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Tracking the storage stability in sesame (*Sesamum indicum* L.): impact of accelerated storage on storability characteristics, seed quality, phytochemical content, and fatty acids

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Abstract
Storage stability under non-optimal conditions is an essential characteristic of Sudanese sesame. To understand opportunities to improve storage stability in sesame, seed quality, storability characteristics, content of fatty acids and phytochemicals, and antioxidant capacity were evaluated in ten Sudanese genotypes subjected to high temperature (55 °C) and humidity (60% RH) for 16 and 32 days. The accelerated storage increased seed color, linoleic acid, fungal growth, and peroxide value, while oil content, oleic acid, water activity, phytochemicals, and antioxidant capacity decreased ($P < 0.05$). The germination rate and content of saturated fatty acids were retained despite the storage ($P > 0.05$). The landrace Abusundoug showed better storage stability than the other genotypes due to generally low fatty acids and high phytochemical contents. The differences in storage stability in the Sudanese genotypes underscore the need for their further evaluation and use in breeding programs to improve sesame shelf life and quality.

Keywords Sesame · Cultivars · Oxidative stability · Accelerated storage conditions

1 Introduction

Sesame (*Sesamum indicum* L.) was domesticated over 3000 years ago and became one of the first oilseed crops utilized by humans [1]. As an oilseed crop suited for tropical regions, sesame continues to be an important commodity by yielding seeds with abundant levels of high-quality edible oils. In addition, sesame seeds contribute considerable amounts of protein and other essential nutrients to the human diet [2]. The sesame seed contains 35–60% oil, 3–19% protein, 13.5% carbohydrate, 5% ash, and a calorific value of 6355 kcal kg^{-1} [3], and it is also a rich source of nutrients such as copper, magnesium, manganese, iron, and vitamins E and B [4–6]. Sesame oil comprises 80% oleic and linoleic acids, while 18% are palmitic, stearic, and linolenic acids [7].

Several studies have indicated that sesame seed oil possesses significant antioxidant properties due to the presence of lignans, tocopherols, and Maillard reaction products [8]. A mixture of sesame and clove oil has also been shown to protect stored products against beetle infestations from, e.g., *Callosobruchus maculatus* [8, 9]. Due to the many positive effects of the

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crop, sesame cultivation is expected to increase globally with a Compound Annual Growth Rate (CAGR) of 2.2% until the end of 2027 [10]. Thus, global sesame production is projected to reach 6.8 million tons shortly, with Sudan, Myanmar, Tanzania, India, Nigeria, and China ranked as the leading producing countries. [11].

Furthermore, sesame is expected to be increasingly recognized as a human health-contributing ingredient in food products [12]. As a result of Sudan being one of the centers of origin and a major producer of sesame, an enormous wealth of genetic diversity in sesame germplasm is present in the country [13]. Thereby, potentially important characters relevant to future sesame production should be present within the Sudanese germplasm.

Sesame, its oil, and other products are used locally in Sudan, but sesame is also Sudan's number one export commodity [14]. Therefore, sesame seeds and/or oil storage is necessary, and most traditional storage methods utilized are similar to those described for Ethiopia [15]. The climate in Sudan consists of desert conditions and temperatures around 45 °C (or even up to 50 °C) in the north and semi-desert or semi-arid conditions in the south [16]. Traditional storage under such a climate is often not beneficial for sesame seeds, which are high in oil and prone to fungal growth. In fact, storage under harsh conditions results in adverse effects on both sesame seeds and oils. Oxidation and fungal infestations during storage often deteriorate oil and seed quality, reduce germination potential, and increase levels of free fatty acids.

Additionally, long storage periods with adverse oxidation events result in color changes of the sesame seeds, destruction of essential fatty acids, and production of trans-acid and conjugated dienes, resulting in limitations of the use of the seeds for a range of agricultural and food applications [17]. Also, antioxidant and prooxidant properties were shown to be negatively affected by such storage conditions [18], which promoted the formation of polar compounds such as oxidized polymers, significantly and negatively affecting human health [19, 20]. Studies on Sudanese sesame have been limited until now, and the crop can be seen as a neglected crop in research. An increased understanding of the effect of harsh storage conditions on the quality of the sesame seeds is lacking. Thus, this study aimed to increase the understanding of how harsh storage conditions affect the sesame seeds' quality by comprehensively assessing color attributes, storability characteristics, phytochemical compound content, and fatty acid profiles concerning oxidative stability under accelerated storage conditions to improve the opportunities for storage stability. Additionally, the study aimed to predict further measures on how sesame seeds should be stored to improve the benefits of sesame for food, production, and export in Sudan and beyond.

2 Material and methods

2.1 Sample collection and preparation

A total of ten genotypes (cultivars landraces) native to Sudan were used in the present study, namely Kenana-2 (KN: whitish released cultivar), Gadarif (GF: whitish released cultivar), Eltayeb (EB: whitish released cultivar), Radoum (RM: whitish landraces), Tagarub (TB: whitish released cultivar), Southern Kordufan (SK: whitish landraces), Bromo (BO: whitish released cultivar), Rufaee (RE: whitish landraces), Hurhairy (HR: dark brown landraces), and Abusundoug (AS: light brown landraces). The genotypes were freshly harvested during the 2021–2022 season and exposed to accelerated storage conditions. Non-stored samples of each genotype were used as control samples and analyzed similarly to the stored samples described below.

The accelerated storage of sesame seeds was carried out over 16 and 32 days in a climate chamber with conditions set to 55 °C and 60% relative humidity (RH). The 55 °C/60% RH storage conditions result in a Q10 value of 3.4 for lipid oxidation, "the process by which lipids undergo oxidative degradation increases 3.4 times when the temperature is raised by 10 degrees Celsius" [21]. These conditions are considered a simulation of commercial storage at 25 °C for 6 and 12 months, which allows an evaluation of sesame seeds' changes in seed quality, storability characteristics, and antioxidant capacity.

2.2 Evaluation of seed quality

2.2.1 Seed color

A colorimeter (Chroma Meter CR 400, manufactured by Minolta, Japan) was used to determine color parameters (L*, a*, and b*) of stored and controlled sesame seeds. A standard white reflector plate was used to calibrate the equipment. The Petri dish attached to the device was filled with 50.0 g of sesame seeds for measurement. Color changes were estimated according to the following equation;

$$\Delta E = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2}$$

where; L* (luminosity); a* (negative = green and positive = red); b* (negative = blue and positive = yellow);. ΔE (the total color difference).

