Frying Performance of Low-Linolenic Acid Soybean Oil

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ABSTRACT: The frying performance of low-linolenic acid soybean oil from genetically modified soybeans was examined. Partially hydrogenated and unhydrogenated low-linolenic acid soybean oils were compared to two partially hydrogenated soybean frying oils. Frying experiments utilizing shoestring potatoes and fish nuggets were conducted. Frying oil performance was evaluated by measuring free fatty acid content, *p*-anisidine value, polar compound content, soap value, maximal foam height, polymeric material content, and Lovibond red color. The hydrogenated low-linolenic soybean oil (Hyd-LoLn) consistently had greater ($P < 0.05$) free fatty acid content and lower *p*-anisidine values and polymeric material content than did the other oils. Hyd-LoLn generally was not significantly different from the traditional oils for polar content, maximal foam height, and Lovibond red color. The low-linolenic acid soybean oil (LoLn) tended to have lower soap values and Lovibond red color scores than did the other oils. LoLn had consistently higher ($P < 0.05$) *p*-anisidine values and polymeric material content than did the other oils, and LoLn generally was not different ($P < 0.05$) from the traditional oils for polar content, maximal foam height, and free fatty acid.

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Deep-fat frying is a popular and convenient food preparation method. The high temperature, as well as the incorporation of oxygen and water, during deep-fat frying necessitate the use of a stable frying oil. Traditionally, partially hydrogenated oils have been used for frying purposes because hydrogenation increases an oil's resistance to thermal and atmospheric oxidation. However, a side effect of hydrogenation is the formation of positional and geometrical fatty acid isomers. Some studies have indicated that there may be adverse health effects due to dietary *trans* fatty acid consumption (1–3).

A recent alternative or complement to hydrogenation is the use of oils with genetically modified fatty acid composition. High-oleic canola, safflower, and sunflower oils, as well as low-linolenic canola and soybean oils, have been developed (4). Several studies have examined the frying performance of modified oils (5–13). Warner and Mounts (8) compared frying stability of genetically modified, low-linolenic, nonhydrogenated and hydrogenated soybean and canola oils to nonhydrogenated, traditional soybean and canola oils. The modified oils had less room odor intensity; lower free fatty acid contents, polar compounds, and foam heights; fewer undesirable odors; and better food quality than the traditional oils after 5 h of frying. Mounts *et al.* (9) compared three lines of low-linolenic acid soybean oil (LoLn) and traditional unhydrogenated soybean oil. However, most soybean oils used for frying purposes were partially hydrogenated. Lowering the linoleic acid content of soybean oil by breeding was beneficial for improved oil quality during cooking and frying. The flavor quality of fried food was enhanced with these oils. LoLn soybean oils were compared to traditionally unhydrogenated and partially hydrogenated soybean oils by Mounts *et al.* (12); frying performance was evaluated by the sensory methods of room odor intensity and potato flavor quality. The results reported by these authors indicate that oils with lowered linolenic acid content produced by hybridization breeding of soybeans are potential alternatives to hydrogenated frying oils.

The present study compares the frying performance, as measured by analytical methods, of unhydrogenated and partially hydrogenated low-linolenic acid soybean oils to two traditional hydrogenated soybean oils.

EXPERIMENTAL METHODS

Materials. Four frying oils were used: a LoLn, a partially hydrogenated low-linolenic acid soybean oil (Hyd-LoLn), a partially hydrogenated soybean oil (C-SBO), and a liquid partially hydrogenated soybean oil (L-SBO) (AC Humko, Memphis, TN). All oils were refined, bleached, and deodorized, and the L-SBO was winterized. Oil processing was done by AC Humko. One part per million of dimethyl polysiloxane antifoam agent was added to the oils prior to their use in frying.

Frying procedure. Two types of food were fried—shoestring (P) potatoes and fish nuggets (F). Two replicate fryings of each food type were made. The oils (5.22 kg) were heated in Intedge F175A electric fryers (Intedge Industries, Inc., Whippany, NJ). The weight of the oil and the vat was recorded and used as a reference value for daily oil replenishing (about 400–450 mL/d). The capacity of each fryer was 5.44 kg. Fryers were not filled to full capacity in order to reduce the chance of spilling the oil when the frying vats were

