Effects of Natural and Synthetic Antioxidants on Changes in Refined, Bleached, and Deodorized Palm Olein During Deep-Fat Frying of Potato Chips

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ABSTRACT: The effects of antioxidants on the changes in quality characteristics of refined, bleached, and deodorized (RBD) palm olein during deep-fat frying (at 180°C) of potato chips for 3.5 h/d for seven consecutive days in five systems were compared in this study. The systems were RBD palm olein without antioxidant (control), with 200 ppm butylated hydroxytoluene (BHT), 200 ppm butylated hydroxyanisole (BHA), 200 ppm oleoresin rosemary, and 200 ppm sage extract. Fried oil samples were analyzed for peroxide value (PV), thiobarbituric acid (TBA) value, iodine value (IV), free fatty acid (FFA) content, polymer content, viscosity, $E^{1\%}_{1\ cm}$ at 232 and 268 nm, color, fatty acid composition, and $C_{18:2}/C_{16:0}$ ratio. Sensory quality of the potato chips fried in these systems prior to storage was also evaluated. The storage stability of fried potato chips for 14 wk at ambient temperature was also determined by means of the TBA values and sensory evaluation for rancid odor. Generally, in the oil, oleoresin rosemary gave the lowest rate of increase of TBA value, polymer content, viscosity, $E^{1\%}_{1\ cm}$ at 232 and 268 nm compared to control and three other antioxidants. The order of effectiveness ($P < 0.05$) in inhibiting oil oxidation in RBD palm olein was oleoresin rosemary > BHA > sage extract > BHT > control. Prior to storage, the sensory evaluation of fried potato chips for each system showed that there was no significant ($P > 0.05$) difference in terms of flavor, odor, texture, and overall acceptability. The same order of effectiveness ($P < 0.05$) of antioxidants was observed for storage stability study of fried potato chips by TBA values. However, there was no significant ($P > 0.05$) difference in sensory evaluation for rancid odor during storage periods.

Paper no. J8855 in *JAOCS 76*, 331–339 (March, 1999).

KEY WORDS: Antioxidant, BHA, BHT, deep fat frying, quality characteristics, RBD palm olein, rosemary, sage.

Deep-fat frying is one of the most commonly used procedures for preparation and manufacture of foods throughout the world. Lipid oxidation is one of the major deteriorative reactions in frying oils and fried foods, and often results in a significant loss of quality (1). It is well known that lipid oxidation can lead to changes in functional, sensory, and nutritive values and even the safety of fried foods (2,3). Generally, these changes reduce consumer acceptance of oxidized products. Antioxidants are added to fats, oils, and foods containing fats to inhibit the development of off-flavors arising from the oxidation of unsaturated fatty acids. However, the commercial use of synthetic antioxidants is strictly controlled, and increasing consumer awareness of food additives and safety have prompted increased interest in the use of natural antioxidants as alternatives to synthetic compounds (4).

Extracts of many plants have been reported to have varying degrees of antioxidant activities in fats and oils (5,6). Many herbs and spices have been shown to possess antioxidant activity, mainly through the pioneering efforts of Chipault and co-workers (7). Results of these studies indicated clearly that the majority of the spices tested possessed some antioxidant activity, with rosemary (*Rosemarinus officinalis* L.) and sage (*Salvia officinalis* L.) being the most potent.

Refined, bleached, and deodorized (RBD) palm olein was used in this study because of its major commercial role in deep-fat frying (8). The study entailed an evaluation of the effectiveness of two commercially available natural antioxidants, oleoresin rosemary and sage extract, in comparison with two commonly used synthetic phenolic antioxidants, butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), during the intermittent deep-fat frying of potato chips.

The effectiveness of synthetic antioxidants in retarding RBD palm olein deterioration has been reported in many papers, but there have been very limited reports on the frying performance of RBD palm olein in the presence of natural antioxidants. Therefore, the primary objective of this study was to assess the frying performance of RBD palm olein treated with natural antioxidants in comparison with synthetic antioxidants. A secondary objective was to study the oxidative stability and organoleptic quality of the fried potato chips produced in these systems.