2.2.2 Germination rate

The germination rate was investigated utilizing 3 replicates of each cultivar for the different storage stages (control = non-stored samples of each cultivar, 16 days, and 32 days) using Petri dishes and filter paper. A total of 100 sesame seeds were used in every replicate. The germination rate of the sesame seeds was evaluated after 3 and 6 days of germination according to the International Seed Test Association [22].

2.2.3 Determination of oil content

Following [23] guidelines for oil extraction, the Soxhlet extraction method was used to determine the amount of oil in seeds. Seeds are ground into powder using a Soxhlet extractor (DWK Life Sciences Kimble™ KIMAX™ Soxhlet Apparatus with Allihn Condenser, Complete unit), and the oil is dissolved in a solvent. Then, the solvent is reheated, vaporized, and condensed over the seeds for several hours to dissolve the oil. Oil percentages were calculated by weighing the oil after it was extracted from the seed. The solvent was subsequently evaporated, resulting in the oil being left.

2.2.3.1 Fatty acid profile Oil extraction from sesame seeds was performed using a two-step solvent extraction process, followed by fatty acid analysis via gas chromatography (GC) as per the modified protocol [24]. The extraction was conducted in triplicate, with each replicate using ten seeds. First, non-polar lipids were extracted using hexane. Subsequently, the seed residue underwent a second extraction with a chloroform/methanol mixture (2:1 v/v) to recover any remaining polar lipids. The extracts from both steps were combined for each replicate to ensure complete lipid recovery. The combined extracts were then subjected to methylation at 90 °C before the n-Heptan partition to prepare fatty acid methyl esters (FAMEs) for GC analysis. An aliquot of 1 µl sample was injected into a GC–MS instrument with FID detector (Agilent Intuvo 9000 GC coupled with 5977B MSD detector and MassHunter workstation software.) operated with a split injection ratio of 10:1 (Gard chip: MS transfer line 250 °C, MS source 230 °C, and MS Quad 150°C). Analyte separation (250°C inlet temperature) utilized a 30 m DB-23 fused silica column (0.25 mm internal diameter and 0.25 µm film thickness) from Agilent. Ultra-high purity helium was used as carrier gas at a 2.5 ml/min programmed constant flow. The thermal ramping protocol for the GC oven began at an initial 150 °C held for 0.2 min, then increased at a gradient of 4 °C/min until reaching 210 °C. Subsequently, the temperature was further raised at 10 °C/min until the final 230 °C and maintained for 7 min. Chromatographic peaks were identified using mass spectral matching against reference signatures in the embedded NIST17 commercial library. Quantification relied on integrating total ion counts for each compound using MassHunter workstation software from Agilent.

2.3 Evaluation of storability characteristics

2.3.1 Fungal growth

Fungal growth in both the control and stored sesame seeds was assessed following the guidelines set by AOAC standards [25]. For each sample, one gram of material was homogenized in 10 ml of 0.1% peptone water using a vortex apparatus for 1 – 2 min, resulting in a final dilution of 1:10. Liquid samples were then serially diluted and plated on an appropriate medium. Specifically, selected dilutions (10^{-5}) of each sample (1 ml) were poured and plated on Petri dishes containing sterile Potato Dextrose Agar (PDA), followed by incubation for 5 days at 25°C. Colony formation was observed daily during the incubation period. Counts of colony-forming units per gram were recorded to quantify fungal growth (log cfu/g).

2.3.2 Water activity

The water activity (a_w) of the sesame seeds was assessed at room temperature using a hygrometer (Humimeter RH2, Schaller, Vienna, Austria) equipped with selectable sensors for measuring air humidity, material moisture, and water activity. The hygrometer was further enhanced with a temperature-controlled system to ensure a stable sampling environment according to the Official Methods of Analysis of the Association of Official Analytical Chemists (2005) described in [26].

2.3.3 Determination of free fatty acids

The free fatty acid (FFA) content in sesame seed was assayed according to [23]. The acidity of the sesame seed flour was calculated as mg KOH required to neutralize them in one-gram grain on a dry matter basis.

2.3.4 Determination of peroxide value

Measurement of peroxide values (PV) is critical for evaluating the progression of oxidation and rancidity development in oilseeds. Peroxide value was determined through the iron (II) thiocyanate assay as described by Østdal, Andersen [27] with brief modifications. Sesame seeds flour (1g) was mixed with methanol: chloroform solution (30 ml), vortexed at 1500 rpm for 30 s, and centrifuged to separate phases. The resulting lower chloroform phase was combined with iron (II) thiocyanate reagent prepared precisely according to documented compositions. After incubating for 5 min, absorbance was measured using a UV–Vis spectrophotometer (Shimadzu UV-1800, Thermo Scientific™ Evolution™ 300, or Agilent Cary 60) at 500 nm against a chloroform blank. Peroxide value was quantified using a standard conversion formula and expressed in milliequivalents (meq) of active oxygen per kilogram of oil ($meqO_2/kg$).

2.4 Determination of phenolic compounds and antioxidant activity

2.4.1 Preparation of phytochemical extracts

The samples were prepared following the procedures described by Talhaoui, Gómez-Caravaca [28]. First, the samples were mixed with absolute methanol (1g: 25 ml w/v) and stirred at room temperature for 24 h. The extraction of the phytochemicals was performed twice, and the extracted solution was then dried under a vacuum with a rotary evaporator to keep them dry for further analysis. All absorbance was measured using a UV–Vis spectrophotometer (Shimadzu UV-1800, Thermo Scientific™ Evolution™ 300, or Agilent Cary 60) at different wavelengths.

2.4.2 Determination of total phenolic content

The Folin-Ciocalteu Index (FCI) assay was used to analyze the total phenolics content (TPC) with slight modifications. Thus, according to [29], a solution of 20 µL (1:10 w/v) dried methanolic extract was mixed with 100 µL of Folin–Ciocalteu reagent, 300 µL of Na_2CO_3 (20%) and 1.58 ml H_2O. Then, the solution was incubated at 20 °C for 2 h. As a comparison to a blank solution, the absorbance was measured at 765 nm. The output was described as mg of gallic acid equivalents (GAE) per gram of sample (DW) based on a calibration curve using different concentrations of gallic acid ($R^2 = 0.99743$).