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*To whom correspondence should be addressed at Dept. of Food Science and Human Nutrition, 205A Agricultural Bioprocessing Lab, 1302 W. Pennsylvania Ave., Urbana, IL 61801. E-mail: eperkins@uiuc.edu picked up for daily weighings to determine oil replenishment amount. The oils were heated to 180°C for 8 h/d for 15 d. A thermometer was used to ensure the accuracy of the fryer temperature gauge. To the heated oil, 227 g of either shoestring potatoes (Kraft Prestige brand grade A, extra-long fancy 1/4″ shoestring # 6804 A-3; Kraft, Glenview, IL) or fish nuggets (Sweet ’n Flaky Sea Nuggets #29111; Fishery Products International, Danvers, MS) were added and fried three times a day for a total of 681 g of food fried each day. Potatoes were fried for 3.5 min and fish nuggets were fried for 5 min. Food was fried after 1, 4, and 7 h of heating time. At the end of the day, 400-g oil samples were collected in amber glass bottles. Oil was replenished to the constant starting weight; the approximate range of oil replenished each day was 450 to 500 g. The samples were flushed with nitrogen and stored at −18°C for 1–2 wk until needed for analysis. Frying was ended after 15 d.

Analysis of initial oils. AOCS Official Procedure Cd 1d-92 was used for iodine value and AOCS Official Method Ca 5Aa-40 was used for free fatty acids (14). The *p*-anisidine value was determined by method Cd18-90, peroxide value by practice Cd 8b-90, and soap value by practice CC 17-79 (14). Polar compounds were determined by solid-phase extraction (15). Polymeric material was determined by gel permeation chromatography (GPC) using two connected columns: Phenomenex P/no 00N-0442-KO Phenogel 5 100 A, 300 mm × 7.8 µ s/no 47192, and Phenomenex P/no 0011-0441-KO Phenogel 5 50 A, 300 mm × 7.8 µ s/no 47191. The GPC mobile phase was tetrahydrofuran at 0.7 mL/min; the detector was a Waters 410 refractometer (Milford, MA); and Maxima 820 software (Milford, MA) was used to record and integrate the data (16). Oil color was measured using a Lovibond tintometer (Salisbury, England). Fatty acid methyl esters (FAME) were prepared by AOCS Official Method Ce 2-66 (14), diluted in hexane, and analyzed by gas–liquid chromatography (GLC) (column: CPSIL 80; column length = 50 m; i.d. = 0.25 µm; film thickness = 0.2 nm; guard column = 5 m; initial temperature = 150°C; initial time = 2 min; rate = 1.0°C/min; final temperature = 195°C; final time = 1 min; carrier gas = H_2; linear velocity = 46.77 cm/s; column flow = 1.38 mL/min; and split ratio = 64:1).

All of the above analytical measurements were done in duplicate and the averages reported.

Tocopherols were measured by the Archer Daniels Midland Company (Decatur, IL) by high-performance liquid chromatography (HPLC) [fluorescence detector, Waters model 474, LC-diol column, 25 cm × 4.6 mm, 5-µm particle size (Supelco Inc., State College, PA)] with hexane/diethyl ether/isopropyl alcohol (75:20:5) as solvent, and sample size = 1 g diluted in 20 mL of isoctane was employed. These measurements were not replicated.

Analysis of heated oils. Free fatty acids, *p*-anisidine value, soap value, polar compounds, polymeric material, and oil color were determined as described above in the analysis of fresh oils. Maximal foam height was measured during frying by using a clamped, open-ended, upright graduated cylinder that rested just above the oil surface (without the basket of food product); when the food was fried, the bottom of the cylinder became submerged a few centimeters and this measurement was recorded before foaming began and at the point of highest foaming. The difference was calculated as maximal foam height. Graduated cylinder volumetric readings were converted to centimeters.

Statistical analysis. Randomized, complete-block analyses of variance (frying experiment replication = block) and least squares difference tests were used to determine if and where significant differences existed among oils at certain frying times for the various analyses. Each food type had two frying replications. Chemical analyses were performed in duplicate except where otherwise stated. The confidence level was 95%. The SAS statistical package produced by the University of Illinois at Urbana-Champaign was used in these statistical analyses (17).

RESULTS AND DISCUSSION

Initial oil quality. The results of the analyses of the fresh oils (Table 1) show that the oils were of good initial quality. As expected, differences did exist between the oils in FAME composition as indicated by gas chromatography (Table 1).

