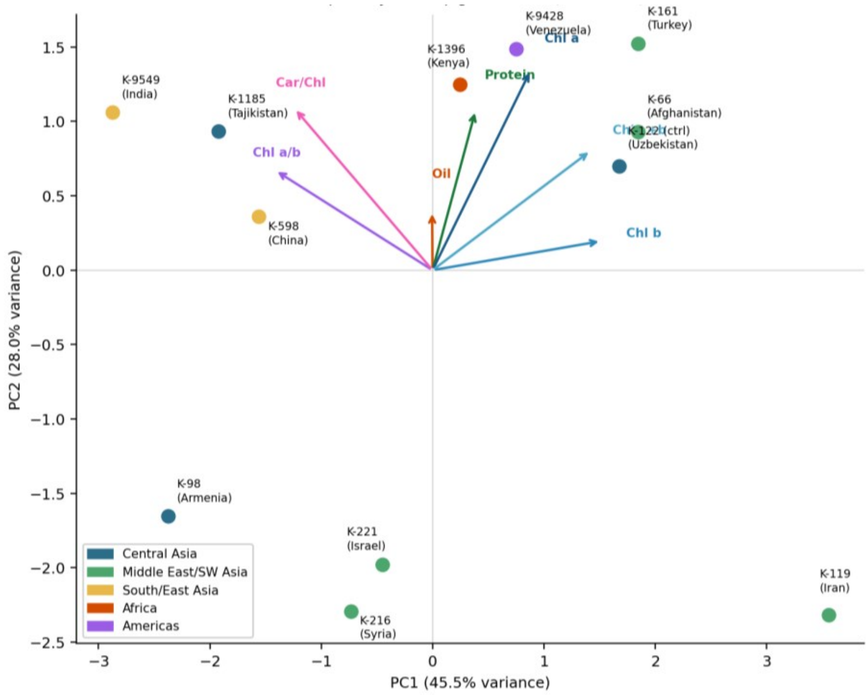


Fig 3. PCA biplot of 12 sesame accessions based on eight biochemical and pigment traits (PC1 × PC2, n = 12).

CPI values are presented in Table 3. The control Tashkentskiy-122 scored highest overall (0.856). Among introduced accessions, K-1185 (Tajikistan) and K-1396 (Kenya) ranked highest (CPI = 0.830 and 0.828), combining above-average oil with high protein. K-9549 (India) ranked fourth (0.699) despite maximum oil, due to its low protein. K-598 (China) scored lowest (0.310) owing to anomalously low oil despite competitive protein.

Table 3

Combined Productivity Index (CPI = 0.6·Oil_norm + 0.4·Protein_norm), ranked descending

Genotype	Country	Oil (%)	Protein (%)	CPI
Tashkentskiy-122	Uzbekistan	50.96	20.95	0.856
K-1185	Tajikistan	52.56	20.11	0.830
K-1396	Kenya	51.92	20.37	0.828
K-9549	India	53.23	18.98	0.699
K-9428	Venezuela	51.18	19.60	0.664
K-161	Turkey	51.20	19.22	0.607
K-66	Afghanistan	51.29	19.16	0.603
K-119	Iran	50.33	19.52	0.598
K-98	Armenia	51.88	18.33	0.515
K-216	Syria	50.48	18.61	0.468
K-221	Israel	49.06	18.55	0.369
K-598	China	43.76	20.37	0.310

Oil_norm and Protein_norm: min-max normalised to [0, 1].