2.4.3 Determination of total flavonoid content

The Quantification of the samples' total flavonoid (TFC) content was determined as described previously [30]. The mixture of methanol extract (1 ml), 5% $NaNO_2$ solution (300 µL), 10% aluminum chloride (300 µL), and 1 mol/L sodium hydroxide (2 ml)was incubated at 25 °C for five minutes. Then, the solution was diluted to a volume of 10 mL with H_2O and vortexed thoroughly. The absorbance was recorded at 510 nm. A calibration curve was generated based on different concentrations of quercetin ($R^2 = 0.9761$). Quercetin equivalents (QEs) per gram of the sample (DW) were considered to calculate TFC.

2.4.4 Antioxidant activity

2.4.4.1 Radical scavenging activity Radical scavenging activity was measured using a 2-diphenyl-1-picrylhydrazyl (DPPH) assay as described by [31]. The DPPH was freshly produced by liquefying 3.9 mg DPPH in 100 ml of methanol to

obtain a 1.00 ± 0.01 unit of absorbance. After this, approximately 100 µl of sample extract or deionized water was mixed with Tris–HCl buffer (50 mM; pH 7.4; 900 µl) and 1000 µl of the DPPH solution, followed by incubation in darkness for 2 h. The absorbance of the mixture was measured at 517 nm. The amount of DPPH scavenging per gram sample is expressed as Trolox equivalents (mg TE/g).

2.4.4.2 Ferric reducing antioxidant power assay The extracts' Ferric Reducing Antioxidant Power (FRAP) was assessed using a UV/visible spectrophotometer at a wavelength of 593 nm, following the method described by Benzie and Devaki [32]. FRAP results were quantified and expressed as micromoles of Trolox equivalents per gram of the sample (mg Trolox/g).

2.4.4.3 ABTS free radical scavenging assay The ABTS radical cation decolorization assay was utilized to assess antioxidant capacity, following an established method by Re, Pellegrini [33] with modifications. The ABTS radical solution was prepared and diluted to an absorbance of 0.700 ± 0.02 at 734 nm and 30 °C before use. For the procedure, the sample was combined with the ABTS working reagent, and the decrease in absorbance was monitored at 1-min intervals for up to 6 min. Final absorbance was used to calculate Trolox equivalence against a standard curve ($R^2 = 0.9986$) and derive inhibition percentages. This colorimetric approach enables the measurement of radical scavenging activity, providing valuable standardized antioxidant capacity information through Trolox values (mg Trolox/g).

2.5 Statistical analysis

All analyses were carried out on three replicated samples, and mean values and standard deviations were calculated. To investigate the significance level of all the measurements across the three different storage conditions (non-stored and stored at 16 and 32 days, respectively) and the cultivar interaction, a two-way ANOVA was conducted using the General Linear Model (GLM) in the Minitab software version 19.2, which was also used to obtain the Pearson correlation matrix plot of highly correlated characteristics. [34]. Finally, the Principal Component Analysis (PCA) was carried out using the Factoextra-package in the R statistical program [35].

3 Results and discussion

3.1 Seed characteristics

The sesame seeds evaluated in this study showed no significant differences in germination rate, neither among cultivars nor due to the storage times applied here ($P > 0.05$; Table 1). Thus, similar to previous findings [36], which have shown a maintained germination rate of over 80% after accelerated storage, the tested sesame seeds in this study were hardy and highly viable after the storage.

Changes of color in sesame seeds while stored have been limitedly studied till now. The present study clearly showed a significant variation among storage times, cultivars, and their interaction for color parameters, including lightness (L*), redness (a*), yellowness (b*), and overall change (ΔE) (Table 1). Thus, the changes in the seed color of sesame were highly affected by the total time the seeds were stored under accelerated conditions. In fact, 32 days of accelerated storage resulted in a highly significant increase in the values of all color parameters (L*, a*, b*, and ΔE), while 16 days of storage instead reduced most color values (Table 1). The color degradation at 16 days may be attributable to the loss of pigments and browning reactions as bioactive compounds are utilized to counter storage stresses. The subsequent increase in coloration after 32 days may result from novel pigment and melanoidin formation from Maillard reactions and phenolic oxidation as constituents degrade further under sustained high temperatures [37, 38].

Among the cultivars evaluated here, the brown cultivars AS and HR (landraces) showed significantly lower L*, higher a*, and lower ΔE than the whitish cultivars. Additionally, the whitish landraces RM, RE, and SK tended to have lower L* but higher a* and lower ΔE compared to the released whitish cultivars KN, GF, EB, TB, and BO. These findings indicate that while color changed for all genotypes during accelerated storage, inherent color differences existed between brown, landrace whitish, and released whitish cultivars that persisted throughout storage. However, a relatively limited number of genotypes were evaluated here, and further research is needed to determine the specific compounds and genetic factors influencing color retention in sesame seeds during prolonged storage stresses. Considerable natural diversity exists in mature sesame seed coloration, ranging from black to white, including gray, brown, golden, yellow, and ivory.

Table 1 Germination and color characteristics of ten sesame genotypes under accelerated storage conditions

