Effects of Processing on Oxidative Stability of Sesame Oil Extracted from Intact and Dehulled Seeds

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ABSTRACT: Oxidative stability of oils extracted from intact and dehulled sesame seeds was determined by monitoring changes in fatty acid composition, iodine value (IV), peroxide value (PV), conjugated diene (CD), *para*-anisidine value (*p*-AV), and 2-thiobarbituric acid (TBA) value and by nuclear magnetic resonance spectroscopy after storage under Schaal oven conditions at 65°C for up to 35 d. The oils from coated seeds were more stable, as reflected in PV, CD, *p*-AV and TBA values, than those extracted from dehulled seeds after roasting at 200°C, steaming at 100°C, roasting at 200°C plus steaming, or microwaving at 2450 MHz, except for TBA values of oil from microwaved seeds. After 35 d of storage at 65°C, the CD, *p*-AV, and TBA values of extracted oil from dehulled microwaved seeds were 17.72, 10.20, and 1.22, respectively, while those of their coated counterparts were significantly ($P < 0.05$) different at 14.20, 16.47, and 1.26, respectively. Few significant changes were evident in the fatty acid composition of oil obtained from either coated and dehulled seeds subjected to different treatments. Nuclear magnetic resonance analyses found that R_{ao} (aliphatic to olefinic protons) and R_{ad} (aliphatic to diallylmethylene protons) ratios increased steadily over the entire storage period, which indicated progressive oxidation of unsaturated fatty acids.

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KEY WORDS: Dehulling, microwaving, oxidative stability, roasting, sesame seed oil, steaming.

Sesame (*Sesamum indicum* L.), also known as sesamum, gingelly and sim-sim, is an important annual oilseed crop cultivated in India, China, Sudan and Burma, which are the major sesame-producing countries and contribute to 60% of the global production (1). Sesame, which has been cultivated for centuries for its high content of edible oil (55%) and protein (20%), is used extensively in baked and confectionery products. The oil, which has a mild odor, requires little or no winterization for use as a salad oil and is used as a cooking oil, for shortening, margarine, soap, and pharmaceuticals, and as a carrier for insecticides.

Dehulling of sesame seeds is necessary because the hulls contain a large amount of undesirable oxalic acid and indigestible fiber; the latter imparts a dark color to the meal. Dehulling eliminates oxalates and also serves as a preliminary step for preparing a nonbitter, light-colored, low-fiber, and protein-rich flour. Dehulling improves oil recovery and also may enhance the nutritional value of sesame products (2). The protein-rich meal obtained after oil extraction is used in animal feed, but meal from dehulled and defatted seeds may also be used in food products as a source of methionine (1). In some Eastern countries, sesame seeds are used mainly for preparing tehina (sesame butter) and halawa tehinia (a sesame sweet). Unlike many other oilseeds, defatted flour obtained from dehulled sesame seeds is devoid of undesirable pigments (3).

The conventional process for preparing of sesame oil involves cleaning, optional dehulling, roasting, grinding, cooking, and pressing (4). Color and composition of the oil are influenced by conditions under which roasting is carried out. Yen and Shyu (5) have reported that oxidative stability of sesame oil depended on the roasting temperature of seeds. At temperatures exceeding 240°C, roasting developed a strong, undesirable flavor in the resultant oil and adversely affected quality (6).

To our knowledge, there are no reports on the effect of dehulling on the stability of sesame oil. Other processing conditions, such as microwaving and steaming, in conjunction with roasting of sesame seed, have not received much attention in the literature. Therefore, the present study was undertaken to investigate the effects of dehulling of sesame seeds and processing conditions on oxidative stability of extracted sesame oils.

MATERIALS AND METHODS

Materials. Seeds from *Sesamum indicum* L. (Giza 24, Egyptian variety) were obtained from Sacs Company (Alexandria, Egypt). All chemicals used were acquired from Sigma (St. Louis, MO) or Aldrich Chemical Company (Milwaukee, WI).

Sample preparation. Seeds used were raw, roasted at 200°C for 20 min, steamed at 100°C for 20 min, roasted at 200°C for 15 min + steamed at 100°C for 7 min, or microwaved at 2450 MHz for 15 min. The roasting temperature of 200°C was selected to prevent development of undesirable flavor as reported for seeds roasted at 240°C. Seed treatments were carried out by spreading one layer of seeds over a

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meshed screen. Roasting was performed in a kitchen convection oven, while roasting was achieved over steam generated from boiling water. Microwaving was carried out in a Panasonic microwave oven (Matsushita Electric of Canada, Mississauga, Ontario). Sesame oils were prepared by extracting 100 g of seeds (coated or dehulled as obtained from the supplier) with 1000 mL of hexane in a Waring blender (Fisher Scientific, Nepeon, Ontario) at 4°C. The extraction was repeated, and combined extracts were desolventized in a rotary evaporator at 35°C.

Storage conditions. Oil (25 mL) samples were kept in open containers (50-mL conical flasks) in the dark in a Precision (Model 2; Fisher Scientific Co., Nepean, Ontario, Canada) oven at 65°C for up to 35 d. Samples were removed after 2, 5, 10, 15, 20, 25, 30, and 35 d. Separate sample containers were used for each oil for each day of analyses.