TABLE 1
Analyses of Initial Oils

	Oil type[b]			
Analysis[a]	LoLn	Hyd-LoLn	C-SBO	L-SBO
Iodine value	118.4	80.6	83.7	95.5
Free fatty acids (%)	0.02	0.02	0.02	0.01
p-Anisidine value	1.52	1.10	2.66	0.79
Peroxide value	0	0	0	0
OSI (h)	6.90	41.95	13.40	25.35
Soap value (ppm)	Trace	Trace	Trace	Trace
Polar material (%)	3.3	2.73	3.0	4.4
Polymeric material (%)	2.0	0.6	0.9	1.1
Lovibond color				
Red	0	0.4	0	0
Yellow	3	8	5	6
Spectrophotometric color	0.4	0.8	0.3	0.8
FAME profile (relative %)				
Major peaks				
16:0	11.8	10.6	11.9	9.7
18:0	5.1	6.8	11.3	3.9
18:1	28.6	73.0	46.0	63.7
18:2	52.0	9.0	29.0	21.9
18:3	2.3	0.1	1.4	0.4
20:0	0.1	0.4	0.1	0.1
trans (%)	0.6	25.5	16.8	25.4
Tocopherols (ppm)				
α	59	4	48	65
β	10	62	12	17
γ	503	33	409	601
δ	139	121	148	235
Total	711	220	616	917

[a] OSI, oxidative stability index; FAME, fatty acid methyl ester.
[b] LoLn = low-linolenic soybean oil, Hyd-LoLn = partially hydrogenated low-linolenic soybean oil, C-SBO = creamy partially hydrogenated soybean oil, L-SBO = liquid partially hydrogenated soybean oil.

The predominant fatty acid of LoLn was linoleic acid (52.0%), and it had 2.3% linolenic acid. Oleic acid was the predominant fatty acid in Hyd-LoLn, C-SBO, and L-SBO at 73.0, 46.0, and 63.7%, respectively. Hyd-LoLn had the least amount of linolenic acid, 0.1%. C-SBO had 1.4% linolenic acid, and L-SBO had 0.4%.

The α, β, γ, and δ isomers of tocopherol were present in all of the oils at total levels of between 220 and 917 ppm (Table 1). The iodine value reflects overall differences in the fatty acid composition of the starting oils, and is commonly used in the industry to help describe a fat. The free fatty acid value is used as a quality measurement of fats and should not exceed 0.05%, thus fats described herein were of good quality, having a free fatty acid content of 0.01–0.02% (Table 1). The peroxide value at 0 and the low results found for the *p*-anisidine values, as well as the absence of soaps (Table 1), further attest to the high quality of the oils used in this study. The results of the Lovibond and spectrophotometric color tests indicated that the oils were initially a pale yellow color (Table 1). The results for the amounts of polar compounds, 2.7–4.4%, are within the range expected since they are comprised primarily of the unsaponifiables from the oils and some diglycerides not removed during the deodorization of the oils during their preparation (Table 1). The amounts of polymeric material found, ranging from 0.6 to 2%, represent the small amount of material formed as a result of the thermal deodorization of the oils during their preparation (Table 1).

Frying oil quality. (i) Percentage free fatty acid value of heated oils. Free fatty acids are primarily a result of hydrolysis, although small amounts may be produced by oxidative reactions (18). Some researchers have questioned their importance in monitoring oil degradation because the percentage of free fatty acids may not correlate with other methods of monitoring oil degradation (18). Free fatty acids are moderately volatile and an unknown amount is lost during heating (18). Moderate levels of free fatty acids have not been linked to inferior food quality (18), and free fatty acids can undergo oxidation and be converted to other products that are not measured by the titration method (19).

Hyd-LoLn consistently had higher free fatty acid values ($P < 0.05$) than did the other oils (Table 2). Regardless of type of food fried, Hyd-LoLn's free fatty acid values were often twice as high as the values of the other oils. The percentage of free fatty acids for Hyd-LoLn was 2.39 and 2.03 for potato and fish frying, respectively, after 120 h of frying; the other oils' percentage of free fatty acids after 120 h of frying ranged from 1.06 (LoLn at F-120 h) to 1.32 (C-SBO at P-120 h). These oils were not significantly different from each other in free fatty acid content except at P-24 h when C-SBO had a significantly higher percentage of free fatty acids than both LoLn and L-SBO. Any antioxidant effect of the tocopherols appears to have been obscured by other differences in the oil, such as fatty acid profile (Table 1).