Genotypes	Germination (%)	Color characteristics			
		L *	**a ***	**b ***	**Δ*E***
KN	98.0 ± 0.4^{A}	72.3 ± 0.4^{C}	5.8 ± 0.1^{H}	16.5 ± 0.05^{G}	4.0 ± 0.4^{C}
GF	98.0 ± 0.4^{A}	71.6 ± 0.6^{C}	8.4 ± 0.02^{CD}	20.9 ± 0.2^{C}	8.0 ± 0.7^{A}
EB	97.0 ± 0.3^{A}	73.3 ± 0.7^{B}	7.8 ± 0.1^{DE}	20.4 ± 0.1^{D}	5.1 ± 0.7^{B}
RM	97.0 ± 0.4^{A}	69.6 ± 0.2^{D}	7.0 ± 0.04^{FG}	18.9 ± 0.02^{E}	1.6 ± 0.2^{DE}
TB	97.0 ± 0.4^{A}	74.3 ± 0.4^{A}	7.6 ± 0.1^{EF}	20.9 ± 0.2^{BC}	5.1 ± 0.4^{B}
SK	97.0 ± 0.5^{A}	71.8 ± 0.4^{C}	8.6 ± 0.2^{C}	21.2 ± 0.3^{B}	3.9 ± 0.4^{C}
BO	95.0 ± 0.5^{A}	74.7 ± 0.7^{A}	7.1 ± 0.02^{FG}	18.8 ± 0.1^{E}	5.2 ± 0.4^{B}
RE	95.0 ± 0.9^{A}	67.6 ± 0.2^{E}	6.8 ± 0.03^{G}	17.8 ± 0.1^{F}	2.0 ± 0.2^{D}
HR	93.0 ± 0.7^{A}	41.3 ± 0.1^{G}	11.7 ± 0.1^{A}	15.3 ± 0.01^{H}	0.9 ± 0.1^{E}
AS	92.0 ± 0.9^{A}	65.6 ± 0.3^{F}	10.1 ± 0.04^{B}	22.4 ± 0.1^{A}	3.8 ± 0.3^{C}
Storage time					
Control	96.0 ± 6.0^{A}	68.9 ± 10.0^{B}	8.0 ± 1.7^{B}	19.5 ± 2.6^{A}	0.0 ± 0.0^{C}
16	96.0 ± 6.0^{A}	66.3 ± 9.0^{C}	7.9 ± 1.8^{B}	18.9 ± 2.0^{B}	4.7 ± 3.0^{B}
32	96.0 ± 4.3^{A}	69.4 ± 11.5^{A}	8.4 ± 1.9^{A}	19.5 ± 2.8^{A}	7.1 ± 3.8^{A}
ANOVA					
F-Value, G	1.42^{NS}	4063.9***	146.5***	1429.9***	219.8***
F-Value, S	0.11^{NS}	375.2***	12.4***	134.4***	2214.0***
F-Value, G*S	0.8^{NS}	312.8***	8.7***	213.5***	101.9***
SE Fit	3.19	0.27	0.25	0.10	0.24

(L *) Luminosity, (a *) Negative = green and positive = red, (b *) Negative = blue and positive = yellow, (ΔE) total color difference, (G) Genotypes, (S) Storability, and values are means (±) SD of triplicate samples. Means in the same column that share the same superscript letters do not differ significantly ($P > 0.05$), ***; ($P < 0.001$), ^{NS}; no significant difference at ($P > 0.05$) as assessed by LSD

KN, Kenana-2; GF, Gadarif; EB, Eltayeb; RM, Radoum; TB, Tagarub; SK, Southern Kordufan; BO, Bromo; RE, Rufaee; HR, Hurhairy; AS, Abusundoug

This rich pigment variation provides opportunities to uncover genotype-specific resilience mechanisms that preserve color integrity under high temperature and humidity conditions. The elucidation of the biochemical basis for differential storage response among cultivars might contribute to guidance in breeding to enhance shelf life, which has also been suggested in previous studies [39]. In addition, previous research has reported that changes in the color of sesame seeds are associated with non-enzymatic browning, which results from polymerization reactions between phenolic compounds and tannins during storage conditions [40]. Thus, the change in sesame seed color reported here is likely the result of such a non-enzymatic browning due to temperature and storage period, similar to what has been reported for rice Park, Kim [41]. The differences found here in whitish color and color changes in landraces as compared to whitish released cultivars might then be the result of higher stability as related to non-enzymatic browning and, thereby, to polymerization between phenolic compounds and tannins in the landraces as compared to in the released cultivars.

Despite the fact that sesame seeds' nutritional value and shelf life depend heavily on oil retention and beneficial fatty acids, the effect of storage on these characteristics has been limitedly evaluated. The present study clearly showed that accelerated storage conditions significantly affected the total oil content and the content of oleic and linoleic acids (Table 2). Thus, corresponding with previous findings [42], the accelerated storage resulted in a decrease in total oil and oleic acid content, while it resulted in an increase in linoleic content and no significant change for the other evaluated fatty acids (Table 2). The fact that the accelerated storage resulted in differences in changes in the content of unsaturated (oleic and linoleic) and saturated (palmitic and stearic) fatty acids reflects the difference in the oxidation rates of these fats. It is well known that the low activation energy of unsaturated fats to form lipid radicals makes these more susceptible to oxidation than saturated fats [43]. Thereby, the oxidative instability of linoleic acid might also impair the shelf life of oil rich in linoleic acid, despite its known health benefits, such as e.g. a LDL cholesterol improver [44]. Accelerated storage conditions with high temperature and humidity are known to increase moisture content in sesame seeds, resulting in oxidation with a break-down of the oil and rancidity [45], which is the likely explanation for the decrease of the total oil content after storage. Ideal storage conditions for sesame seeds include cool, dry, and dark environments with low humidity, which will help preserve and prevent the oil content from spoilage.

Table 2 Oil content and content of fatty acids (mg/µl) of ten sesame genotypes under accelerated storage conditions