Chemical analyses. Fatty acid analysis was performed as described previously (7). Official AOCS methods (8) were used for the determination of peroxide value (PV, Method Cd 8-53), iodine value (IV, Method Cd 1-25), and 2-thiobarbituric acid (TBA, Method Cd 19-90) value. The *para*-anisidine value (*p*-AV, Method 2.504) and conjugated dienes (CD, method 2.505) were determined by IUPAC (9) methods of analyses.

Nuclear magnetic resonance (NMR). NMR spectra of oil samples were recorded with a 300-MHz NMR spectrometer (General Electric GN-300; General Electric, Freemont, CA). Tetramethylsilane was used as an internal standard. Approximately 35 mg of oil was dissolved in $CDCl_3$ for NMR analysis. The total number of protons under each peak was determined on the basis of integration of the terminal methyl protons of the triacylglycerol molecules (10).

Statistical analysis. Storage tests were not replicated; however, all chemical and instrumental measurements were replicated three times, and mean values ± standard deviations are reported. Analysis of variance and Tukey's studentized range test were performed at a level of $P < 0.05$ to evaluate the significance of differences between mean values. Relationships between NMR parameters were established by linear regression.

RESULTS AND DISCUSSION

Fatty acid composition. Fatty acid composition of oils extracted from coated and dehulled seeds after roasting, steaming, roasting plus steaming and microwaving is summarized in Table 1. Although significant ($P < 0.05$) differences existed for the five prominant fatty acids of oils from different treatments or seeds, no specific trends were evident for the minor compositional changes. The ratio of unsaturated to saturated fatty acids was high with 85% oleic and linoleic acids. Yen (6) reported no change in fatty acid composition of sesame oil extracted from seeds roasted at 220°C, whereas the content of oleic and linoleic acids was drastically reduced when seeds were roasted at >240°C. Similarly, Yoshida and Kajimoto (11) found that the fatty acid composition of sesame oil

TABLE 1
Fatty Acid Composition of Sesame Seed Oil Extracted from Coated and Dehulled Seeds[a]

Fatty acid composition	Treatment				
	R	S	RS	M	RW
			Coated		
16:0	$8.4 \pm 0.05^{a,b,c}$	8.5 ± 0.04^{b}	8.2 ± 0.05^{c}	9.1 ± 0.07^{d}	8.6 ± 0.06^{b}
16:1	0.1 ± 0.02^{a}	0.1 ± 0.03^{a}	0.1 ± 0.02^{a}	0.1 ± 0.05^{a}	0.2 ± 0.04^{a}
18:0	4.9 ± 0.04^{a}	4.9 ± 0.09^{a}	5.0 ± 0.06^{a}	5.4 ± 0.03^{b}	$5.1 \pm 0.05^{a,b}$
18:1n-9	$40.2 \pm 0.09^{a,b}$	39.4 ± 0.10^{c}	39.9 ± 0.10^{a}	40.6 ± 0.11^{b}	38.6 ± 0.10^{d}
18:1n-11	$1.0 \pm 0.02^{a,b}$	1.1 ± 0.04^{a}	0.8 ± 0.03^{b}	$0.9 \pm 0.04^{a,b}$	$0.9 \pm 0.03^{a,b}$
18:2	$43.9 \pm 0.12^{a,b}$	44.0 ± 0.09^{a}	$44.3 \pm 0.17^{a,c}$	43.3 ± 0.14^{b}	44.8 ± 0.20^{c}
18:3	0.5 ± 0.04^{a}	0.5 ± 0.05^{a}	0.4 ± 0.06^{a}	0.4 ± 0.04^{a}	0.4 ± 0.02^{a}
20:0	0.6 ± 0.04^{a}	0.7 ± 0.03^{a}	0.6 ± 0.02^{a}	0.6 ± 0.03^{a}	0.6 ± 0.03^{a}
20:1	0.2 ± 0.01^{a}	0.4 ± 0.02^{a}	0.4 ± 0.02^{a}	0.3 ± 0.01^{a}	0.4 ± 0.02^{a}
20:2	0.2 ± 0.01^{a}	0.2 ± 0.01^{a}	0.2 ± 0.02^{a}	—	0.2 ± 0.01^{a}
			Dehulled		
16:0	8.3 ± 0.04^{a}	8.4 ± 0.06^{a}	8.9 ± 0.08^{b}	9.1 ± 0.10^{b}	8.9 ± 0.10^{b}
16:1	0.1 ± 0.01^{a}	0.1 ± 0.00^{a}	0.1 ± 0.02^{a}	0.1 ± 0.01^{a}	0.2 ± 0.03^{a}
18:0	4.9 ± 0.04^{a}	5.3 ± 0.09^{b}	5.3 ± 0.07^{b}	5.7 ± 0.06^{c}	5.3 ± 0.10^{b}
18:1n-9	40.0 ± 0.14^{a}	39.8 ± 0.20^{a}	39.4 ± 0.35^{a}	40.0 ± 0.56^{a}	39.6 ± 0.30^{a}
18:1n-11	0.8 ± 0.05^{a}	0.8 ± 0.06^{a}	0.8 ± 0.10^{a}	0.9 ± 0.06^{a}	0.8 ± 0.08^{a}
18:2	44.4 ± 0.65^{a}	44.1 ± 0.78^{a}	$43.9 \pm 0.90^{a,b}$	43.4 ± 1.08^{b}	43.7 ± 0.66^{b}
18:3	0.3 ± 0.04^{a}	0.4 ± 0.03^{a}	0.4 ± 0.05^{a}	0.3 ± 0.02^{a}	0.4 ± 0.06^{a}
20:0	0.6 ± 0.03^{a}	0.7 ± 0.05^{a}	0.5 ± 0.02^{a}	0.7 ± 0.01^{a}	0.7 ± 0.03^{a}
20:1	0.2 ± 0.00^{a}	0.3 ± 0.01^{a}	0.2 ± 0.01^{a}	—	0.3 ± 0.02^{a}
20:2	0.1 ± 0.00^{a}	0.1 ± 0.01^{a}	0.1 ± 0.01^{a}	—	0.1 ± 0.01^{a}