TABLE 2
Free Fatty Acid Content (%)[a]

	Oil type			
Sample	LoLn	C-SBO	L-SBO	Hyd-LoLn
P-24 h	0.0^{c}	0.1^{b}	0.0^{c}	0.2^{a}
P-48 h	0.2^{b}	0.2^{b}	0.2^{b}	0.5^{a}
P-72 h	0.4^{b}	0.4^{b}	0.4^{b}	0.8^{a}
P-96 h	0.7^{b}	0.8^{b}	0.7^{b}	1.5^{a}
P-120 h	1.2^{b}	1.3^{b}	1.3^{b}	2.4^{a}
F-24 h	0.1^{b}	0.1^{b}	0.1^{b}	0.2^{a}
F-48 h	0.2^{b}	0.2^{b}	0.2^{b}	0.4^{a}
F-72 h	0.4^{b}	0.4^{b}	0.4^{b}	0.7^{a}
F-96 h	0.6^{b}	0.6^{b}	0.7^{b}	1.3^{a}
F-120 h	1.1^{b}	1.1^{b}	1.2^{b}	2.0^{a}

[a] P, shoestring potato; F, fish nuggests; h, hours of heating/frying. See Table 1 for abbreviations. Means within the same row sharing a common superscript roman letter (a–d) are not significantly different at the 95% confidence level.

(ii) Anisidine value of heated oils. p-Anisidine value is a measurement of aldehyde content, particularly the 2-alkenals and 2,4-dienals. The oxidative deterioration of an oil and the oil's starting fatty acid composition will affect *p*-anisidine value. Aldehydes are formed as oxidative degradation products and are important flavor compounds.

Hyd-LoLn consistently had lower *p*-anisidine values ($P < 0.05$) than all of the other oils, regardless of the type of food fried (Table 3). This was expected based on its fatty acid composition. Conversely, LoLn consistently had the highest *p*-anisidine values; these values were significantly higher than all of the other oils at P-32 h, P-64 h, P-96 h, F-16 h, F-32 h, F-48 h, F-80 h, and F-96 h. L-SBO had lower *p*-anisidine values than LoLn except for P-16 h. C-SBO tended to have lower *p*-anisidine values than LoLn.

(iii) Soap value. Soap value is a measurement of the amount of sodium oleate, a compound whose presence has been found to lower oil interfacial tension (21) and increase foaming (22). Among the oils used to fry fish nuggets, LoLn

TABLE 3
Anisidine Value

	Oil type[b]			
Sample[a]	LoLn	C-SBO	L-SBO	Hyd-LoLn
P-16 h	41.4^{a}	31.5^{b}	37.6^{a,b}	14.3^{c}
P-32 h	53.8^{a}	47.9^{b}	41.8^{b}	20.1^{c}
P-48 h	56.3^{a}	53.1^{a,b}	48.6^{b}	26.4^{c}
P-64 h	61.7^{a}	57.9^{b}	51.3^{c}	26.5^{d}
P-80 h	68.5^{a}	64.0^{a}	49.9^{b}	29.4^{c}
P-96 h	65.7^{a}	62.5^{b}	49.9^{c}	32.3^{d}
P-112 h	61.2^{a}	61.0^{a}	49.1^{b}	35.1^{c}
F-16h h	63.3^{a}	37.4^{b}	37.7^{b}	17.5^{c}
F-32 h	71.3^{a}	50.5^{b}	49.7^{b}	23.7^{c}
F-48 h	67.6^{a}	55.4^{b}	54.4^{b}	28.8^{c}
F-64 h	68.3^{a}	61.9^{a,b}	54.1^{b}	27.5^{c}
F-80 h	71.2^{a}	57.7^{b}	49.7^{c}	26.5^{d}
F-96 h	72.5^{a}	58.7^{b}	48.9^{c}	25.8^{d}
F-112 h	71.3^{a}	58.2^{a,b}	53.1^{b}	26.7^{c}

[a] See Table 2 for abbreviations.
[b] See Table 1 for abbreviations. Means within the same row sharing a common superscript roman letter (a–d) are not significantly different at the 95% confidence level.

samples tended to have the lowest soap value for all frying times (Table 4); LoLn's soap values were significantly lower than values for both of the traditional oils (L-SBO and C-SBO) at F-48 h, F-72 h, and F-96 h. In the shoestring potato frying experiment, LoLn's soap values were lower ($P < 0.05$) or not significantly different from the traditional oils. Hyd-LoLn's soap values were lower ($P < 0.05$) or not significantly different from the traditional oils regardless of the type of food fried or frying time.