Genotypes	Oil content (%)	Content of fatty acids (mg/µl)						
		Palmitic	**Stearic**	**Oleic**	**Linoleic**	**Linolenic**	**Arachidic**	**Eicosenoic**
KN	**47.0 ± 0.1^{A}**	0.8 ± 0.01^{DE}	0.7 ± 0.01^{BC}	2.2 ± 0.1^{ABC}	3.9 ± 0.1^{BC}	0.03 ± 0.0^{AB}	0.10 ± 0.0^{BC}	0.02 ± 0.0^{AB}
GF	46.5 ± 0.2^{A}	0.9 ± 0.01^{CDE}	0.7 ± 0.01^{BC}	2.3 ± 0.1^{ABC}	4.5 ± 0.1^{ABC}	0.03 ± 0.0^{AB}	0.07 ± 0.0^{ABC}	0.02 ± 0.0^{AB}
EB	46.7 ± 0.1^{A}	1.0 ± 0.01^{ABCD}	0.8 ± 0.01^{AB}	2.9 ± 0.1^{ABC}	5.1 ± 0.1^{A}	0.03 ± 0.0^{AB}	0.09 ± 0.0^{AB}	0.02 ± 0.0^{AB}
RM	46.6 ± 0.1^{A}	0.8 ± 0.02^{E}	0.6 ± 0.01^{C}	1.7 ± 0.04^{BC}	3.5 ± 0.1^{C}	0.02 ± 0.0^{B}	0.07 ± 0.0^{CD}	0.01 ± 0.0^{AB}
TB	46.4 ± 0.2^{A}	1.0 ± 0.01 ^{BCD}	0.8 ± 0.01^{ABC}	2.7 ± 0.2^{ABC}	4.8 ± 0.1^{AB}	0.03 ± 0.0^{AB}	0.08 ± 0.0^{ABC}	0.02 ± 0.0^{AB}
SK	46.4 ± 0.1^{A}	0.9 ± 0.01^{BCDE}	0.7 ± 0.01^{ABC}	2.6 ± 0.1^{ABC}	4.0 ± 0.1^{BC}	0.02 ± 0.0^{B}	0.08 ± 0.0^{ABC}	0.02 ± 0.0^{AB}
BO	46.8 ± 0.1^{A}	1.0 ± 0.01^{ABC}	0.8 ± 0.01^{ABC}	3.0 ± 0.2^{ABC}	5.1 ± 0.1^{A}	0.03 ± 0.0^{AB}	0.09 ± 0.0^{ABC}	0.02 ± 0.0^{AB}
RE	46.4 ± 0.1^{A}	1.1 ± 0.01^{AB}	0.8 ± 0.01^{AB}	3.3 ± 0.3^{AB}	5.2 ± 0.1^{A}	0.10 ± 0.0^{AB}	0.09 ± 0.0^{A}	0.03 ± 0.0^{AB}
HR	46.4 ± 0.1^{A}	**1.2** ± 0.01^{A}	**0.9** ± 0.01^{A}	**4.3** ± 0.1^{A}	**5.4** ± 0.1^{A}	**0.07** ± 0.0^{A}	**0.10** ± 0.0^{A}	**0.04** ± 0.0^{A}
AS	46.4 ± 0.1^{A}	0.5 ± 0.01^{F}	0.4 ± 0.01^{D}	1.0 ± 0.1^{C}	2.2 ± 0.1^{D}	0.02 ± 0.0^{B}	0.04 ± 0.01^{D}	0.01 ± 0.0^{B}
Storage time								
Control	47.5 ± 0.7^{A}	0.9 ± 0.2^{A}	0.7 ± 0.1^{A}	3.3 ± 2.1^{A}	4.1 ± 1.2^{B}	0.04 ± 0.04^{A}	0.08 ± 0.02^{A}	0.03 ± 0.03^{A}
16	45.4 ± 0.6^{C}	0.9 ± 0.2^{A}	0.7 ± 0.1^{A}	2.1 ± 0.8^{B}	4.4 ± 1.0^{AB}	0.03 ± 0.01^{A}	0.08 ± 0.02^{A}	0.02 ± 0.00^{A}
32	46.7 ± 0.6^{B}	1.0 ± 0.2^{A}	0.7 ± 0.1^{A}	2.4 ± 1.0^{B}	4.6 ± 1.1^{A}	0.03 ± 0.01^{A}	0.08 ± 0.02^{A}	0.02 ± 0.01^{A}
ANOVA								
F-value, G	0.97^{NS}	22.5***	13.2***	3.96***	18.4***	2.72***	10.8***	1.80^{NS}
F-Value, S	67.4***	2.90^{NS}	1.90^{NS}	6.50***	3.55***	1.70^{NS}	0.40^{NS}	2.00^{NS}
F-Value, G*S	1.14^{NS}	0.30^{NS}	0.40^{NS}	0.24***	0.26^{NS}	0.83^{NS}	0.31^{NS}	0.70^{NS}
SE Fit	0.40	0.07	0.80	0.20	0.40	0.01	0.01	0.01

(G) Genotypes, (S) Storability, and values are means (±) SD of triplicate samples. Means in the same column that share the same superscript letters do not differ significantly ($P > 0.05$), ***; ($P < 0.001$), ^{NS}; no significant difference at ($P > 0.05$) as assessed by LSD

KN, Kenana-2; GF, Gadarif; EB, Eltayeb; RM, Radoum; TB, Tagarub; SK, Southern Kordufan; BO, Bromo; RE, Rufaee; HR, Hurhairy; AS, Abusundoug

However, differences in the content of the various fatty acids evaluated were noted among the cultivars, although the oil content did not differ significantly (Table 2). Generally, high levels of most fatty acids were recorded for the dark brown cultivar HR, while low levels were noted for the light brown cultivar AS (Table 2). Previous studies have indicated that genetic factors determine the oil content, fatty acid synthesis, and sesame compound retention during storage [46]. The present study included a relatively limited number of genotypes, and further elucidation of the genetic and biochemical basis for fatty acid stability during accelerated storage, including a higher number of genotypes, is a prerequisite if breeding for these characters should be possible.

3.2 Storability characteristics

Fungal growth, a_w, FFA, and PV exhibited significant differences both across storage conditions and among cultivars (Table 3). In general, fungal growth and PV increased with prolonged accelerated storage, while the significantly highest values for a_w and PV were recorded after 16 days of accelerated storage (Table 3). As shown by others [17], fungal infections are normally increasing if seeds are stored at high relative humidity levels, although a high FFA concentration also promotes fungal infection [47]. Additionally, a high FFA content contributes to rancidity and results in off-flavors and odors in oilseeds during storage and has, therefore, been associated with limitations in industrial uses of sesame [17]. However, in the present investigation, the FFA content was not significantly higher after 32 days of storage than in control samples. The FFA content was significantly higher at 16 days of storage, which might result from reduced lipase enzyme activity from heat damage during storage, as reported by others [48]. Oils and fats in sesame are commonly tested for oxidative rancidity with PV, a measure of the oxidation of hydroperoxides, which are unstable and readily decompose into volatile aldehydes [49]. As lipid oxidation decreases as storage time increases, PV is primarily useful as a flavor quality indicator in the early stages of lipid oxidation [50].

