Oxidative and Flavor Stabilities of Soybean Oils with Low- and Ultra-Low-Linolenic Acid Composition

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ABSTRACT: The effects of linolenic acid (18:3) concentration, combined with TBHQ addition, temperature, and storage time, on the oxidative and flavor stabilities of soybean oils (SBO) were evaluated. During storage under fluorescent light at both 21 and 32°C, the SBO with ultra-low-18:3 concentration (1.0%, ULSBO) generally had greater oxidative stability than did SBO with low-18:3 concentration (2.2%, LLSBO). The ULSBO had about half the *p*-anisidine value of LLSBO throughout storage. Although the ULSBO initially had significantly greater PV and poorer (lower) sensory scores for overall flavor quality than did LLSBO, significant differences disappeared with storage. The ULSBO had a lower content of polar compounds and greater oil stability indices than did LLSBO when TBHQ was present. All oils were more oxidatively stable with TBHQ addition, but the TBHQ addition did not result in improved flavor stability early in storage. In all tests, oils stored at 32°C were less stable than oils stored at 21°C. The TBHQ had a better antioxidant capacity when the 18:3 concentration was lower. The retardation effect of TBHQ on lipid oxidation and the improved stability of ULSBO over LLSBO were more easily detected when the storage temperature was higher.

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KEY WORDS: Fatty acid composition, flavor stability, linolenic acid concentration, oxidative stability, soybean oil.

Soybean oil (SBO) has a good nutritional profile because of its high proportion of unsaturated FA, but SBO has poor oxidative stability and is prone to flavor deterioration. The FA linolenic acid (18:3) oxidizes very quickly and is the most important precursor of flavor deterioration in 18:3-containing oils (1,2). Hydroperoxides formed by oxidation of 18:3 can break down to many undesirable flavor compounds such as 2,4-heptadienal, 2-butylfuran, 2- and/or 3-hexenal, 2-pentenal, and butanal (3). To improve oxidative stability and flavor quality, the SBO may be hydrogenated to reduce the concentration of PUFA; however, *trans* FA (*t*FA) are formed during this process. Because of health concerns over the presence of *t*FA in our diets (4,5), lowering the 18:3 content to a level similar to that obtained by partial hydrogenation, but without *trans* formation, has been an objective of plant breeders. Another advantage to producing oils needing no additional processing is that fewer processing costs should result in more profit for farmers and processors (6). Previous studies (7–9) determined that the oxidative and flavor stabilities of oils were inversely proportional to the initial 18:3 concentration. Although considerable information is available regarding the relationship between oxidative and flavor stability of SBO and 18:3 concentration, soybean breeders need more precise compositional targets to produce SBO that have good oxidative and flavor stabilities. The objective of this research was to study the effects of two low levels of 18:3 concentration (~1.0 and 2.2%) combined with TBHQ addition, temperature, and storage time on the oxidative and flavor stabilities of SBO.

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MATERIALS AND METHODS

SBO and design. Soybeans (*Glycine max*) with low-18:3 (2.2%) and ultra-low-18:3 (1.0%) concentrations, grown in summer 2000 in Iowa (weather zone 2), were obtained from Protein Technologies, Inc. (St. Louis, MO). The low-linolenic acid (LL) soybeans were crushed at the Montana Power Group plant (Culverston, MT), and the ultra-low-linolenic acid (UL) soybeans were crushed at the POS Pilot Plant Corporation in Saskatoon (Saskatchewan, Canada). Both oils were hexane-extracted and refined, bleached, deodorized, and bottled at the POS Plant. Citric acid (50 ppm) was added to the oils during the cool-down stage of deodorization. The antioxidant, TBHQ (100 ppm), was added to half of each oil type at the deodorization step before bottling in co-extruded polyethylene terephthalate (PET) plastic bottles. The bottles were sparged with nitrogen until they contained less than 2% oxygen in the headspace, then sealed. It was not possible to measure the oxygen concentration in the actual bottles being used in the study, because the caps would be ruined in the process. Thus, identical bottles were sealed with a septum after oil processing and nitrogen sparging, and their headspace oxygen content was measured by inserting a syringe through the seal, withdrawing the headspace, and injecting the headspace onto a Hewlett-Packard GC (HP model 5890, series II) equipped with a MS detector (HP model 5972). The percentage oxygen was calculated from the oxygen-to-nitrogen ratio in the headspace. Bottled oils were sent to Iowa State University (ISU; Ames, IA) for evaluation. Thus, four SBO treatments were tested, including low-18:3 SBO (LLSBO), LLSBO with the addition of 100 ppm TBHQ (LLSBOW), ultra-low-18:3 SBO (ULSBO), and ULSBO with the addition of 100 ppm TBHQ (ULSBOW). For each of these four treatments, two bottles were retained at arrival, and the remaining bottles were stored under fluorescent