[a]After roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M), and from the raw (RW) state. Results are mean values of three determinations ± standard deviation. Values in each row bearing the same superscripts are not significantly ($P > 0.05$) different from one another.

remained unchanged after 8 min of microwave heating but exhibited a significant ($P < 0.05$) reduction in its linoleic acid content after 12 min of microwaving; similar to the results obtained in the present study. However, studies of Yoshida and Kajimoto (11) showed no significant ($P > 0.05$) difference in the amount of oleic acid after exposing the seeds to microwave heating for 16 min. This latter result does not correspond to those in the present study because the relative content of oleic acid of the oil from microwaved seeds increased ($P < 0.05$) from 38.6 to 40.6% under similar conditions.

Iodine value (IV). The IV of sesame oils decreased with increasing storage time for all treatments of coated and dehulled seeds, but the changes were slightly greater in oils extracted from coated seeds than from dehulled seeds (Table 2). The lowest IV values in the study were 99.3 and 99.4 for oils from coated seeds with roasted and microwaved treatments aged 35 d. Yen (6) reported IV of 103–108 for fresh oils prepared from both raw and roasted sesame seeds (180–240°C). These values are slightly lower than the values of 111 and 112 in the present study.

Peroxide value (PV). Oils from coated seeds had significantly ($P < 0.05$) lower PV than those from their dehulled counterparts for all treatments by 15 d of storage (Table 3). The PV of oils from coated seeds did not exceed 50 for up to 25 d of storage after all treatments, except for oil from roasted seeds, which reached a PV of 50.3. However, at 25 d of storage at 65°C, all oils from all treatments of dehulled seeds had a PV exceeding 50, except for the raw sample. This might be due to the presence of antioxidant compounds in sesame hulls that were transferred to the oil during extraction (study in progress) thus enhancing its oxidative stability. Alternatively, sesame hulls may protect and retain sesamolin, sesamol and tocopherols, which occur naturally in the seed (12) and thus be responsible for the high stability of the extracted oil. The oils extracted from dehulled raw and roasted-steamed seeds oxidized faster ($P < 0.05$) than the same treated oils from coated seeds. PV of oils after 35 d of storage were 20.92 and 113.28 for the dehulled raw, and 36.43 and 119.10 for the roasted–steamed oils from coated and dehulled seeds, respectively.

The induction period for oxidation of sesame oil extracted from coated seeds was longer than that from dehulled seeds subjected to different treatments. Deterioration of sesame oil from dehulled seeds proceeded faster than that of the oil from coated seeds during the storage period. The PV of oils extracted from dehulled roasted seeds were significantly ($P < 0.05$) higher than treatments steamed, roasted–steamed, microwaved and dehulled raw at all storage times. The PV of oils extracted from coated seeds after microwaved treatment were significantly ($P < 0.05$) higher than PV of oils extracted from dehulled raw or roasted–steamed seeds. Yoshida and Kajimoto (13) reported that PV increased gradually with increasing time of microwave heating; changing from 1.02 before heating to 2.25 and 3.23 after heating for 12 and 16 min, respectively. In this study, the corresponding change was significant ($P < 0.05$) from 0.46 to 0.89 after microwave heating for 15 min. Existing differences in the variety and storage conditions of seeds might be responsible for observed differ-

TABLE 2
Effect of Storage Under Schaal Oven Conditions at 65°C on the Iodine Values of Hexane-Extracted Oils[a]