Similarly to previous studies by Abdelazim, Mahmoud [51], the PV increased gradually and rapidly as the storage period increased. The same author reported that sesame cake extract degraded the oxidation in soybean oil compared to other extracts. Thus, low PV values in sesame cultivars might be connected to a high antioxidant capacity in those

Table 3 Storability characteristics of sesame genotypes under accelerated storage conditions

Genotypes	Fungal growth (log cfu/g)	Water activity (a_w)	Free fatty acid (FFA; mgKOH/g)	Peroxide value (PV; meq O_2/g)
KN	5.7 ± 0.01^{B}	0.32 ± 0.005^{AB}	0.36 ± 0.01^{B}	1.48 ± 0.08^{D}
GF	2.8 ± 0.02^{C}	0.29 ± 0.004^{CD}	0.44 ± 0.04^{A}	1.35 ± 0.05^{F}
EB	5.9 ± 0.13^{A}	0.31 ± 0.005^{BCD}	0.38 ± 0.01^{AB}	1.27 ± 0.05^{G}
RM	0.0 ± 0.00^{D}	0.33 ± 0.001^{A}	0.34 ± 0.01^{B}	1.42 ± 0.07^{E}
TB	0.0 ± 0.00^{D}	0.30 ± 0.005^{BCD}	0.39 ± 0.02^{AB}	1.49 ± 0.08^{D}
SK	0.0 ± 0.00^{D}	0.29 ± 0.005^{D}	0.44 ± 0.01^{A}	1.33 ± 0.05^{F}
BO	0.0 ± 0.00^{D}	0.31 ± 0.001^{ABC}	0.33 ± 0.01^{B}	1.85 ± 0.09^{A}
RE	0.0 ± 0.00^{D}	0.32 ± 0.001^{AB}	0.36 ± 0.01^{B}	1.62 ± 0.07^{B}
HR	5.7 ± 0.01^{B}	0.32 ± 0.007^{AB}	0.36 ± 0.01^{B}	1.88 ± 0.09^{A}
AS	2.8 ± 0.01^{C}	0.29 ± 0.005^{CD}	0.39 ± 0.03^{AB}	1.56 ± 0.08^{C}
Storage time				
Control	2.1 ± 2.1^{C}	0.3 ± 0.04^{B}	0.3 ± 0.1^{B}	0.7 ± 0.1^{C}
16	2.2 ± 2.5^{B}	0.4 ± 0.02^{A}	0.5 ± 0.1^{A}	1.6 ± 0.4^{B}
32	2.5 ± 2.9^{A}	0.2 ± 0.01^{C}	0.3 ± 0.1^{B}	2.3 ± 0.3^{A}
ANOVA				
F-Value, G	55,830.1***	10.3***	2.0***	318.8***
F-Value, S	953.6***	447.5***	32.2***	16,051.1***
F-Value, G*S	484.7***	8.2***	4.5***	179.22***
SE Fit	0.02	0.01	0.04	0.02

(G) Genotypes, (S) Storability, and values are means (±) SD of triplicate samples. Means in the same column that share the same superscript letters do not differ significantly ($P > 0.05$), ***; ($P < 0.001$), ^{NS}; no significant difference at ($P < 0.05$) as assessed by LSD

KN, Kenana-2; GF, Gadarif; EB, Eltayeb; RM, Radoum; TB, Tagarub; SK, Southern Kordufan; BO, Bromo; RE, Rufaee; HR, Hurhairy; AS, Abusundoug

seeds. Water activity (a_w) is an essential measure of available moisture for chemical reactions, microbial growth, and shelf-life stability of products [52]. In the present study, the a_w increased significantly ($P < 0.0001$) to 0.4 after 16 days, while it was reduced back to 0.2 ($P < 0.0001$) after 32 days of storage. This reduction in a_w after prolonged storage is likely due to high temperature and duration, and proper aw maintenance has, in previous investigations, been found critical for seed viability over time [53].

Fungal growth was found to differ significantly among the studied genotypes, with the significantly highest fungal growth in the cultivar EB (5.9 log cfu/g), followed by the cultivars KN and HR (5.7 log cfu/g), while no fungal growth was observed in the RM, TB, SK, BO, and RE cultivars. In principle, some of the genotypes were likely infected at the beginning of the storage period, and on those genotypes, an increase in fungal growth was noted over the storage period. Although clear genotypic differences were noted for a_w, FFA, and PV, no clear pattern was observed regarding the cultivar type. Thus, breeding for these characters will need additional information regarding the genetic background of the differences observed.

3.3 Phytochemical compounds and antioxidant activity

The accelerated storage conditions clearly impacted TPC, TFC, FRAP, and ABTS, which all decreased significantly with the storage time (Table 4), while no change in DPPH was noted. Phenolic compounds and antioxidants play an essential protective role in the oil seeds by directly reacting with and neutralizing free radicals that cause oxidative damage [54]. Previous investigations on other crops, e.g., pistachios and soybeans [55], have also reported decreased phytochemicals and antioxidant activity with storage. Bragança, Ziegler [56] found that phytochemicals and antioxidant capacity reduction over storage periods might result from oxidation and chemical reactions during high-temperature stress. The DPPH assay is used to measure the radical scavenging activity, and lignans, as well as lignin glycosides in sesame cake, have been found to have sufficient radical scavenging activity [57]. The retained DPPH activity during the storage of sesame seeds shown in this work suggests that sesame antioxidants preserve free radical neutralization even after accelerated aging. In previous studies, sesame antioxidants have contributed to preventing oxidation associated with quality

Table 4 Phenolic compounds and antioxidant activity of sesame genotypes seeds under accelerated storage conditions