(iv) Percentage total polar material of heated oils. Oxidative, thermal, and thermal oxidative degradation products are polar in nature. In some countries, 27% total polar material has been established as a maximum limit for frying oils (23). There were no significant differences among oils at any of the measured frying times for fish nuggets (Table 5). But potatoes fried for 48, 96, and 120 h exhibited significant differences in polar content. At P-48 h, C-SBO had the highest polar content ($P < 0.05$) of all oils and Hyd-LoLn was higher ($P < 0.05$) than both L-SBO and LoLn. At P-96 h, C-SBO had a greater polar content ($P < 0.05$) than LoLn and L-SBO, but Hyd-LoLn's polar content was not significantly different from any of the other oils. At P-120 h, the polar contents of C-SBO and LoLn were similar and higher ($P < 0.05$) than Hyd-LoLn, which was greater ($P < 0.05$) than L-SBO. When the polar material in the oils LoLn and Hyd-LoLn were separated by GPC, different polar component profiles were revealed. Figure 1A and B show the polar component profile for LoLn used to fry shoestring potatoes and fish nuggets, respectively. LoLn's predominant polar component was polymeric material, a product of thermal and oxidative degradation. On the other hand, Hyd-LoLn (Fig. 1C and D) generally had lower amounts of polymeric material in its polar fraction than LoLn, and higher relative percentages of diglycerides, a product of hydrolysis. This observation agrees with the high percentage of free fatty acid titration results obtained for Hyd-LoLn, since free fatty acids also are a product of hydrolysis. The polar component level for LoLn reached 18.47%. The polar component profile for L-SBO (Fig. 2A and B) used for potato and fish frying, respectively, indicated that polymeric material and large amounts of diglycerides were formed as a result of potato frying; during fish frying the major component formed was polymeric material. In comparison the use of C-SBO for frying potatoes and fish (Fig. 2C and D), respectively, indicated that potato frying produced primarily polymeric material, while fish frying produced high amounts of polymeric material as well as diglycerides.

TABLE 4
Soap Value (ppm)

	Oil type[b]			
Sample[a]	LoLn	C-SBO	L-SBO	Hyd-LoLn
P-24 h	4.9^{c}	8.8^{a}	6.8^{b}	$8.1^{a,b}$
P-48 h	7.8^{b}	9.7^{a}	7.5^{b}	6.5^{b}
P-72 h	10.7^{b}	$12.3^{a,b}$	10.5^{b}	13.5^{a}
P-96 h	10.1^{b}	15.9^{a}	$12.9^{a,b}$	13.7^{a}
P-120 h	16.1^{b}	24.2^{a}	$19.8^{a,b}$	21.2^{a}
F-24 h	14.4^{b}	26.1^{a}	17.9^{b}	19.6^{b}
F-48 h	23.0^{b}	35.0^{a}	34.6^{a}	$29.5^{a,b}$
F-72 h	29.1^{c}	44.9^{a}	$38.6^{a,b}$	$31.3^{b,c}$
F-96 h	35.9^{b}	47.5^{a}	44.4^{a}	$43.9^{a,b}$
F-120 h	46.2^{b}	55.5^{a}	$47.7^{a,b}$	$52.1^{a,b}$

[a] See Table 2 for abbreviations.
[b] See Table 1 for abbreviations. Means within the same row sharing a common superscript roman letter (a–d) are not significantly different at the 95% confidence level.