MATERIALS AND METHODS

Materials. RBD palm olein (*Elaeis guineenis* var. tenera) was obtained from a local refinery. Oleoresin rosemary (Herbalox® Brand, Type O) and sage extract (Herbalox® Sea-

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soning, Type S-O) were gifts from Kalsec Inc., Kalamazoo, MI (Gulf Chemicals Sdn. Bhd., Petaling Jaya, Malaysia). BHA and BHT were obtained from Sigma Chemical Co. (St. Louis, MO). Potatoes (Russet var.) were bought from a local supermarket. All chemicals and solvents used were of analytical grade unless otherwise specified.

Fresh potatoes were peeled and sliced to a thickness of 2 mm using a mechanical slicer. They were kept submerged in distilled water at room temperature. They were then slightly blotted dry with tissue paper before weighing into 100 g batch for frying.

Frying experiments. Frying experiments were carried out in various systems that contained: RBD palm olein without antioxidant or control (System I); RBD palm olein with 200 ppm BHT (System II); RBD palm olein with 200 ppm BHA (System III); RBD palm olein with 200 ppm oleoresin rosemary (System IV); and RBD palm olein with 200 ppm sage extract (System V). Frying experiments were conducted in two replicates on each system.

RBD palm olein (4.5 kg) was put into a Valentine batch fryer (Type: T4, Valentine Equipment Ltd., Reading, United Kingdom). The temperature was brought up to 60°C, then 200 ppm of BHT, BHA, oleoresin rosemary, or sage extract was added in systems II, III, IV, and V, respectively. The oil was stirred for 10 min to ensure dissolution of antioxidant. In the case of system I (control), the oil also was held for 10 min at 60°C, although no antioxidant was added. The temperature was then raised to 180°C during 20 min. Frying started 20 min after the temperature had reached 180°C. A batch of 100 g raw potato chips was fried for 2.5 min at 17.5 min intervals for a period of 3.5 h per day for seven consecutive days. This is equivalent to 10 fryings per day and 70 fryings for seven consecutive days. The fryer was left uncovered during the frying period. At the end of the tenth frying, the fryer was switched off and the temperature was allowed to drop to 60°C. Oil samples for analysis (120 g) were collected in amber bottles at 60°C for further analyses. All samples were stored under nitrogen at 4°C. Analysis of oil was carried out immediately after the frying experiment and completed within 2 wk. The lid of the fryer was then put on and the oil was allowed to cool overnight. The frying was continued the next day. Fresh oil was not added to the frying vessel. Chips on the first day of frying (First to tenth batches) were kept for sensory assessment.

Analyses of oils. The IUPAC (9) methods were employed for determinations of peroxide value (PV) and ultraviolet absorbances at 232 and 268 nm. The PORIM (10) test methods were used for assessment of iodine value, free fatty acid (FFA) content, and fatty acid composition. A modified thiobarbituric acid (TBA) test (11) was employed to measure the extent of oxidation. Oil color was measured in a 1-in. cell in a Lovibond® Tintometer (Salibury, United Kingdom) (10) and viscosity was monitored by using a Brookefield viscometer (Stoughton, MA). Polymer content was analyzed according to the method of Peled *et al.* (12). The quality assessments were monitored across the seven consecutive days of frying. Each reported value is the mean of six analyses from two replications.

Analyses of fried potato chips. The sensory analysis was used to assess the organoleptic quality of the chips on the first day of frying by using a nine-point hedonic scale (14). Forty experienced panelists were selected from students and laboratory staffs of the Faculty of Food Science and Biotechnology, Universiti Putra Malaysia. Each sample was coded with a three-digit random number. Panelists were required to evaluate the sensory attributes of the chips, namely, flavor, odor, texture, and overall acceptability, by giving a score ranging from 1 (like extremely) to 9 (dislike extremely).