Genotypes	Phenolic compounds		Antioxidant capacity		
	TPC (mg GAE/g)	**TFC** (mg QE/g)	**DPPH** (mg Trolox/g)	**FRAP** (mg Trolox/g)	**ABTS** (mgTrolox/g)
KN	3.9 ± 0.3^{G}	46.5 ± 0.8^{E}	4.8 ± 0.3^{A}	3.6 ± 0.2^{FG}	12.0 ± 0.2^{B}
GF	4.9 ± 0.1^{D}	$\mathbf{103.4} \pm 3.3^{\mathbf{A}}$	4.9 ± 0.2^{A}	3.3 ± 0.3^{G}	11.4 ± 0.4^{C}
EB	2.9 ± 0.1^{H}	88.1 ± 5.5^{B}	4.9 ± 0.2^{A}	$\mathbf{2.3} \pm 0.1^{\mathbf{H}}$	9.9 ± 0.6^{D}
RM	5.6 ± 0.3^{C}	56.3 ± 0.6^{D}	4.8 ± 0.2^{A}	5.0 ± 0.3^{D}	8.7 ± 0.5^{E}
TB	7.5 ± 0.5^{B}	46.3 ± 0.9^{E}	4.9 ± 0.2^{A}	6.6 ± 0.2^{C}	6.2 ± 0.5^{G}
SK	4.2 ± 0.2^{F}	53.2 ± 1.0^{D}	4.8 ± 0.3^{A}	9.2 ± 0.6^{B}	11.2 ± 0.6^{C}
BO	$\mathbf{2.8} \pm 0.1^{\mathbf{H}}$	$\mathbf{42.1} \pm 2.4^{\mathbf{F}}$	4.9 ± 0.2^{A}	3.3 ± 0.2^{G}	5.1 ± 0.1^{H}
RE	4.6 ± 0.2^{E}	45.2 ± 1.4^{EF}	$4.7 \pm 0.3^{\mathbf{A}}$	4.2 ± 0.1^{EF}	$\mathbf{4.4} \pm 0.2^{\mathbf{I}}$
HR	4.3 ± 0.4^{EF}	43.8 ± 1.3^{EF}	4.9 ± 0.2^{A}	4.6 ± 0.3^{DE}	7.0 ± 0.3^{F}
AS	$\mathbf{10.2} \pm 0.3^{\mathbf{A}}$	63.3 ± 0.8^{C}	$\mathbf{5.0} \pm 0.2^{\mathbf{A}}$	$\mathbf{10.5} \pm 0.8^{\mathbf{A}}$	$\mathbf{16.9} \pm 0.3^{\mathbf{A}}$
Storage time					
Control	7.9 ± 3.1^{A}	79.1 ± 36.0^{A}	4.9 ± 0.4^{A}	8.7 ± 5.2^{A}	13.2 ± 4.6^{A}
16	4.5 ± 2.2^{B}	53.3 ± 13.6^{B}	4.9 ± 0.1^{A}	4.1 ± 1.9^{B}	8.7 ± 3.9^{B}
32	2.9 ± 1.8^{C}	44.1 ± 16.6^{C}	4.8 ± 0.5^{A}	3.0 ± 1.2^{C}	5.9 ± 3.4^{C}
ANOVA					
F-Value, G	1429.8***	653.7***	1.5^{NS}	397.4***	4006.4***
F-Value, S	6283.1***	1653.3***	1.8^{NS}	1657.6***	12,668.9***
F-Value, G*S	183.9***	144***	1.1^{NS}	118.7***	391***
SE Fit	0.1	1.4	0.01	0.2	0.1

(TPC) Total phenolic compounds, (TFC) Total flavonoid compounds, (DPPH) 2,2-diphenyl-1-picrylhydrazyl, (FRAP) Ferric Reducing Antioxidant Power, (ABTS) 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid), (G) Genotypes, (S) Storability, and values are means (±) SD of triplicate samples. Means in the same column that share the same superscript letters do not differ significantly ($P > 0.05$), ***; ($P < 0.001$),^{NS}; no significant difference at ($P > 0.05$) as assessed by LSD

KN, Kenana-2; GF, Gadarif; EB, Eltayeb; RM, Radoum; TB, Tagarub; SK, Southern Kordufan; BO, Bromo; RE, Rufaee; HR, Hurhairy; AS, Abusundoug

deterioration in oils and oilseeds [58]. Thus, the present results suggest that bioactive compounds in sesame seeds might continue to effectively scavenge free radicals and mitigate oxidative damage during storage stress.

Differences in the content of phytochemicals and antioxidant capacity were noted among the genotypes in the present study (Table 4). In general, high content and capacity were found for the light brown landrace AS, except for TFC, for which the whitish-released cultivar GF showed the highest value (Table 4). However, no consistency was found in the variation of phytochemicals and antioxidant capacity among the evaluated genotypes, and additional studies incorporating a higher number of genotypes are needed to understand the genetic background for the variation.

3.4 Multivariable analysis and remarks outlook

The first principal component (PC1; explaining 34.2% of the variation) of the Principal Component Analysis (PCA) separated mainly the content of fatty acids with negative PC1 values from the content of phytochemicals and antioxidant capacity, with positive PC1 values (Fig. 1A), which indicates that samples with high fatty acid content showed low phytochemical content and low antioxidant capacity, as well as vice versa, which was verified by a Pearson correlation analysis (Fig. 1B). The PCA also visualized that prolonged storage decreased phytochemicals and antioxidant capacity (Table 4), as the control samples were placed further to the positive side along the PC1 axes than the samples stored at 32 days (Fig. 1A). The second principal component (PC2, explaining 23.8% of the variation) separated the samples based on storage time, with the control samples showing negative PC2 values and the samples stored at 32 days showing the most positive PC2 values. The loadings contributing mainly to the separation of the samples according to storage were PV (peroxide value), DC (change in color), and OC (oil content), where control samples showed low PV (Table 3) and DC (Table 1), and low OC (Table 2), oppositely to samples stored during 32 days. Previous studies have shown that the storability characteristics of oilseeds are affected by a range of factors, including moisture content, oil content, and insect