Storage period (d)	Treatment				
	R	S	RS	M	RW
			Coated		
0	111.0 ± 0.65^{a}	111.8 ± 0.73^{a}	111.7 ± 0.59^{a}	111.1 ± 0.50^{a}	111.7 ± 0.45^{a}
2	108.6 ± 0.62^{a}	$109.3 \pm 0.57^{a,b}$	$109.4 \pm 0.33^{a,b}$	$109.2 \pm 0.59^{a,b}$	110.2 ± 0.59^{b}
5	107.2 ± 0.49^{a}	$108.6 \pm 0.54^{b,c}$	$108.0 \pm 0.41^{a,b,c}$	$107.7 \pm 0.65^{a,b}$	109.0 ± 0.49^{c}
10	$106.6 \pm 0.57^{a,b}$	$107.1 \pm 0.51^{a,b}$	$107.1 \pm 0.41^{a,b}$	106.3 ± 0.41^{a}	107.6 ± 0.37^{b}
15	104.8 ± 0.73^{a}	$105.8 \pm 0.49^{a,b}$	106.2 ± 0.73^{b}	$105.1 \pm 0.45^{a,b}$	106.3 ± 0.45^{b}
20	103.6 ± 0.51^{a}	105.6 ± 0.57^{b}	105.7 ± 0.45^{b}	103.4 ± 0.51^{a}	105.9 ± 0.57^{b}
25	101.7 ± 0.62^{a}	104.2 ± 0.50^{b}	104.7 ± 0.41^{b}	102.1 ± 0.41^{a}	105.8 ± 0.53^{b}
30	100.9 ± 0.61^{a}	102.8 ± 0.79^{b}	103.1 ± 0.29^{b}	100.2 ± 0.70^{a}	103.8 ± 0.41^{b}
35	100.9 ± 0.61^{a}	102.8 ± 0.79^{b}	103.1 ± 0.29^{b}	100.2 ± 0.70^{a}	103.8 ± 0.41^{b}
			Dehulled		
0	$111.3 \pm 0.41^{a,b}$	110.3 ± 0.42^{a}	$111.5 \pm 0.64^{a,b}$	110.7 ± 0.50^{a}	112.3 ± 0.65^{b}
2	108.7 ± 0.50^{a}	109.9 ± 0.57^{a}	109.8 ± 0.53^{a}	110.0 ± 0.41^{a}	112.0 ± 0.43^{b}
5	106.8 ± 0.52^{a}	108.4 ± 0.41^{b}	108.6 ± 0.45^{b}	109.4 ± 0.50^{b}	111.4 ± 0.49^{c}
10	104.5 ± 0.24^{a}	108.1 ± 0.41^{b}	107.8 ± 0.45^{b}	108.6 ± 0.59^{b}	110.8 ± 0.49^{c}
15	103.2 ± 0.33^{a}	$107.9 \pm 0.57^{b,c}$	106.5 ± 0.42^{b}	108.1 ± 0.46^{c}	108.9 ± 0.65^{c}
20	102.7 ± 0.16^{a}	107.4 ± 0.50^{b}	106.1 ± 0.45^{c}	107.6 ± 0.29^{b}	108.2 ± 0.62^{b}
25	102.1 ± 0.24^{a}	105.8 ± 0.57^{b}	105.6 ± 0.54^{b}	$106.3 \pm 0.43^{b,c}$	106.9 ± 0.43^{c}
30	101.4 ± 0.32^{a}	103.9 ± 0.64^{b}	103.6 ± 0.57^{b}	103.3 ± 0.49^{b}	105.7 ± 0.45^{c}
35	100.7 ± 0.49^{a}	101.8 ± 0.28^{b}	102.7 ± 0.28^{b}	101.1 ± 0.22^{c}	104.6 ± 0.41^{d}

[a]From coated and dehulled sesame seeds after roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M) and from the raw (RW) state. Results are mean values of three determinations ± standard deviation. Values in each row bearing the same superscripts are not significantly ($P > 0.05$) different from one another.

TABLE 3
Effect of Storage Under Schaal Oven Conditions at 65°C on the Peroxide Values (meq/kg) of Hexane-Extracted Oils[a]

Storage period (d)	Treatment R	S	RS	M	RW
			Coated		
0	0.88 ± 0.05[a]	0.79 ± 0.04[a]	0.98 ± 0.06[a]	0.89 ± 0.06[a]	0.46 ± 0.04[b]
2	1.96 ± 0.06[a]	1.21 ± 0.07[b]	1.43 ± 0.06[b]	1.89 ± 0.05[a]	2.13 ± 0.07[a]
5	4.73 ± 0.09[a]	2.68 ± 0.10[d]	3.80 ± 0.12[c]	6.75 ± 0.09[b]	2.72 ± 0.10[d]
10	15.83 ± 0.23[a]	7.34 ± 0.15[c]	5.86 ± 0.12[d]	14.98 ± 0.11[b]	5.73 ± 0.11[d]
15	24.82 ± 0.28[a]	13.39 ± 0.25[c]	7.25 ± 0.19[e]	22.43 ± 0.18[b]	8.46 ± 0.11[d]
20	37.25 ± 0.28[a]	27.72 ± 0.27[b]	9.64 ± 0.26[d]	36.66 ± 0.19[a]	11.04 ± 0.19[c]
25	50.33 ± 0.34[a]	47.22 ± 0.34[b]	18.45 ± 0.32[d]	49.45 ± 0.23[a]	14.94 ± 0.21[c]
30	62.65 ± 0.43[a]	60.29 ± 0.36[b]	26.22 ± 0.29[c]	62.83 ± 0.35[a]	17.36 ± 0.30[d]
35	81.02 ± 0.65[a]	76.42 ± 0.68[b]	36.43 ± 0.39[c]	76.85 ± 0.61[b]	20.92 ± 0.43[d]
			Dehulled		
0	2.34 ± 0.05[a]	0.49 ± 0.03[d]	1.74 ± 0.09[b]	1.00 ± 0.10[c]	0.80 ± 0.04[c]
2	4.78 ± 0.04[a]	1.44 ± 0.04[c]	3.64 ± 0.08[b]	1.60 ± 0.09[c]	1.43 ± 0.07[c]
5	10.15 ± 0.20[a]	1.78 ± 0.06[b]	4.57 ± 0.05[c]	2.92 ± 0.10[d]	3.50 ± 0.11[c]
10	28.24 ± 0.13[a]	4.59 ± 0.06[d]	11.01 ± 0.16[c]	11.40 ± 0.16[b,c]	11.77 ± 0.15[b]
15	42.53 ± 0.16[a]	23.45 ± 0.18[c]	28.57 ± 0.12[b]	12.23 ± 0.13[e]	16.56 ± 0.23[d]
20	49.82 ± 0.14[a]	37.29 ± 0.17[c]	41.65 ± 0.16[b]	29.75 ± 0.62[d]	29.46 ± 0.24[d]
25	79.85 ± 0.11[a]	59.23 ± 0.22[b]	52.54 ± 0.18[d]	54.00 ± 0.47[c]	47.52 ± 0.16[e]
30	118.12 ± 0.16[a]	92.45 ± 0.23[b]	89.62 ± 0.22[d]	89.65 ± 0.47[d]	84.69 ± 0.27[c]
35	160.75 ± 0.35[a]	130.44 ± 0.45[b]	119.10 ± 0.66[d]	121.55 ± 0.61[d]	113.28 ± 0.59[c]