In addition, fried potato chips taken on the first day of frying were packed in aluminum laminate bags and stored at ambient temperature (27–30°C) for storage analysis. During storage analysis, bags were sampled at the start of the storage period (Day 0) and at 2-wk intervals for a period of 14 wk. TBA values and sensory scores for rancid odor were concurrently evaluated during these storage periods. For rancid odor analysis, the chips were presented to a sensory panel comprising 10 trained panelists with previous experience on food rancidity. Before evaluation, chips (10 g) from each system were transferred from the aluminum laminate package and placed in 10 transparent glass bottles (30 mL) with screw-capped lids. The bottles were kept for 1 h in a 50°C regulated oven to help the odor to develop in the headspace; this preparation facilitated odor perception by the panelists. Panelists were instructed to remove the lid of the bottle and take three short sniffs. Then they were asked to rate each according to a predetermined attribute scale ranging from 0 (bland) to 6 (markedly disagreeable off-flavor, very rancid) (15). Analyses were conducted under red light to mask any color differences in the chips.

Statistical analysis. Data were statistically analyzed by two-way analysis of variance procedure using an SAS (16) software package. Significant differences ($P < 0.05$) between means were further determined by Duncan's multiple-range test.

RESULTS AND DISCUSSION

Characteristics of fresh RBD palm olein used in frying experiments. The initial characteristics of RBD palm olein used in the study are given in Table 1. The RBD palm olein was of good quality, as indicated by its initial low PV of 1.55 meq/kg and FFA content of 0.10%. The fatty acid composition of RBD palm olein is within the range for Malaysian palm olein (17).

Quality changes in RBD palm olein systems during frying. The changes in quality parameters of RBD palm olein used for intermittent frying of potato chips in the presence and absence of antioxidants are given in Tables 2–5. Table 6 gives the fatty acid composition of the used RBD palm olein in five different systems over time. A range of parameters was used because no one parameter can depict frying life accurately (18). The oil system without antioxidants (System I) experienced a greater degree of deterioration than oil systems with

TABLE 1
Characteristics of Fresh RBD Palm Olein Used in Frying Experiments[a]

Characteristics of the oil	Value[b]
Peroxide value (meq hydroperoxide/kg oil)	1.55 ± 0.05
TBA value ((moles malonaldehyde/kg oil)	12.94 ± 0.53
Iodine value (g of I_2/100 g oil)	56.25 ± 0.21
FFA content (%)	0.10 ± 0.00
Polymer content (%)	0.01 ± 0.00
$E^{1\%}_{1\ cm}$ at 232 nm[c]	1.54 ± 0.02
$E^{1\%}_{1\ cm}$ at 268 nm[c]	0.40 ± 0.02
Color (red/yellow units)	0.55 ± 0.00R
	6.00 ± 0.05Y
Viscosity (centipoise)	45.13 ± 0.13
Fatty acid composition (%)	
$C_{12:0}$	0.29 ± 0.01
$C_{14:0}$	1.17 ± 0.01
$C_{16:0}$	41.13 ± 0.07
$C_{18:0}$	4.11 ± 0.01
$C_{18:1}$	43.35 ± 0.08
$C_{18:2}$	9.72 ± 0.02
Others	0.23 ± 0.00
$C_{18:2}/C_{16:0}$ ratio	0.24 ± 0.00

[a]RBD, refined, bleached, and deodorized; TBA, thiobarbituric acid; FFA, free fatty acid.
[b]Each value is the mean of three analyses of one sample.
[c]Not corrected for triglyceride absorption.

antioxidants (Systems II, III, IV, and V). The extent of oil deterioration was best reflected in the changes in peroxide and TBA values, polymer content, viscosity, $E^{1\%}_{1\ cm}$ at 232 nm and 268 nm, and $C_{18:2}/C_{16:0}$ ratio. The iodine value, FFA content, and color also provided supporting evidence for the extent of oil deterioration, although the changes in these values were not as apparent as those in the above-mentioned parameters.