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light with uniform exposure of 70 footcandle light intensity at 21 and 32°C for 12 mon. Duplicate bottles of oil from each treatment were analyzed in duplicate at 0, 2, 4, 6, 8, 10, and 12 mon of storage.

Chemicals. Tetrachloroethane (98+%), lauroyl peroxide (97%), *p*-anisidine (99%), and sodium methoxide (0.5 M solution in methanol, ACS reagent) were purchased from Aldrich Chemical Co. (Milwaukee, WI). Isooctane, *s*-diphenylcarbazide, ethyl ether, acetic acid glacial (certified ACS grade), and petroleum ether (Optima) were purchased from Fisher Scientific Inc. (Fairlawn, NJ). Silica gel 60, particle size 0.063–0.200 mm, was from E. Merck Science (Gibbstown, NJ). The individual tocopherols, including *d*-α-tocopherol, *d*-γ-tocopherol, and *d*-δ-tocopherol (90% pure), were purchased from Sigma-Aldrich, Inc. (St. Louis, MO).

FA composition by GC. FA compositions of SBO were determined by converting TAG into FAME according to a method described by Hammond (10). The GC conditions were the same as described by Shen *et al*. (6).

Tocopherol contents by HPLC. Tocopherol contents of the oils were determined according to AOCS Official Method Ce 8-89 (11) by using the System Gold® HPLC equipped with a UV detector and solvent miser silica 5-μ column (length 250 mm, i.d. 2.1 mm; Alltech Associates, Inc., Deerfield, IL). Tocopherol content in native soybean seeds was obtained from oil extracted with hexane after crushing the seed with a hydraulic press, as described by Hammond (10).

Oil stability indices (OSI). The OSI were analyzed according to AOCS Official Method Cd 12b-92 (11) with the Oxidative Stability Instrument (Onion, Inc., Rockland, MA) at 110°C with an air flow rate of 150 mL/min.

PV. The PV was determined by the Stamm test as modified by Hamm *et al*. (12). The commercially available tetrachloroethane was purified by the following steps: adding 1% lauroyl peroxide, heating in a boiling water bath for 1 h, distilling at 60°C by using a rotary evaporator, adding 0.2% *s*-diphenylcarbazide, heating in a boiling water bath for 1 h, distilling at 60°C with the rotary evaporator, and, finally, collecting the purified solvent from the receiver flask. Purity of the solvent was judged by having a nil or nearly nil reading at 565 nm on a spectrophotometer.

p-*Anisidine value (*p-*AV).* The *p*-AV was measured by using AOCS Official Method Cd 18-90 (11).

Polar compounds. The percentage of polar compounds was measured according to AOCS Official Method Cd 20-91 (11).

Lovibond colors (colors). Colors were measured based on AOCS Official Method Cc 13e-92 (11) by using an AOCS Tintometer AF710 with a sample tube depth of 5.25 in. (13.3 cm).

Sensory evaluations. Sensory evaluations were conducted according to AOCS Recommended Practice Cg 2-83 (11). A 15-member trained descriptive panel was used to evaluate overall flavor quality and individual off-flavor intensities of SBO. All panelist candidates were trained during three 1.5-h sessions. During training, panelists were given standards for off-flavor characteristics found in SBO. These standards included fresh SBO purchased from a local store and SBO treated to have buttery, grassy, and painty flavors, and a bitter taste (0.1% caffeine in commercial fresh SBO), respectively, prepared according to AOCS method Cg 2-83 (11). Panelists who could not recognize these standards after training were dismissed as panelists.