[a]From coated and dehulled sesame seeds after roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M) and from the raw (RW) state. Results are mean values of three determinations ± standard deviation. Values in each row bearing the same superscripts are not significantly ($P > 0.05$) different from one another.

ences between these and the literature values. However, PV do not represent the absolute oxidative state of an oil because hydroperoxides, the primary oxidation products, are unstable on heating and transform rapidly to secondary oxidation products (14).

Conjugated dienes (CD). CD reflects the degree of formation of primary products of lipid oxidation due to a shift in double-bond position upon oxidation of methylene-interrupted lipid dienes or polyenes (15). CD values of all oils extracted from dehulled seeds were significantly ($P < 0.05$) higher than those of oils extracted from their coated counterparts, after 25 d of storage (Table 4). However, CD values did not exceed 9.60 and 8.40 for oils extracted from coated dehulled raw and roasted–steamed seeds, respectively, after 35 d of storage while corresponding values for oil from microwaved coated seeds reached 14.20; all these values were significantly ($P < 0.05$) different from one another. On the other hand, CD values of oils extracted from roasted–steamed, dehulled raw, and microwaved dehulled seeds reached 19.40, 17.30, and 17.72 after 35 d, respectively, whereas CD was 25.37 for oil from roasted dehulled seeds. The CD value for oil from roasted dehulled seeds was 25.37 at 35 d, whereas that from the same treatment for coated seeds reached a maximum of 15.20. Moreover, the roasted–steamed treatment was significantly ($P < 0.05$) more effective in preventing the generation of conjugated hydroperoxides compared to roasted, microwaved, and steamed treatments of coated seeds. The CD value of oil extracted from coated seeds after microwaved treatment was significantly ($P < 0.05$) higher than oils extracted from roasted–steamed and dehulled raw seeds after 15 d of storage but was generally close to those of extracted oils from roasted and steamed seeds. The changes in CD paralleled trends observed for PV, and a correlation coefficient of 0.944 existed between PV and CD. Jackson (16) indicated that formation of hydroperoxides normally coincided with CD formation.

2-Thiobarbituric acid (TBA) values. The TBA values, expressed as μg malonaldehyde equivalents per g sample, of oils extracted from coated and dehulled sesame seeds increased slowly during the storage period for all samples. Moreover, TBA values of oils (Table 5) from microwaved seeds were only 1.22 for dehulled samples and 1.26 for coated samples after 35 d of storage. Corresponding differences between coated and dehulled samples of R, S and RS seeds after 35 d of storage were insignificant ($P > 0.05$). The low TBA values of sesame oils may be due either to the presence of sesamol and γ-tocopherol in the oil or to the low content of linolenic acid (0.3–0.5%). These low levels are similar to those reported in the literature (15,17).

para-Anisidine values (P-AV). A gradual increase in *p*-AV of oils after different treatments of coated and dehulled seeds was observed as storage period increased (Table 6). The increase of *p*-AV was higher for all oils extracted from dehulled seeds, compared to coated seeds, except for that from microwaved treatment after the entire storage period. Moreover, oil extracted from coated seeds after microwaved treatment showed the highest *p*-AV (16.47) for coated samples, whereas oil extracted from dehulled seeds after steamed and roasted treatments exhibited the highest *p*-AV of 17.40 and 14.85, respectively. Oils extracted

TABLE 4
Effect of Storage Under Schaal Oven Conditions at 65°C on the Production of Conjugated Dienes of Hexane-Extracted Oils[a]