Changes in PV and TBA value. The changes in PV and TBA value during frying are presented in Table 2. The PV rose and fell during frying, which is the same pattern observed for peroxides in most deep-fat frying studies (19,20). Peroxides under deep fat frying conditions are unstable and can break down to carbonyl and aldehydic compounds under conditions of high heat, air, and light, as present in deep fat frying operations (21). The results of this study showed that in System I, the formation of peroxides seemed to increase rapidly from day 0 to day 3 of frying, then dropped over the last 4 d of frying. In Systems II, III, IV, and V, results showed that there was a marked increase after the first 4 d of frying but a decrease during the last 3 d of frying. Since high heat (180 ± 5°C) was used on these systems, peroxides formed during oxidation may have decomposed to secondary oxidation products (15). RBD palm olein with the addition of antioxidants (Systems II, III, IV, and V) had PV that were significantly ($P < 0.05$) lower than those of the control throughout the duration of the study. Within Systems II, III, IV, and V, the 200 ppm BHA (System III) and oleoresin rosemary (System IV) were not significantly ($P > 0.05$) different from each other, and the 200 ppm BHT (System II) and sage extract (System V) were also not significantly ($P > 0.05$) different from each other. However, Systems III and IV had PV that were significantly ($P < 0.05$) lower than the PV of Systems II and V. In general, these results indicated that oleoresin rosemary and BHA were more effective in reducing formation of peroxides in RBD palm olein during frying than sage extract and BHT. Judging from the PV, the oxidative stability was decreased in the order oleoresin rosemary ≈ BHA > sage extract ≈ BHT > control.

TBA values of all systems increased progressively with the frying time. The TBA test has been widely used as an objective measure of secondary oxidation products of oils. It relates to the level of malondialdehyde formed during oxidation of lipids. It was assumed that accumulation of these products during consecutive days of frying affected the oil quality

TABLE 2
Changes in Peroxide and TBA Values of RBD Palm Olein During Frying[a]