TABLE 5
Polar Compounds and Polymeric Materials

	Oil type[b]			
Sample[a]	LoLn	C-SBO	L-SBO	Hyd-LoLn
Polar comounds (%)				
P-24 h	4.7^{a}	5.3^{a}	5.5^{a}	4.6^{a}
P-48 h	6.1^{c}	7.2^{a}	6.2^{c}	6.6^{b}
P-72 h	7.2^{a}	7.9^{a}	7.4^{a}	7.9^{a}
P-96 h	10.1^{b}	12.6^{a}	10.1^{b}	$11.5^{a,b}$
P-120 h	16.8^{a}	17.5^{a}	13.7^{c}	15.4^{b}
F-24 h	6.32^{a}	6.54^{a}	6.45^{a}	6.1^{a}
F-48 h	9.8^{a}	9.2^{a}	9.7^{a}	8.7^{a}
F-72 h	12.5^{a}	12.0^{a}	13.6^{a}	11.7^{a}
F-96 h	14.7^{a}	14.5^{a}	14.9^{a}	14.0^{a}
F-120 h	18.5^{a}	18.0^{a}	18.2^{a}	17.9^{a}
Polymeric materials (%)				
P-24 h	3.1^{a}	3.3^{a}	2.6^{b}	2.1^{b}
P-48 h	5.1^{a}	$4.6^{a,b}$	$4.5^{a,b}$	3.5^{b}
P-72 h	7.3^{a}	$6.2^{a,b}$	4.5^{b}	4.2^{b}
P-96 h	7.7^{a}	6.8^{a}	6.5^{a}	4.9^{b}
P-120 h	10.9^{a}	$8.8^{a,b}$	9.2^{a}	7.2^{b}
F-24 h	2.2^{a}	1.5^{b}	1.6^{b}	1.2^{b}
F-48 h	3.3^{a}	2.7^{b}	$2.2^{b,c}$	1.7^{c}
F-72 h	3.9^{a}	$3.4^{a,b}$	$2.7^{b,c}$	1.9^{c}
F-96 h	5.2^{a}	5.8^{a}	3.9^{b}	3.5^{b}
F-120 h	9.3^{a}	8.6^{a}	6.3^{b}	5.9^{b}

[a] See Table 2 for abbreviations.
[b] See Table 1 for abbreviations. Means within the same row sharing a common superscript roman letter (a–d) are not significantly different at the 95% Confidence Level.

(v) Percentage total polymeric material. Polymeric material is formed as a result of oxidative and thermal reactions. The film that coats fryer vats and baskets is caused by polymeric material and can be difficult to clean. Also, some polymeric material may have a bitter flavor (25). Dimers, trimers, and higher molecular weight polymers are considered to be polymeric material. LoLn generally had the highest polymeric material content (Table 5), Conversely, Hyd-LoLn consistently had the lowest amount of polymeric material; its polymeric material was lower ($P < 0.05$) than LoLn in all instances, and Hyd-LoLn was lower ($P < 0.05$) than both traditional oils at F-120 h.

(vi) Maximal foam height. Foam height often is used to determine the oil "throw-away" point in industry. Both polymeric material and fatty acid soaps may increase foaming (23,26). LoLn tended to have the greatest foam height regardless of type of food fried and frying time (Table 6), but its foam height was only significantly greater than all of the other oils at F-96 h. Hyd-LoLn tended to have the lowest foam