For the actual tests, the SBO were held at 50°C; placed in plastic cups labeled with random, three-digit codes; and presented in random order to panelists. To avoid tasting fatigue and flavor carryover, panelists were asked to expectorate the sample after tasting and to rinse their mouths with distilled water between tasting samples. Tests were conducted in individual, lighted booths. The oils were evaluated for overall flavor quality on a 10-point scale (10 = excellent quality, 9 and 8 = good, 7 and 6 = fair, 5 and 4 = poor, 3, 2, and 1 = very poor) and for intensity of individual flavors described by the AOCS method Cg 2-83 (11) on a 10-point scale (10 = bland, 9 = trace, 8 = faint, 7 = slight, 6 = mild, 5 = moderate, 4 = definite, 3 = strong, 2 = very strong, 1 = extreme). Individual flavors included nutty, buttery, corny, beany, hydrogenated, burned, weedy, grassy, rubbery, melon, painty, and fishy. Overall flavor-quality scores were calculated as the average of all scores given by the panelists. Intensity of a flavor was calculated as the average of the intensity scores by the panelists who detected the flavor.

Triangle tests were done following standard procedures (13) to determine whether the overall flavor characteristics between SBO, with and without TBHQ addition, were different.

Statistical analysis. A randomized $2 \times 2 \times 2$ factorial design was used. Data from all treatments were analyzed by an SAS full-way variance procedure (14). Differences in mean values among treatments were determined by the least significant difference test at $\alpha = 0.05$ unless listed otherwise.

RESULTS AND DISCUSSION

FA composition, calculated oxidizability, iodine value (*IV*), and *Totox value*. Initially, all the ULSBO treatments contained similar amounts of 16:0 and 18:0, slightly more 18:1, slightly less 18:2, and less 18:3 (1.0%) than did all the LLSSBO treatments (2.2% 18:3) (Table 1). Values for calculated oxidizability and IV suggest that all the ULSBO treatments would be more stable than all the LLSBO treatments. There were no differences in FA composition, calculated oxidizability, or IV between LLSBO and LLSBOW and between ULSBO and ULSBOW. The FA composition of all oils did not change during storage at 21 or 32°C for 12 mon.

Tocopherols. Initially and after 12-mon storage, the ULSBO and ULSBOW contained much less α-, γ-, δ-, and total tocopherols than did LLSBO and LLSBOW (Table 2). The ULSBO and ULSBOW had less total loss and a slightly lower percentage of total loss than did LLSBO and LLSBOW, suggesting that tocopherols in ULSBO and ULSBOW were less consumed or exhausted than in LLSBO and LLSBOW.

To determine whether the differences in tocopherol contents between the ULSBO and LLSBO were inherent in the beans or resulted during processing, seeds from two lines of UL and three lines of LL soybeans grown in four different environments and of the same genetic background as those used in the current

TABLE 1
FA Composition (area %), Calculated Oxidizability[a], Iodine Value[b], and Totox Value[c] of Soybean Oils (SBO) with Low- and Ultra-Low-Linolenic Acid (18:3) Concentrations

	FAME								
Oils[d]	16:0 (palmitic)	18:0 (stearic)	18:1 (oleic)	18:2 (linoleic)	18:3 (linolenic)	Oxidizability	Iodine value	Totox value Before	Totox value After
LLSBO	11.1	5.0	23.0	58.7	2.2	6.8	127.2	6.1	55.9
ULSBO	11.4	5.0	25.2	57.4	1.0	6.4	123.7	2.8	43.6