Storage period (d)	Treatment R	S	RS	M	RW
			Coated		
0	3.09 ± 0.06[a]	3.07 ± 0.06[a]	2.66 ± 0.05[b]	2.87 ± 0.04[c]	2.34 ± 0.03[d]
2	3.45 ± 0.04[a]	3.20 ± 0.11[b]	3.11 ± 0.09[b]	3.26 ± 0.07[a,b]	3.06 ± 0.06[b]
5	3.89 ± 0.11[a]	3.49 ± 0.16[b]	3.45 ± 0.10[b]	3.81 ± 0.09[a]	3.29 ± 0.10[b]
10	4.60 ± 0.11[a]	4.39 ± 0.16[a]	4.40 ± 0.14[a]	4.50 ± 0.10[a]	4.10 ± 0.11[b]
15	5.26 ± 0.05[a]	5.00 ± 0.15[b,c]	4.79 ± 0.14[c]	7.25 ± 0.09[a]	4.69 ± 0.12[c]
20	8.35 ± 0.18[a]	7.21 ± 0.15[b]	6.65 ± 0.18[c]	8.43 ± 0.11[a]	5.25 ± 0.11[d]
25	12.40 ± 0.16[a]	8.49 ± 0.21[b]	7.92 ± 0.21[b]	9.24 ± 0.14[c]	6.41 ± 0.13[d]
30	14.27 ± 0.08[a]	12.11 ± 0.25[b]	8.42 ± 0.24[c]	11.11 ± 0.16[d]	7.11 ± 0.13[e]
35	15.20 ± 0.27[a]	14.80 ± 0.21[a,b]	9.60 ± 0.28[c]	14.20 ± 0.20[b]	8.40 ± 0.14[d]
			Dehulled		
0	3.07 ± 0.05[a]	2.62 ± 0.07[b]	2.48 ± 0.06[c]	2.23 ± 0.05[d]	2.23 ± 0.05[d]
2	3.90 ± 0.09[a]	2.86 ± 0.05[b]	3.22 ± 0.08[c]	2.90 ± 0.05[b]	2.67 ± 0.08[b]
5	5.24 ± 0.14[a]	3.38 ± 0.07[c]	3.72 ± 0.10[b]	3.31 ± 0.05[c]	3.22 ± 0.09[c]
10	6.10 ± 0.11[a]	3.84 ± 0.11[b]	3.96 ± 0.09[b]	3.53 ± 0.10[c]	3.40 ± 0.15[c]
15	7.82 ± 0.14[a]	5.55 ± 0.11[b]	5.84 ± 0.10[b]	4.57 ± 0.10[c]	4.43 ± 0.15[c]
20	10.30 ± 0.12[a]	6.48 ± 0.13[b]	7.23 ± 0.15[c]	5.83 ± 0.15[d]	5.65 ± 0.12[d]
25	13.27 ± 0.16[a]	10.30 ± 0.12[b]	10.36 ± 0.13[b]	9.99 ± 0.15[b,c]	9.66 ± 0.21[c]
30	19.20 ± 0.15[a]	14.93 ± 0.16[b]	16.96 ± 0.13[c]	14.60 ± 0.12[b]	13.94 ± 0.20[d]
35	25.37 ± 0.14[a]	19.20 ± 0.16[b]	19.40 ± 0.14[b]	17.72 ± 0.17[c]	17.30 ± 0.20[c]

[a]From coated and dehulled sesame seeds after roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M) and from the raw (RW) state. Results are mean values of three determinations ± standard deviation. Values in each row bearing the same superscripts are not significantly ($P > 0.05$) different from one another.

TABLE 5
Effect of Storage Under Schaal Oven Conditions at 65°C on the 2-Thiobarbituric Acid Reactive Substances (TBARS; Malonaldehyde Equivalents in μg/g oil) Values of Hexane-Extracted Oils[a]

Storage period (d)	Treatment R	S	RS	M	RW
			Coated		
0	0.22 ± 0.02[a]	0.21 ± 0.02[a,b]	0.14 ± 0.03[c]	0.18 ± 0.02[a,b,c]	0.15 ± 0.02[b,c]
2	0.30 ± 0.02[a]	0.25 ± 0.03[a,b]	0.18 ± 0.05[b]	0.22 ± 0.02[a,b]	0.19 ± 0.03[b]
5	0.57 ± 0.10[a]	0.46 ± 0.08[a,b]	0.34 ± 0.07[b]	0.40 ± 0.04[a,b]	0.32 ± 0.04[b]
10	0.70 ± 0.06[a]	0.64 ± 0.07[a,b]	0.50 ± 0.08[b]	0.56 ± 0.04[a,b]	0.48 ± 0.06[b]
15	0.92 ± 0.13[a]	0.89 ± 0.14[a]	0.69 ± 0.10[a]	0.74 ± 0.04[a,b]	0.65 ± 0.07[a]
20	1.09 ± 0.08[a]	0.95 ± 0.05[a,b]	0.84 ± 0.07[b]	0.90 ± 0.04[b]	0.78 ± 0.07[b]
25	1.20 ± 0.18[a]	1.11 ± 0.14[a,b]	0.96 ± 0.14[a,b]	0.99 ± 0.07[a,b]	0.89 ± 0.09[b]
30	1.32 ± 0.14[a]	1.20 ± 0.10[a,b]	1.05 ± 0.06[b]	1.10 ± 0.07[a,b]	1.00 ± 0.05[b]
35	1.49 ± 1.15[a]	1.32 ± 0.13[a,b]	1.14 ± 0.08[b]	1.26 ± 0.10[a,b]	1.10 ± 0.10[b]
			Dehulled		
0	0.25 ± 0.04[a]	0.22 ± 0.05[a]	0.16 ± 0.06[a]	0.16 ± 0.05[a]	0.15 ± 0.05[a]
2	0.35 ± 0.05[a]	0.32 ± 0.08[a]	0.20 ± 0.03[a]	0.18 ± 0.06[a]	0.18 ± 0.08[a]
5	0.66 ± 0.10[a]	0.59 ± 0.09[a]	0.36 ± 0.06[b]	0.32 ± 0.07[b]	0.30 ± 0.05[b]
10	0.79 ± 0.11[a]	0.70 ± 0.10[a]	0.50 ± 0.10[b]	0.48 ± 0.08[b]	0.45 ± 0.06[b]
15	0.92 ± 0.12[a]	0.89 ± 0.09[a]	0.68 ± 0.13[a,b]	0.68 ± 0.10[a,b]	0.63 ± 0.10[b]
20	1.06 ± 0.10[a]	0.98 ± 0.10[a,b]	0.85 ± 0.13[a,b]	0.86 ± 0.10[a,b]	0.79 ± 0.10[b]
25	1.22 ± 0.22[a]	1.14 ± 0.14[a]	0.95 ± 0.09[a]	0.98 ± 0.14[a]	0.90 ± 0.10[a]
30	1.37 ± 0.17[a]	1.32 ± 0.13[a]	1.10 ± 0.10[a]	1.11 ± 0.15[a]	1.03 ± 0.14[a]
35	1.65 ± 0.20[a]	1.49 ± 0.16[a,b]	1.20 ± 0.20[b]	1.22 ± 0.22[b]	1.15 ± 0.13[b]