Characteristic	Day	System I (control)	System II (BHT)	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
Peroxide value	0	$1.53 \pm 0.05^{a}_{H}$	$1.57 \pm 0.14^{a}_{G}$	$1.57 \pm 0.10^{a}_{G}$	$1.57 \pm 0.10^{a}_{G}$	$1.50 \pm 0.09^{a}_{G}$
(meq hydroperoxide/	1	$13.73 \pm 0.33^{a}_{F}$	$7.13 \pm 0.27^{b}_{F}$	$5.83 \pm 0.23^{c}_{F}$	$5.70 \pm 0.23^{c}_{F}$	$6.93 \pm 0.37^{b}_{F}$
kg oil)	2	$19.22 \pm 0.38^{a}_{C}$	$11.17 \pm 0.29^{b}_{C}$	$9.96 \pm 0.18^{c}_{C}$	$8.60 \pm 0.38^{d}_{D}$	$11.03 \pm 0.40^{b}_{C}$
	3	$21.46 \pm 0.50^{a}_{A}$	$12.16 \pm 0.29^{b}_{B}$	$10.82 \pm 0.31^{c}_{B}$	$10.40 \pm 0.35^{c}_{B}$	$12.26 \pm 0.45^{b}_{B}$
	4	$20.82 \pm 0.36^{a}_{B}$	$12.57 \pm 0.23^{b}_{A}$	$11.89 \pm 0.33^{c}_{A}$	$11.16 \pm 0.41^{d}_{A}$	$12.77 \pm 0.14^{b}_{A}$
	5	$18.68 \pm 0.65^{a}_{D}$	$11.96 \pm 0.26^{b}_{B}$	$9.71 \pm 0.28^{d}_{C}$	$9.03 \pm 0.19^{e}_{C}$	$11.06 \pm 0.57^{c}_{C}$
	6	$15.78 \pm 0.32^{a}_{E}$	$9.22 \pm 0.35^{b}_{D}$	$8.20 \pm 0.18^{c}_{D}$	$7.50 \pm 0.41^{d}_{E}$	$9.37 \pm 0.22^{b}_{D}$
	7	$12.82 \pm 0.36^{a}_{G}$	$8.80 \pm 0.35^{b}_{E}$	$6.53 \pm 0.27^{d}_{E}$	$7.20 \pm 0.36^{c}_{E}$	$8.46 \pm 0.34^{b}_{E}$
TBA value	0	$13.11 \pm 0.35^{a}_{H}$	$12.90 \pm 0.63^{a}_{H}$	$13.16 \pm 0.89^{a}_{H}$	$13.24 \pm 1.16^{a}_{H}$	$13.03 \pm 0.61^{a}_{H}$
(μmoles	1	$30.16 \pm 0.75^{a}_{G}$	$27.12 \pm 0.78^{b}_{G}$	$24.19 \pm 0.56^{c}_{G}$	$24.91 \pm 0.68^{c}_{G}$	$27.49 \pm 0.70^{b}_{G}$
malondialdehyde/	2	$44.45 \pm 1.13^{a}_{F}$	$41.75 \pm 0.82^{b}_{F}$	$39.30 \pm 0.87^{d}_{F}$	$36.25 \pm 0.90^{e}_{F}$	$40.57 \pm 0.93^{c}_{F}$
kg oil)	3	$51.34 \pm 0.79^{a}_{E}$	$47.04 \pm 0.27^{c}_{E}$	$48.41 \pm 0.93^{b}_{E}$	$44.18 \pm 0.92^{d}_{E}$	$48.06 \pm 0.28^{b}_{E}$
	4	$61.04 \pm 0.96^{a}_{D}$	$55.16 \pm 0.91^{b}_{D}$	$51.91 \pm 0.69^{c}_{D}$	$51.90 \pm 0.76^{c}_{D}$	$54.70 \pm 0.22^{b}_{D}$
	5	$67.07 \pm 0.60^{a}_{C}$	$64.29 \pm 1.74^{b}_{C}$	$62.64 \pm 1.10^{c}_{C}$	$53.04 \pm 0.75^{d}_{C}$	$62.91 \pm 0.54^{c}_{C}$
	6	$78.37 \pm 0.73^{a}_{B}$	$74.75 \pm 0.77^{b}_{B}$	$73.91 \pm 0.52^{c}_{B}$	$71.88 \pm 0.54^{d}_{B}$	$73.54 \pm 0.49^{c}_{B}$
	7	$95.49 \pm 0.44^{a}_{A}$	$80.94 \pm 0.80^{b}_{A}$	$78.85 \pm 0.27^{c}_{A}$	$76.13 \pm 0.75^{d}_{A}$	$80.60 \pm 0.22^{b}_{A}$