[a]Oxidizability = [oleate% + 10.3 (linoleate%) + 21.6 (linolenate%)]/100 (Ref. 1).
[b]Iodine values were calculated from the FAME profile, according to AOCS Official Method Cd 1c-85 (Ref. 11).
[c]Totox value = [*p*-AV + 2 PV] (Ref. 16) of SBO initially and at the end of the 12-mon storage; the values are the means of all LLSBO or all ULSBO, regardless of the level of TBHQ addition and storage temperature.
[d]LLSBO = SBO with low-18:3 concentration; ULSBO = SBO with ultra-low-18:3 concentration.

study were analyzed (McCord, K., personal communication). There were no differences in the concentrations of tocopherol homologs or total tocopherol concentration between the ULSBO and LLSBO, or among the different growing environments. A tendency observed by Shmulovich (15) for increased polyunsaturation of SBO with increased tocopherol content did not exist in the current study. Thus, the differences in the tocopherol concentrations found in the processed oils used in the current study were likely a result of processing. Nonetheless, and despite the lower tocopherol levels, ULSBO showed better stability than did LLSBO as discussed in the following sections.

OSI. The OSI of all SBO treatments decreased during storage, suggesting a decrease in oxidative stability overall (Table 3). Throughout storage, oils with TBHQ addition had significantly greater OSI than did the oils without TBHQ addition for the same 18:3 concentration and storage temperature. The LLSBO tended to have greater OSI values than did the ULSBO when TBHQ was absent and at the same storage temperature, but differences were small and not usually statistically significant. When TBHQ was present, the opposite trend was observed; that is, the ULSBOW had a greater OSI than did the LLSBOW at the same storage temperature. The statistical analysis for a null interaction hypothesis between the effects of 18:3 content and TBHQ addition on OSI revealed an interaction ($P < 0.001$). Oils stored at 21°C had greater OSI than did the oils stored at 32°C with the same 18:3 content and TBHQ level. But, in general, the differences were significant only when TBHQ was present, which suggests an interaction between the effects of temperature and TBHQ addition on OSI. Statistical analysis demonstrated an interaction ($P = 0.0061$) between the effects of temperature and TBHQ addition on OSI. The antioxidant TBHQ is a common chain-breaking antioxidant used in food lipids to interfere with either chain propagation or initiation of lipid oxidation *via* free radical reactions (2).

TABLE 2
Tocopherol Concentrations (μg/g) of Soybean Oils Before and After Storage[a]

	Tocopherol homolog									
	α		γ		δ		Total		Total	%
Oil[b]	Before	After	Before	After	Before	After	Before	After	loss[c]	Loss
LLSBO21	249	221	402	343	120	104	770	668	102[a,b]	13[a]
LLSBOW21	280	235	396	348	117	107	793	689	104[a,b]	13[a]
ULSBO21	125	104	204	209	35	31	364	344	20[c]	6[b]
ULSBOW21	125	103	210	194	36	32	372	329	42[c]	11[a,b]
LLSBO32	249	248	402	347	120	100	770	695	75[b,c]	10[a,b]
LLSBOW32	280	237	396	344	117	102	793	684	109[a]	14[a]
ULSBO32	125	119	204	192	35	28	364	339	25[c]	7[b]
ULSBOW32	125	98	210	195	36	31	372	324	47[c,d]	13[a]
Comparison[d]										
LLSBO	264	235	399	260	119	103	782	684	98[a]	13[a]
ULSBO	125	106	207	197	36	31	368	334	34[b]	9[a]
W/O TBHQ	187	173	303	187	77	66	567	511	56[a,b]	10[a]
W TBHQ	202	168	303	270	77	68	582	507	76[a,b]	13[a]
21°C	195	166	303	250	59	53	575	508	67[a,b]	11[a]
32°C	195	151	303	270	59	50	575	510	64[a,b]	11[a]

[a]Individual and total tocopherol concentrations of SBO before and after the 12-mon storage. The values are averages of duplicate analyses, with an overall SD of 4.1.
[b]See Table 1 for definitions of LLSBO and ULSBO. Presence of W means with TBHQ; W/O = without TBHQ; 21 or 32 refers to storage temperature in °C.
[c]Values in the same column with roman supercript letters in common were not significantly different ($P < 0.05$).
[d]Comparison of the means at two levels of one treatment factor, regardless of the levels of the other two factors.