DISCUSSION

The range of total chlorophyll observed in this study (1.48-1.98 mg g^{-1} f.w.) is consistent with values reported for sesame under comparable field conditions (Koca et al., 2007; Bahrami & Razmjoo, 2012). The 34% difference between extremes is physiologically meaningful in terms of potential photosynthetic carbon fixation capacity. The Chl a/b ratios of 1.60-2.39 likely reflect evolutionary photoecology of the source regions: K-119 (Iran) with the lowest ratio presents an expanded LHCII suited for moderate or variable irradiance, whereas K-9549 (India) and K-598 (China) with higher ratios reflect sun-type chloroplast organisation characteristic of high-irradiance tropical environments (Boardman, 1977). The collapse of Chl (a+b) in K-98 (Armenia) at capsule formation, from 1.71 to 1.24 mg g^{-1} f.w., indicates early chloroplast degradation: earlier senescence implies faster nitrogen remobilisation to seeds but limits late-season photosynthate supply.

Oil content of 43.76% in K-598 (China) is substantially below the range reported for sesame under favourable growing conditions: Li et al. (2014) found 37.6-63.2% across 369 SSR-characterised accessions; Gharby et al. (2015) reported 48-57% in Moroccan cultivars. The consistency of the low value across three seasons (interannual CV=0.06%) excludes environmental factors; this is a genetically fixed characteristic of K-598. Whether it reflects altered activity in fatty acid biosynthesis genes (FatA/FatB, FAD2) or reallocation of carbon to non-storage compounds remains to be determined by targeted biochemical or genomic analysis. At the opposite extreme, K-9549 (India) at 53.23% oil with interannual CV = 0.03% represents an exceptionally stable high-oil donor for breeding programmes.

The central multivariate finding - structural orthogonality of pigment traits (PC1+PC2) and seed quality traits (PC3) in PCA - has important practical implications. It indicates that genotypic ranking by leaf chlorophyll content does not predict ranking by oil or protein content in this accession set. This contrasts with observations in some other oilseed crops where flag-leaf greenness correlates with yield components (Araus et al., 2018), and suggests that in sesame the source-sink relationship is mediated by additional regulatory layers - including capsule number, seeds per capsule, and individual seed-filling duration - that dilute any direct pigment-to-composition signal. Consequently, SPAD-based non-destructive chlorophyll screening would not be a useful indirect selection criterion for seed biochemical quality in sesame breeding.

Among introduced accessions, K-1185 (Tajikistan) showed the highest CPI (0.830) combining above-average oil (52.56%) with high protein (20.11%) and low interannual CV. Its Central Asian origin (Tajikistan) suggests photoperiod and temperature adaptation compatible with Uzbek growing conditions, which reduces the risk of phenological mismatch when using this accession in local breeding programmes (Amanova & Rustamov, 2018). K-1396 (Kenya) matched it in CPI (0.828) with similarly competitive biochemical profile. Given that most available sesame research in Central Asia has focused on yield and oil rather than combined oil-protein evaluation (Amanova, 2012; Yusupov, 2025), the CPI framework proposed here offers a transparent, quantitative tool for multi-trait ranking that can be adapted by changing the weighting coefficients depending on the target market.

CONCLUSION

Twelve *Sesamum indicum* accessions were characterised over three growing seasons in Uzbekistan for photosynthetic pigment composition, seed oil content, and protein accumulation. All traits showed highly significant genotypic differentiation ($p < 0.001$) oil ranged 43.76-53.23%, protein 18.33-20.95%, and total chlorophyll 1.48-1.98 mg g^{-1} f.w. All traits were highly stable across years (interannual CV < 1%). PCA demonstrated that pigment-related variation (PC1+PC2 = 73.5%) is structurally independent from seed oil-protein variation (PC3 = 15.3%), confirming that leaf chlorophyll indices cannot predict seed biochemical composition in this germplasm. K-1185 (Tajikistan) and K-1396 (Kenya) are recommended as the best-balanced introduced accessions for combined oil-protein improvement; K-9549 (India) as a high-oil donor. K-598 (China) requires further investigation into the genetic basis of its anomalously low oil content before inclusion in breeding programmes.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the Research Institute of Plant Genetic Resources for providing the sesame germplasm collection used in this study. The authors thank the staff of Chirchiq State Pedagogical University experimental station for assistance with field experiments.

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