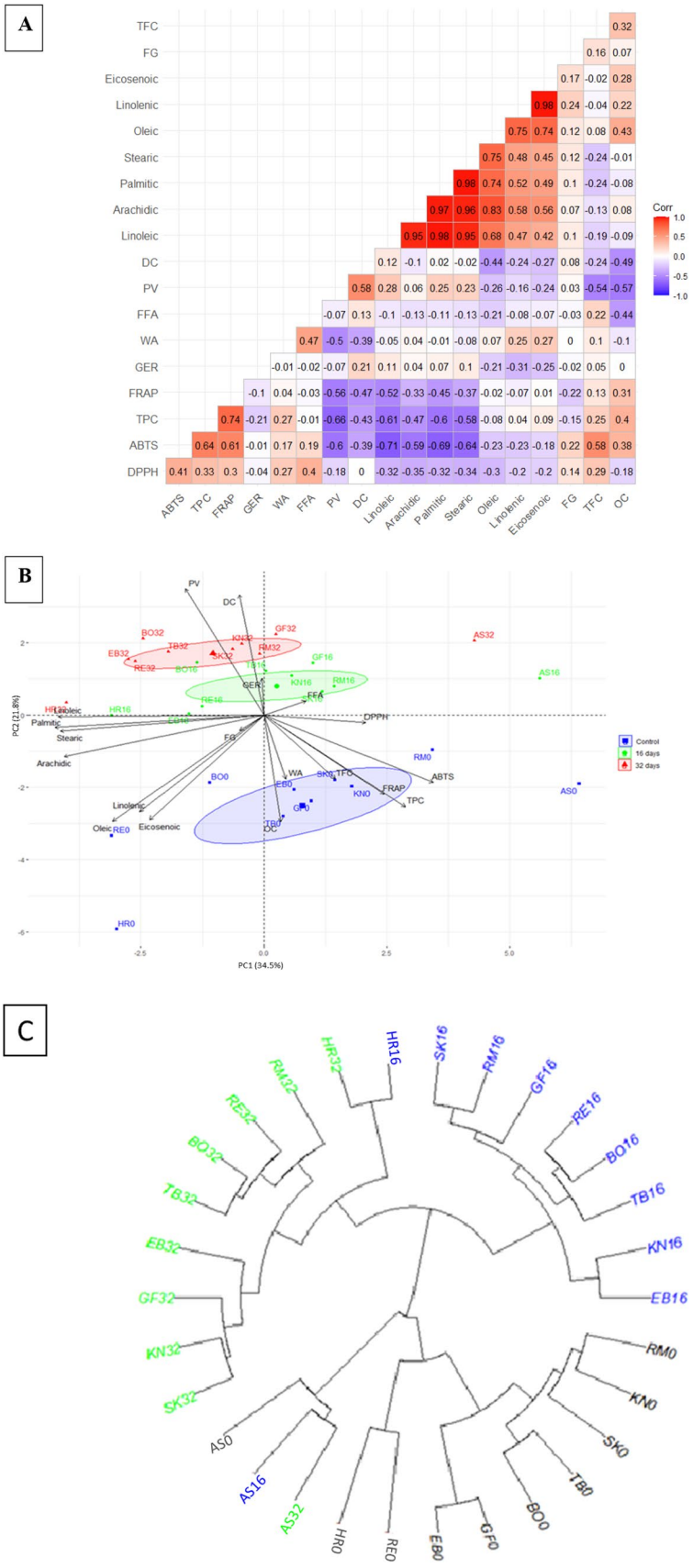

Fig. 1 Multivariate analyses comparing seed quality and storability characteristics, content of oil, fatty acids and phytochemicals, as well as antioxidant capacity in seeds of 10 sesame genotypes stored under control and accelerated condition; **A** biplot, from the principle component of analysis (PCA), combining the loading and score plot results, where Kenana-2 (KN), Gadarif (GF), Eltayeb (EB), Radoum (RM), Tagarub (TB), Southern Kordufan (SK), Bromo (BO), Rufaee (RE), Hurhairy (HR), Abusundoug (AS), Total color difference (DC), Total phenolic compounds (TPC), Total flavonoid compounds (TFC), 2,2-diphenyl-1-picrylhydrazyl (DPPH), Ferric Reducing Antioxidant Power (FRAP), 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), Water activity (WA), Germination (GER), Free fatty acids (FFA), Fungal growth (FG), and Oil content (OC), **B** correlation coefficients from a Pearson correlation analyses, and **C** a hierarchical dendrogram showing relatedness of different samples durin different length of storage

infestation [59]. Here, we could determine the importance and changes of various characters that impact the storability of sesame seeds. The important ones, e.g., PV, DC, OC, and content of phytochemicals and fatty acids, need further evaluation, and genotypic variation must be determined to be used in breeding for more storage-tolerant cultivars.

A hierarchical dendrogram (Fig. 1C), which explains the performance of the sesame cultivars across storage lengths, clustered the material into three main groups (0 days, 16 days, and 32 days) with a few exceptions. Thus, interestingly, all the AS (light brown landrace) samples (AS0 = control, AS16 and AS32 = stored 16 and 32 days) clustered together with the control (0) samples, indicating a high storage stability in that genotype. The AS genotype was found to have low levels of fatty acids (Table 2) and high levels of phytochemicals and antioxidant potential (Table 4), placing it with the highest positive PC1 values (Fig. 1A) among the genotypes. Additionally, HR16 was clustered with HR32 (dark brown landrace) in the cluster with accelerated storage in 32 days, indicating low storage stability in this genotype. The HR genotype was found to have a high content of fatty acids (Table 2), and HR16 and HR32 were placed with the most negative PC1 values. Therefore, the present results contribute a basis for understanding essential characteristics to evaluate storage stability in sesame. The AS and the HR are Sudanese landraces, and none have been previously evaluated concerning storage quality. Previous studies have indicated the importance of incorporating genes from landraces into adapted cultivars to improve the quality traits for long shelf-life and storage [60]. Thus, specifically, AS should be further evaluated for storage stability characteristics and genes behind such characters, including an evaluation of performance over additional seasons.

4 Conclusions

The seed quality, storability characteristics, phytochemicals content, and antioxidant potential were significantly affected by accelerated storage and the length of this storage in sesame. In principle, seed color increased, oil content and oleic acid decreased, while linoleic acid increased, and fungal growth and peroxide values increased. In contrast, water activity decreased, and phytochemicals and antioxidant potential decreased as correlated with the length of the accelerated storage time. Seed color change, peroxide value, and oil content were found to be the most important characteristics of sesame, correlating with the accelerated storage time. Among the ten evaluated genotypes, one landrace (Abusundoug, light brown) exhibited superior storage stability compared to the others, which enhanced stability correlated with lower polyunsaturated fatty acids and higher levels of phytochemicals, resulting in increased antioxidant potential. Given these favorable characteristics, it is recommended that Abusundoug be further evaluated for its potential incorporation into sesame breeding programs to improve seed storage stability and nutritional quality. The findings reported here indicate a potential to improve the storage stability of Sudanese sesame, which is extremely important in this high-value commodity crop for Sudan. Under current circumstances, the produced sesame seeds in Sudan are subjected to harsh storage conditions (especially high temperatures), which mostly have a negative impact on the quality of the seeds and the oil. Improving the storage stability will contribute to income opportunities for the country and its farmers, especially as the interest in sesame oil is growing in the world market. Thus, to achieve improved storage stability in Sudanese sesame, a more extensive range of genetic material should be analyzed for fatty acid composition, phytochemical content, and antioxidant capacity to assess the variability of these components more fully across different sesame accessions. Furthermore, the genes behind the content of these characters need to be evaluated. Additionally, accelerated storage experiments should be carried out on genotypes with exceptionally high and low levels of the identified components and grown in various environments (years and localities) to increase the understanding of storage stability.

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Declarations

Competing interests The authors declare no competing interests.

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