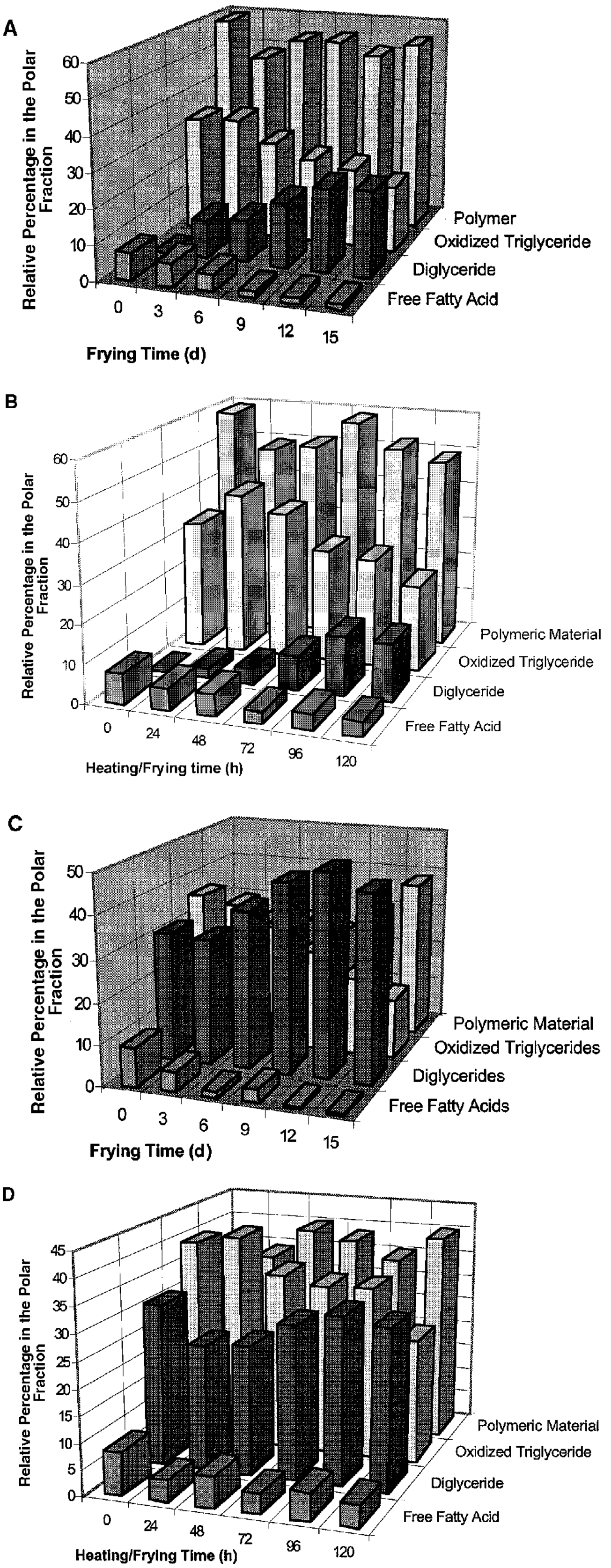

FIG. 1. Polar component distribution. (A) Low-linolenic (LoLn) soybean oil, potato frying; (B) LoLn from fish frying; (C) partially hydrogenated low-linolenic (Hyd-LoLn) soybean oil, potato frying; (D) Hyd-LoLn oil from fish frying.

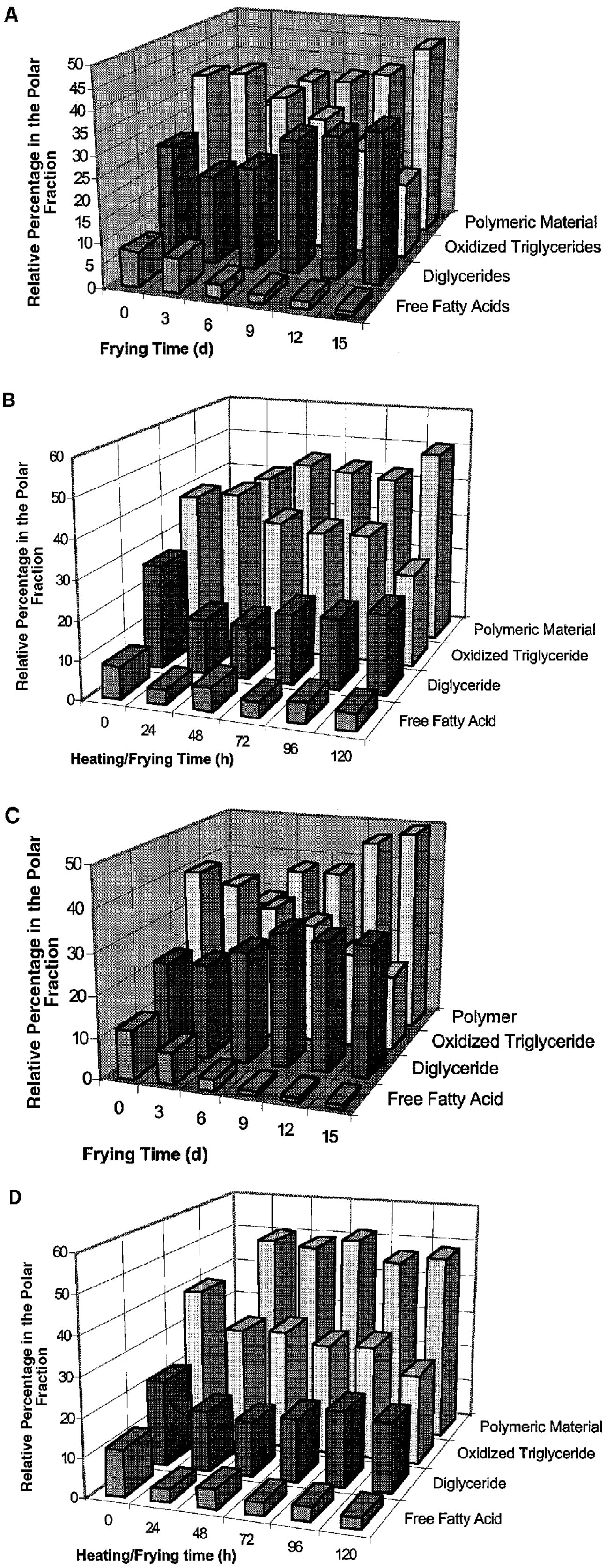

FIG. 2. Polar component distribution. (A) Liquid partially hydrogenated soybean oil (L-SBO), potato frying; (B) L-SBO vat oil from fish frying; (C) creamy partially hydrogenated soybean oil (C-SBO), potato frying; (D) C-SBO oil from fish frying.