TABLE 3
Oil Stability Indices (OSI) (h at 110°C), PV (meq/kg), *p*-Anisidine Values (*p*-AV) (mmol/kg), Polar Compound Percentages (%), and Sensory Evaluations for Overall Oil Quality of Soybean Oils[a] with Low- and Ultra-Low-Linolenic Acid Concentrations

	Soybean	Storage time (mon)						
Analysis[b]	oil	0	2	4	6	8	10	12
OSI	LLSBO21	6.9c	4.9^{b}	4.8^{d}	4.1^{d}	4.0^{d}	3.9^{c}	3.8^{c}
	ULSBO21	5.2^{c}	4.2^{b}	3.6^{d,e}	3.3^{d,e}	3.1^{e}	2.9^{c}	2.8^{c}
	LLSBOW21	17.4^{b}	15.8^{a}	12.6^{b}	11.8^{b}	11.5^{a}	11.0^{a}	10.7^{a}
	ULSBOW21	20.7^{a}	15.9^{a}	14.0^{a}	13.2^{a}	11.8^{a}	11.8^{a}	11.3^{a}
	LLSBO32	6.9^{c}	4.6^{b}	4.6^{d}	4.0^{d}	3.7^{d,e}	3.4^{c}	3.2^{c}
	ULSBO32	5.2^{c}	4.1^{b}	3.3^{e}	3.1^{e}	3.0^{e}	2.7^{c}	2.4^{c}
	LLSBOW32	17.4^{b}	15.1^{a}	9.2^{c}	10.0^{c}	9.4^{c}	8.6^{b}	8.1^{b}
	ULSBOW32	20.7^{a}	16.2^{a}	12.6^{b}	11.7^{b}	10.4^{b}	8.8^{b}	8.4^{b}
PV	LLSBO21	0.3^{b}	1.5^{c}	3.1^{b,c,d}	3.4^{e}	8.4^{c,d}	15.0^{b}	27.3^{a}
	ULSBO21	0.4^{a}	3.6^{a}	4.6^{b}	4.8^{c}	10.5^{b,c}	11.5^{c,d}	20.8^{b}
	LLSBOW21	0.3^{b}	1.1^{c}	1.7^{d}	1.8^{e}	4.1^{e}	7.1^{d}	8.3^{d}
	ULSBOW21	0.2^{b}	1.5^{c}	2.0^{d}	2.1^{e}	7.0^{c,d,e}	8.5^{d}	9.7^{d}
	LLSBO32	0.3^{b}	2.8^{b}	3.7^{b,c}	6.8^{a}	14.5^{a}	20.0^{a}	29.3^{a}
	ULSBO32	0.4^{a}	4.3^{a}	7.7^{a}	7.9^{a}	13.4^{a,b}	14.0^{b,c}	25.1^{a,b}
	LLSBOW32	0.3^{b}	1.5^{c}	3.9^{b,c}	4.0^{d}	7.6^{c,d,e}	13.4^{b,c}	14.5^{c}
	ULSBOW32	0.2^{b}	1.4^{c}	2.7^{c,d}	3.4^{e}	3.4^{d,e}	9.6^{d}	12.7^{c,d}
p-AV	LLSBO21	5.5^{a}	7.2^{b}	7.3^{c}	7.5^{b}	8.0^{b}	12.9^{b}	13.0^{c}
	ULSBO21	2.3^{b}	2.9^{d}	3.0^{f,g}	3.0^{e}	4.2^{d,e}	7.3^{c}	8.8^{d}