[a]From coated and dehulled sesame seeds after roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M) and from the raw (RW) state. Results are mean values of three determinations ± standard deviation. Values in each row bearing the same superscripts are not significantly ($P > 0.05$) different from one another.

TABLE 6
Effect of Storage Under Schaal Oven Conditions at 65°C on *para*-Anisidine Values (*p*-AV) of Hexane-Extracted Oils[a]

Storage period (d)	Treatment R	S	RS	M	RW
			Coated		
0	1.45 ± 0.06^{a}	1.36 ± 0.06^{a}	1.16 ± 0.07^{b}	1.27 ± 0.05^{a}	1.12 ± 0.07^{c}
2	2.04 ± 0.10^{a}	1.79 ± 0.12^{b}	1.49 ± 0.08^{c}	1.53 ± 0.10^{c}	1.36 ± 0.09^{c}
5	2.53 ± 0.12^{a}	$2.34 \pm 0.13^{a,c}$	2.06 ± 0.14^{d}	$2.22 \pm 0.12^{b,c}$	1.94 ± 0.09^{d}
10	3.72 ± 0.14^{a}	$3.81 \pm 0.10^{a,c}$	2.45 ± 0.17^{d}	$3.47 \pm 0.15^{b,c}$	2.65 ± 0.10^{d}
15	4.54 ± 0.20^{b}	3.92 ± 0.17^{c}	2.68 ± 0.18^{e}	4.86 ± 0.16^{a}	3.34 ± 0.12^{d}
20	5.38 ± 0.16^{b}	4.95 ± 0.17^{c}	3.45 ± 0.26^{e}	6.46 ± 0.26^{a}	4.37 ± 0.15^{d}
25	8.62 ± 0.25^{b}	8.15 ± 0.22^{c}	6.85 ± 0.19^{d}	9.13 ± 0.30^{a}	6.16 ± 0.43^{e}
30	9.93 ± 0.29^{b}	9.44 ± 0.27^{b}	7.69 ± 0.30^{c}	12.75 ± 0.38^{a}	6.92 ± 0.26^{d}
35	12.35 ± 0.40^{b}	12.63 ± 0.33^{b}	10.46 ± 0.33^{c}	16.47 ± 0.47^{a}	9.73 ± 0.29^{d}
			Dehulled		
0	1.42 ± 0.06^{a}	1.47 ± 0.13^{a}	1.12 ± 0.11^{a}	1.12 ± 0.12^{a}	1.10 ± 0.09^{a}
2	1.84 ± 0.11^{b}	$1.69 \pm 0.15^{b,c}$	1.45 ± 0.16^{c}	2.34 ± 0.18^{c}	1.92 ± 0.24^{b}
5	$214 \pm 0.16^{a,b}$	1.85 ± 0.14^{b}	3.27 ± 0.27^{c}	2.96 ± 0.28^{c}	2.34 ± 0.25^{a}
10	2.42 ± 0.14^{a}	3.01 ± 0.21^{b}	3.81 ± 0.22^{c}	3.55 ± 0.28^{c}	$3.25 \pm 0.30^{b,d}$
15	3.85 ± 0.15^{a}	$4.31 \pm 0.22^{a,b}$	4.58 ± 0.31^{b}	4.26 ± 0.26^{b}	4.34 ± 0.34^{b}
20	4.98 ± 0.12^{a}	5.07 ± 0.24^{a}	4.76 ± 0.21^{b}	5.73 ± 0.30^{b}	4.82 ± 0.32^{a}
25	5.28 ± 0.19^{a}	7.42 ± 0.28^{b}	6.92 ± 0.30^{b}	7.14 ± 0.35^{b}	6.94 ± 0.37^{b}
30	10.03 ± 0.14^{a}	12.51 ± 0.36^{b}	8.46 ± 0.41^{c}	8.31 ± 0.49^{c}	$8.84 \pm 0.27^{a,c}$
35	14.85 ± 0.33^{a}	17.40 ± 0.43^{b}	10.78 ± 0.45^{c}	10.20 ± 0.46^{c}	11.87 ± 0.46^{d}

[a]From coated and dehulled sesame seeds after roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M) and from the raw (RW) state. Results are mean values of three determinations ± standard deviation. Values in each row bearing the same superscripts are not significantly ($P > 0.05$) different from one another.