TABLE 6
Maximum Foam Height and Lovibond Red Color Value

Sample[a]	Oil Ttype[b]			
	LoLn	C-SBO	L-SBO	Hyd-LoLn
Maximum foam height (cm)				
P-24 h	0.5a	0.4^{a}	0.3^{a}	Negligible
P-48 h	1.0a	$0.9^{a,b}$	0.6^{b}	0.7^{b}
P-72 h1.1a	1.0^{a}	0.9^{a}	0.7^{a}	
P-96 h	1.3a	1.3^{a}	1.2^{a}	1.2^{a}
P-120 h	1.4^{a}	1.3^{a}	1.3^{a}	1.3^{a}
F-24 h	Negligible	Negligible	Negligible	Negligible
F-48 h	0.3^{a}	0.4^{a}	0.3^{a}	0.3^{a}
F-72 h	0.8^{a}	$0.5^{a,b}$	0.6^{a}	0.4^{b}
F-96 h	0.9^{a}	0.7^{b}	$0.5^{b,c}$	0.5^{c}
F-120 h	1.0^{a}	$0.8^{a,b}$	0.6^{b}	0.5^{b}
Lovibond red color value				
P-24 h	1.7^{c}	2.7^{b}	3.0^{b}	3.3^{a}
P-48 h	4.8^{b}	6.3^{a}	7.3^{a}	7.2^{a}
P-72 h8.3^{a}	10.5^{a}	11.9^{a}	11.2^{a}	
P-96h h	13.8^{b}	17.6^{a}	19.1^{a}	18.6^{a}
P-120 h	24.8	$>27.93^{c}$	$>27.93^{c}$	$>27.93^{c}$
F-24 h	3.8^{b}	4.1^{b}	$4.7^{a,b}$	5.4^{a}
F-48 h	8.3^{a}	8.3^{a}	9.6^{a}	10.0^{a}
F-72 h	13.5^{b}	$13.9^{a,b}$	17.5^{a}	16.9^{a}
F-96 h	22.8^{a}	22.1^{b}	$>27.93^{c}$	$>27.93^{c}$
F-120 h	$>27.93^{c}$	$>27.93^{c}$	$>27.93^{c}$	$>27.93^{c}$

[a] See Table 2 for abbreviations.

[b] See Table 1 for abbreviations. Means within the same row sharing a common superscript roman letter (a–d) are not significantly different at the 95% confidence level.

[c] Measurements were off-scale.

height; its foam height was lower ($P < 0.05$) than LoLn at P-48 h, F-72 h, F-96 h, and F-120 h, but its foam height was never significantly different from at least one of the traditional oils.

The foaming during shoestring potato frying quickly reached a maximal height, whereas the foaming during fish nugget frying was slower to begin and more prolonged and erratic. A possible explanation for this is the relative difference in food thickness and surface area between the shoestring potatoes and the fish nuggets; the shoestring potatoes were thinner cut, allowing water to escape more quickly.

(vii) Lovibond red color. Oil darkens as it is used for frying, and oil color is used in the food industry for rapid monitoring of frying oil quality. However, the darkening of oil may be influenced by trace pigments (27) and tocopherols (28) in the frying oil.

LoLn generally had slower development of red color than did the other oils (Table 6). LoLn's Lovibond red value was lower ($P < 0.05$) than all of the other oils at P-24 h, P-48 h, and P-96 h. Both Hyd-LoLn and L-SBO tended to have the highest Lovibond red color values, and these two oils were seldom significantly different from each other.

Shoestring potatoes vs. fish nuggets. Most analyses showed that the oil used to fry fish nuggets degraded faster than the oil used to fry shoestring potatoes. The exceptions were free fatty acid content and foam height. A possible explanation for this increased oxidative degradation is the migration of oil from the fish into the frying oil, since fish oil tends to be more polyunsaturated, and thus more prone to oxidation, than soybean oil.

Overall assessment of oils. No one oil had superior performance in any of the analytical frying performance evaluations. Hyd-LoLn did appear to have the best oxidative stability, as judged by its significantly lower *p*-anisidine values and low polymeric material content, yet Hyd-LoLn had more rapid hydrolytic degradation, as evidenced by its free fatty acid values.

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