	LLSBOW21	5.5^{a}	7.5^{b}	6.5^{d}	7.0^{c}	6.9^{b,c}	13.7^{b}	9.8^{d}
	ULSBOW21	2.0^{b}	2.4^{d}	2.4^{g}	2.5^{f}	2.8^{e}	5.6^{c}	3.9^{e}
	LLSBO32	5.5^{a}	8.5^{a}	9.3^{a}	12.1^{a}	12.3^{a}	19.1^{a}	27.0^{a}
	ULSBO32	2.3^{b}	3.9^{c}	5.5^{e}	6.1^{d}	7.1^{b,c}	14.2^{b}	17.1^{b}
	LLSBOW32	5.5^{a}	7.8^{a,b}	8.0^{b}	7.5^{b}	6.7^{b,c,d}	18.9^{a}	14.8^{c}
	ULSBOW32	2.0^{b}	2.9^{d}	3.1^{f}	3.0^{e}	4.8^{c,d,e}	13.9^{b}	7.9^{d}
Polar compound percentages	LLSBO21	2.6^{a}	2.9^{d}	3.5^{b}	3.7^{b,c,d}	4.0^{b,c}	4.1^{b}	4.2^{b}
	ULSBO21	2.5^{a}	3.0^{d}	3.1^{c}	3.4^{d}	3.5^{c,d}	3.4^{c}	3.9^{b,c}
	LLSBOW21	2.2^{a}	3.0^{c}	3.1^{c}	3.8^{b,c}	4.2^{a,b}	4.3^{b}	4.1^{b}
	ULSBOW21	2.6^{a}	2.9^{d}	2.9^{c}	3.5^{c,d}	3.6^{d}	3.5^{c}	4.2^{b}
	LLSBO32	2.6^{a}	3.3^{a}	4.0^{a}	3.9^{b}	4.7^{a}	4.8^{a}	4.7^{a}
	ULSBO32	2.5^{a}	3.1^{b}	3.7^{a,b}	3.9^{b}	4.2^{a,b}	4.3^{b}	4.2^{b}
	LLSBOW32	2.2^{a}	3.3^{d}	3.8^{a,b}	4.1^{a}	4.0^{b,c}	4.1^{b}	4.3^{b}
	ULSBOW32	2.6^{a}	3.2^{d}	3.5^{b}	3.6^{b,c,d}	3.6^{c,d}	3.7^{c}	3.6^{c}
Sensory for overall oil quality[c]	LLSBO21	8.4^{a}	7.5^{a}	7.5^{a,b}	5.5^{a,b}	5.2^{a,b}	4.9^{a}	3.2^{a}
	ULSBO21	7.8^{b}	7.5^{a}	7.5^{a}	5.7^{a,b}	5.7^{a}	4.1^{a,b,c}	3.4^{a}
	LLSBOW21	8.4^{a}	7.5^{a}	6.9^{a,b}	6.3^{a}	4.9^{a,b,c}	3.5^{a,b,c}	3.3^{a}
	ULSBOW21	7.7^{b}	6.8^{a}	6.6^{a,b,c}	5.2^{a,b}	4.8^{a,b,c}	4.4^{a,b}	3.4^{a}
	LLSBO32	8.4^{a}	7.2^{a}	6.2^{b,c}	5.1^{a,b}	4.2^{b,c}	3.6^{a,b,c}	3.3^{a}
	ULSBO32	7.8^{b}	7.2^{a}	6.6^{a,b,c}	5.4^{a,b}	4.5^{b,c}	2.9c	2.7^{a}
	LLSBOW32	8.4^{a}	7.1^{a}	5.5^{c}	5.1^{a,b}	4.1^{b,c}	3.7^{a,b,c}	2.7^{a}
	ULSBOW32	7.7^{b}	7.1^{a}	6.3^{a,b,c}	4.9^{b}	4.1^{c}	3.0$^{b.c}$	3.2^{a}