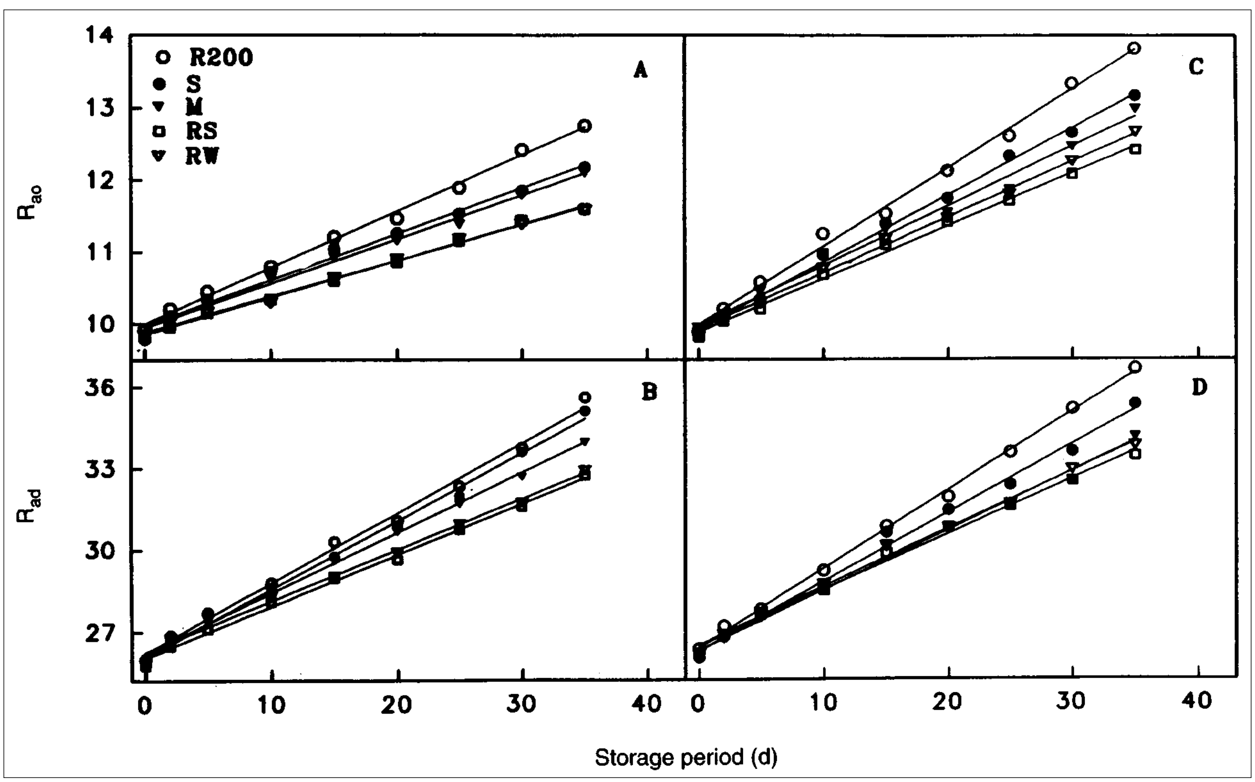

FIG. 1. Relationship between the ratio of aliphatic to olefinic (R_{ao}) protons and storage at 65°C for 35 d, (A); relationship between the ratio of aliphatic to diallylmethylene (R_{ad}) protons and storage period, (B); for sesame oil extracted from coated seeds after different treatments. Corresponding results for oil extracted from dehulled seeds are given in (C) and (D), respectively. Treatments employed were roasting at 200°C (R), steaming at 100°C (S), roasting at 200°C + steaming (RS), microwaving at 2450 MHz (M) and in the raw (RW) state.

from dehulled raw or roasted–steamed seeds both exhibited the lowest *p*-AV after the entire storage period. Presence of hulls may somehow retard the effect of microwave heating on seeds. The *p*-AV and TBA values of oils extracted from microwaved coated seeds were 1.27 and 0.18, respectively; these values were much lower than those (2.04 and 1.03, respectively) reported by Yoshida and Kajimoto (11) and are perhaps due to existing differences in oil extraction.

NMR spectroscopy. The ^{1}H NMR spectra exhibited changes in relative proportions of aliphatic, olefinic, and diallylmethylene protons of sesame oils during storage. The ratios of aliphatic to olefinic (R_{ao}) and aliphatic to diallylmethylene (R_{ad}) protons are shown in Figure 1. There was a gradual and significant ($P < 0.05$) increase in both R_{ao} and R_{ad} values during storage for oils extracted from both coated and dehulled seeds, indicating progressive oxidation of unsaturated fatty acids of oils from raw and treated seeds. Oils from dehulled seeds after all treatments showed higher R_{ao} and R_{ad} values than oil from coated seeds after the same treatments. This reflected lower numbers of total olefinic and diallylmethylene protons in sesame oil from dehulled seeds than those from coated seeds. Meanwhile, a corresponding gradual increase was observed for total number of aliphatic protons in all oils examined.

Oxidative stability of sesame oil was decreased by dehulling of seeds, especially for oils obtained from raw and roasted–steamed seeds. Possible release of natural antioxidants, present in seed hulls of coated samples, may be responsible for better stability of these oils as compared with the oil from dehulled seeds. However, the reason for better stability of oils from raw and roasted–steamed seeds is unknown. Moreover, oils extracted from coated and dehulled seeds after microwaving oxidized more quickly than those from other treatments. Therefore, microwaving is not recommended for preparing stable sesame oil, while roasting–steaming treatment provided the oil with the most oxidative stability.

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