[a]Each value in the table represents the mean ± standard deviation of six analyses from two replications. Means within each row with different superscripts are significantly ($P < 0.05$) different. Means within each column with different subscripts are significantly ($P < 0.05$) different. BHT, butylated hydroxytoluene; BHA, butylated hydroxyanisole. See Table 1 for other abbreviations.

TABLE 3
Changes in Iodine Value and FFA Content of RBD Palm Olein During Frying[a]

Characteristic	Day	System I (control)	System II (BHT)	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
Iodine value	0	$56.98 \pm 0.15^{a}{}_{A}$	$56.47 \pm 0.33^{b}{}_{A}$	$56.58 \pm 0.15^{b}{}_{A}$	$56.60 \pm 0.27^{b}{}_{A}$	$56.46 \pm 0.33^{b}{}_{A}$
(g of I_2/100 g oil)	1	$55.33 \pm 0.28^{b}{}_{B}$	$55.51 \pm 0.11^{a,b}{}_{B}$	$55.70 \pm 0.31^{a}{}_{B}$	$55.60 \pm 0.15^{a,b}{}_{B}$	$55.75 \pm 0.32^{a}{}_{B}$
	2	$53.02 \pm 0.21^{c}{}_{C}$	$54.53 \pm 0.43^{b}{}_{C}$	$54.63 \pm 0.77^{b}{}_{C}$	$53.91 \pm 0.26^{b}{}_{C}$	$54.12 \pm 0.17^{a,b}{}_{C}$
	3	$51.47 \pm 0.40^{c}{}_{D}$	$52.55 \pm 0.18^{b}{}_{D}$	$52.25 \pm 0.26^{b}{}_{D}$	$53.14 \pm 0.47^{a}{}_{D}$	$52.44 \pm 0.48^{a}{}_{D}$
	4	$50.11 \pm 0.58^{c}{}_{E}$	$50.79 \pm 0.49^{b}{}_{E}$	$51.28 \pm 0.53^{a,b}{}_{E}$	$51.41 \pm 0.53^{a,b}{}_{E}$	$51.78 \pm 0.56^{a}{}_{E}$
	5	$48.62 \pm 0.44^{d}{}_{F}$	$49.23 \pm 0.59^{c,d}{}_{F}$	$49.77 \pm 0.87^{b,c}{}_{F}$	$50.72 \pm 0.51^{a}{}_{F}$	$50.22 \pm 0.25^{a,b}{}_{F}$
	6	$43.45 \pm 0.59^{b}{}_{G}$	$44.21 \pm 0.47^{b}{}_{G}$	$44.17 \pm 0.88^{b}{}_{G}$	$45.97 \pm 0.68^{a}{}_{G}$	$45.49 \pm 0.33^{a}{}_{G}$
	7	$41.83 \pm 0.56^{c}{}_{H}$	$42.74 \pm 0.40^{b}{}_{H}$	$42.50 \pm 0.17^{b}{}_{H}$	$43.56 \pm 0.57^{a}{}_{H}$	$43.33 \pm 0.12^{a}{}_{H}$
FFA content (%)	0	$0.10 \pm 0.00^{a}{}_{H}$	$0.10 \pm 0.00^{a}{}_{H}$	$0.10 \pm 0.00^{a}{}_{H}$	$0.10 \pm 0.00^{a}{}_{H}$	$0.10 \pm 0.00^{a}{}_{H}$
	1	$0.16 \pm 0.01^{a}{}_{G}$	$0.15 \pm 0.01^{b}{}_{G}$	$0.14 \pm 0.01^{b}{}_{G}$	$0.15 \pm 0.01^{b}{}_{G}$	$0.15 \pm 0.01^{b}{}_{G}$
	2	$0.24 \pm 0.01^{a}{}_{F}$	$0.20 \pm 0.01^{b}{}_{F}$	$0.20 \pm 0.03^{b}{}_{F}$	$0.20 \pm 0.01^{b}{}_{F}$	$0.20 \pm 0.00^{b}{}_{F}$
	3	$0.35 \pm 0.01^{a}{}_{E}$	$0.32 \pm 0.00^{b}{}_{E}$	$0.32 \pm 0.01^{b}{}_{E}$	$0.29 \pm 0.02^{b}{}_{E}$	$0.34 \pm 0.01^{b}{}_{E}$
	4	$0.45 \pm 0.00^{a}{}_{D}$	$0.45 \pm 0.01^{a}{}_{D}$	$0.42 \pm 0.01^{b}{}_{D}$	$0.41 \pm 0.00^{c}{}_{D}$	$0.44 \pm 0.01^{a}{}_{D}$
	5	$0.57 \pm 0.01^{a}{}_{C}$	$0.57 \pm 0.01^{a,b}{}_{C}$	$0.55 \pm 0.01^{c,d}{}_{C}$	$0.54 \pm 0.01^{d}{}_{C}$	$0.56 \pm 0.01^{b,c}{}_{C}$
	6	$0.69 \pm 0.01^{a}{}_{B}$	$0.68 \pm 0.01^{a}{}_{B}$	$0.66 \pm 0.01^{b}{}_{B}$	$0.65 \pm 0.01^{b}{}_{B}$	$0.68 \pm 0.01^{a}{}_{B}$
	7	$0.81 \pm 0.01^{a}{}_{A}$	$0.80 \pm 0.01^{a}{}_{A}$	$0.77 \pm 0.01^{c}{}_{A}$	$0.76 \pm 0.01^{c}{}_{A}$	$0.79 \pm 0.02^{b}{}_{A}$

[a]Each value in the table represents the mean ± standard deviation of six analyses from two replications. Means within each row with different superscripts are significantly ($P < 0.05$) different. Means within each column with different subscripts are significantly ($P < 0.05$) different. See Tables 1 and 2 for abbreviations.

and were responsible for the development of rancid odors and off-flavor of the oil. The control (System I) consistently had the highest TBA values among the five systems throughout the seven consecutive d of frying. The other treatments, in order of the level (highest) of TBA value, were BHT ≈ sage extract > BHA > oleoresin rosemary.