[a]See footnote *d* in Table 1 and footnote *b* in Table 2 for definitions of SBO treatments.
[b]Values in the same column for each test with supercript roman letters in common were not significantly different ($P < 0.05$).
[c]Overall oil-quality score is based on the scale: 10 = excellent; 9 and 8 = good; 7 and 6 = fair; 5 and 4 = poor; 3, 2, and 1 = very poor.

These results and interactions between the effects of 18:3 content and TBHQ addition, and between the effects of temperature and TBHQ addition on OSI, showed that TBHQ had a better antioxidant capacity when the 18:3 concentration was lower. The retardant effect of TBHQ on lipid oxidation was detected more easily when the storage temperature was higher.

PV. The effects of the treatment factors (18:3 concentration, TBHQ addition, and storage temperature) on PV were complex. Statistical analyses of the data showed interactions between the effects of 18:3 concentration and temperature ($P = 0.0006$); between the effects of 18:3 content and TBHQ addition ($P < 0.0001$); and among the effects of 18:3 content, TBHQ addition, and temperature ($P = 0.0625$, close but not statistically significant) on PV.

When TBHQ was absent and at the same storage temperature, the ULSBO initially had significantly greater PV than did LLSBO stored at the same temperature (Table 3). But the trend reversed during storage over 10 mon at 21°C and over 8 mon at 32°C. The interaction between the effects of 18:3 concentration and temperature on the PV suggests that the improved stability of ULSBO over LLSBO appeared sooner at a higher storage temperature. When TBHQ was present, at 21°C, the ULSBOW had a greater PV than did the LLSBOW; at 32°C, the ULSBOW had a lower PV than did LLSBOW. The

interactions between the effects of 18:3 content and TBHQ addition and among the effects of 18:3 content, TBHQ addition, and temperature on PV suggest that TBHQ had a better antioxidant capacity when the 18:3 concentration was lower. The retardation effect of TBHQ on lipid oxidation and the improved stability of ULSBO over LLSBO were more easily detected when the storage temperature was higher.

The TBHQ addition had a great effect on PV (Table 3). As storage progressed, all the oils with TBHQ addition had lower PV than did the oils without TBHQ addition for the same 18:3 concentration and storage temperature. Also, temperature played an important role in the formation of lipid hydroperoxides. During storage, oils stored at 21°C generally developed lower PV than did oils stored at 32°C for the same 18:3 concentration and TBHQ level, although the differences were not always significant.

p-AV. Throughout storage, ULSBO had significantly lower *p*-AV than did LLSBO at the same temperature and TBHQ levels, except for oils with TBHQ stored at 32°C for 8 mon (Table 3). Such results are in agreement with descriptions by other researchers who noted differences in *p*-AV of oils with different FA compositions (11,16). After storage began, oils with TBHQ addition had lower *p*-AV than did oils without TBHQ addition at the same 18:3 concentration and storage temperature except for LLSBO at 21°C and at a 2- and 10-mon storage. This result and the interactions between the effects of 18:3 concentration and TBHQ addition ($P = 0.0011$), storage temperature and TBHQ addition ($P = 0.0016$), and 18:3 concentration and storage temperature ($P < 0.0001$) on *p*-AV again suggest that TBHQ had a better antioxidant capacity when the 18:3 concentration was lower. The retardation effect of TBHQ on lipid oxidation and the improved stability of ULSBO over LLSBO were more easily detected when the storage temperature was higher. After 2 mon, oils stored at 32°C had significantly greater *p*-AV than did oils stored at 21°C with the same 18:3 concentration and TBHQ levels, except for LLSBO with TBHQ at 8-mon storage (Table 3).

The *p*-AV method determines the amount of aldehydes (principally 2-alkenals and 2,4-dienals) present; however, the color intensity of the yellowish reaction products formed depends not only on the amounts of aldehydic compounds present but also on their structure (11). A double bond in the carbon chain conjugated with the carbonyl double bond increases the molar absorbance by four to five times, that is, the 2-alkenals and dienals, especially, contribute substantially to the value found. Oils with high PUFA levels may have *p*-AV of >10.0 mmol/kg even when fresh, largely because of the structure of the aldehydes (17). The *p*-AV is comparable only within an oil type because of the initial difference in the value (16).

The Totox value, taking into account the limit of the *p*-AV method, was calculated as the sum of *p*-AV and 2 PV as shown in Table 1 (16). Initially, ULSBO had lower Totox than did LLSBO. There were no differences in Totox between LLSBO and LLSBOW or between ULSBO and ULSBOW. By the end of the 12-mon storage, ULSBO still had lower Totox than did LLSBO (Table 1).

Polar compounds. Generally, ULSBO had lower polar compound percentages than did LLSBO at the same temperature and TBHQ level, especially as storage progressed (Table 3). At 32°C, oils with TBHQ addition tended to have lower values than did the oils without TBHQ addition at the same 18:3 level, especially as storage progressed. There was no such trend at 21°C. Statistical analysis confirmed the interaction between the effects of temperature and TBHQ addition ($P < 0.0001$) on polar compound percentages. Oils stored at 21°C had lower values than did the oils stored at 32°C when TBHQ was absent, especially as storage progressed. These results and the interaction again suggest that the retardation effect of TBHQ on lipid oxidation was more easily detected when the storage temperature was higher.

Colors. There were no interactions between the effects of 18:3 concentration, temperature, or TBHQ addition on color changes. Initially, ULSBO (3 yellow, 0.2 red) and ULSBOW (3 yellow, 0.2 red) had significantly lower mean yellow and red readings than did LLSBO (5 yellow, 0.5 red) and LLSBOW (4 yellow, 0.4 red), respectively (data not shown). But the pigment decomposition rate did not depend on the effect of 18:3 concentration on color changes. The initial differences disappeared when all the oils became too pale to be read by the equipment at the end of the 12-mon storage. TBHQ addition had no effect on the yellow and red color changes of the SBO. The speed of pigment decomposition was greater at 32 than at 21°C.

Sensory evaluations. Initially, LLSBO and LLSBOW had significantly better overall flavor-quality scores than did ULSBO and ULSBOW, respectively (Table 3). At the 2-mon storage, significant differences disappeared, and the ULSBO tended to have better overall flavor quality later in storage, especially at 21°C. A similar trend was observed in the change of PV of the oils, demonstrating that ULSBO was more stable than LLSBO despite the initial more oxidized level of ULSBO than LLSBO due to processing. Generally, oils stored at 21°C had better overall flavor quality than did oils stored at 32°C with the same 18:3 concentration and TBHQ level, especially as storage time increased. The TBHQ addition tended to have a negative effect on overall flavor quality by sensory evaluations, especially through 8 mon of storage. By 10 and 12 mon, however, TBHQ addition tended to enhance overall oil-quality scores.

To further evaluate the impact of TBHQ on oil flavor, an untrained 33-member panel was used to compare the overall flavor characteristics of fresh commercial SBO without TBHQ addition to that of fresh commercial SBO with 100 ppm and to that of fresh commercial SBO with 200 ppm TBHQ addition by triangle tests. No difference was found between the overall flavor characteristics of SBO without TBHQ addition and SBO with either 100 or 200 ppm TBHQ addition. More extensive sensory evaluations might reveal more information on the impact of TBHQ on oil flavor. A previous study on the effect of TBHQ on oil flavor stability found that TBHQ treatment did not enhance the flavor stability of oils (18).

For individual flavors, the predominant attributes detected by panelists in the SBO included painty, fishy, grassy, beany, nutty, and buttery flavors. The Pearson correlation coefficients

between the intensity of painty, fishy, grassy, beany, nutty, and buttery flavors and overall oil-quality scores were 0.870, 0.731, 0.687, 0.681, 0.403, and 0.002, respectively. That is, the intensity of painty, fishy, grassy, and beany flavors had strong correlations with overall oil-quality scores in sensory evaluations, whereas the intensity of nutty and buttery flavors had weak or no correlations with overall flavor quality. The sensory evaluation data of SBO with overall oil quality and multiple individual flavors represent typical multivariate data. Interpretation of the effects of 18:3 concentration, TBHQ addition, and temperature on individual flavor intensities and integrating the impact of individual flavor on overall sensory characteristics of SBO is beyond the scope of this paper; however, a more sophisticated method to simplify the representation of sensory characteristics of SBO is in progress.

In general, flavor scores paralleled those of the objective test results, in showing a slight advantage in stability and flavor quality, especially over time, of ULSBO over LLSBO. The results showed a further advantage of ULSBO in that, despite lower total tocopherol and tocopherol homolog concentrations in the initial and finished oils, ULSBO still emerged as better oil.

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