With reference to PV and TBA values in Table 2, it was clear that in the case of oleoresin rosemary (System IV), the rates of increase in PV and TBA values were lower than in the four other systems. The effectiveness of oleoresin rosemary and sage extract as lipid antioxidants has been attributed mainly to their ability to remain stable at high temperature (22). Commercial rosemary and sage extracts contain carnosol, carnosic acid, and rosmanol (23) as their primary phenolic antioxidants that react with lipid or hydroxyl radicals and convert them into stable products (24). The major antioxidants in these extracts may be protected by other substances such as flavonoids, found in smaller amounts, which provide thermal stability and enhanced antioxidative activity (22). BHA and BHT are commercially available synthetic phenolic antioxidants, and, as might be expected from their similar molecular structures, BHA and BHT are similar in performance relative to PV and TBA values (Table 2).

Changes in iodine value (IV) and FFA content. Changes in IV and FFA content during seven consecutive days of frying in all systems are given in Table 3. Iodine value is a measure of overall unsaturation and is widely used to characterize oils and fats. Thus, a decrease in iodine value is consistent with the decreasing number of double bonds in an oil as it becomes oxidized. The changes in iodine value over 7 d of frying were 15.15, 13.73, 14.08, 13.04, and 13.13 g of I_2/100 g oil for Systems I, II, III, IV, and V, respectively. A significantly ($P < 0.05$) larger change in iodine value in the control (System I) compared to the other four systems indicated that the rate of oxidation of unsaturated fatty acids was reduced in the presence of antioxidants. The significantly ($P < 0.05$) smaller change in iodine value in Systems IV and V compared to that of Systems II and III showed that less oxidation of unsaturated fatty acids was taking place in Systems IV and V at a greater rate. Therefore, the changes in IV showed that both oleoresin rosemary and sage extract were comparatively more effective in protecting oxidation of unsaturated fatty acid than BHA and BHT.

FFA content is a measure of the acidic components in the oil. Generally, the determination of FFA by titration does not differentiate between acids formed by oxidation and those formed by hydrolysis (25). Although the FFA content is an index of hydrolytic rancidity, it was nevertheless measured, as free acids contribute to the development of off-flavors and off-odors in the product. At the end of the frying period, FFA contents were 0.81, 0.80, 0.77, 0.76, and 0.79% for Systems I, II, III, IV, and V, respectively. The increment of FFA content in oil systems with antioxidants was in the order: oleoresin rosemary ≈ BHA < sage extract < BHT. However, the higher FFA contents of the oil system without antioxidants compared to those with antioxidants cannot be ascribed to direct antioxidant action. This is because phenolic antioxidants act by inhibiting oxidation reactions and have no direct effect on hydrolytic reactions (26).

Changes in polymer content, viscosity, and color. The changes in polymer content, viscosity, and color of all systems are presented in Table 4. It is well known that as oxidation of oil exposed to frying temperatures proceeds, the polymer content increases (27). Increases in polymer content are due to formation of higher molecular weight substances by polymerization (12). The results showed that the polymer content of all systems increased slowly over the first 5 d of frying, followed by a marked increase over the last 2 d of frying. It was noted

TABLE 4
Changes in Polymer Content, Viscosity, and Color of RBD Palm Olein During Frying[a]

Characteristic	Day	System I (control)	System II (BHT)	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
Polymer content (%)	0	$0.03 \pm 0.01^{a}{}_{G}$	$0.02 \pm 0.01^{a,b}{}_{H}$	$0.01 \pm 0.00^{b}{}_{G}$	$0.01 \pm 0.00^{b}{}_{H}$	$0.01 \pm 0.00^{b}{}_{H}$
	1	$0.84 \pm 0.03^{a}{}_{H}$	$0.55 \pm 0.02^{c}{}_{G}$	$0.51 \pm 0.02^{d}{}_{F}$	$0.42 \pm 0.02^{e}{}_{G}$	$0.60 \pm 0.01^{b}{}_{G}$
	2	$1.04 \pm 0.06^{b}{}_{F}$	$1.05 \pm 0.02^{b}{}_{F}$	$1.10 \pm 0.05^{a}{}_{E}$	$0.82 \pm 0.02^{c}{}_{F}$	$1.07 \pm 0.01^{a,b}{}_{F}$
	3	$1.36 \pm 0.04^{a}{}_{E}$	$1.28 \pm 0.08^{b}{}_{E}$	$1.33 \pm 0.05^{a,b}{}_{D}$	$1.18 \pm 0.02^{c}{}_{E}$	$1.30 \pm 0.01^{a,b}{}_{E}$
	4	$1.80 \pm 0.04^{a}{}_{D}$	$1.53 \pm 0.04^{b}{}_{D}$	$1.47 \pm 0.08^{c}{}_{D}$	$1.37 \pm 0.02^{d}{}_{D}$	$1.38 \pm 0.01^{d}{}_{D}$
	5	$2.33 \pm 0.07^{a}{}_{C}$	$2.02 \pm 0.04^{b}{}_{C}$	$1.70 \pm 0.02^{d}{}_{C}$	$1.74 \pm 0.04^{d}{}_{C}$	$1.86 \pm 0.02^{c}{}_{C}$
	6	$3.51 \pm 0.04^{a}{}_{B}$	$3.24 \pm 0.07^{b}{}_{B}$	$3.01 \pm 0.43^{b,c}{}_{B}$	$3.14 \pm 0.13^{b,c}{}_{B}$	$2.90 \pm 0.04^{c}{}_{B}$
	7	$5.00 \pm 0.14^{a}{}_{A}$	$4.50 \pm 0.14^{b}{}_{A}$	$4.51 \pm 0.13^{b}{}_{A}$	$3.89 \pm 0.18^{d}{}_{A}$	$4.29 \pm 0.15^{c}{}_{A}$
Viscosity (centipoise)	0	$45.33 \pm 0.13^{a}{}_{H}$	$45.33 \pm 0.13^{a}{}_{H}$	$45.33 \pm 0.13^{a}{}_{H}$	$45.08 \pm 0.13^{b}{}_{H}$	$45.17 \pm 0.13^{b}{}_{H}$
	1	$49.08 \pm 0.13^{a}{}_{G}$	$48.08 \pm 0.13^{c}{}_{G}$	$47.67 \pm 0.26^{d}{}_{G}$	$47.83 \pm 0.13^{d}{}_{G}$	$48.67 \pm 0.13^{b}{}_{G}$
	2	$50.42 \pm 0.13^{b}{}_{F}$	$50.42 \pm 0.20^{b}{}_{F}$	$49.42 \pm 0.13^{d}{}_{F}$	$50.17 \pm 0.13^{c}{}_{F}$	$50.75 \pm 0.00^{a}{}_{F}$
	3	$54.58 \pm 0.26^{a}{}_{E}$	$52.42 \pm 0.13^{c}{}_{E}$	$51.50 \pm 0.22^{d}{}_{E}$	$52.50 \pm 0.22^{c}{}_{E}$	$53.08 \pm 0.13^{b}{}_{E}$
	4	$58.75 \pm 0.00^{a}{}_{D}$	$55.25 \pm 0.27^{d}{}_{D}$	$54.83 \pm 0.13^{e}{}_{D}$	$55.58 \pm 0.20^{c}{}_{D}$	$56.17 \pm 0.13^{b}{}_{D}$
	5	$64.17 \pm 0.13^{a}{}_{C}$	$60.83 \pm 0.13^{c}{}_{C}$	$60.92 \pm 0.13^{c}{}_{C}$	$60.50 \pm 0.22^{d}{}_{C}$	$61.58 \pm 0.13^{b}{}_{C}$
	6	$75.67 \pm 0.13^{a}{}_{B}$	$71.50 \pm 0.22^{c}{}_{B}$	$72.33 \pm 0.13^{b}{}_{B}$	$68.92 \pm 0.13^{d}{}_{B}$	$71.33 \pm 0.13^{c}{}_{B}$
	7	$82.83 \pm 0.13^{a}{}_{A}$	$79.92 \pm 0.13^{b}{}_{A}$	$77.83 \pm 0.13^{d}{}_{A}$	$76.58 \pm 0.13^{e}{}_{A}$	$78.08 \pm 0.13^{c}{}_{A}$
Color (red units)[b]	0	$0.55R^{d}{}_{G}$	$0.80R^{a}{}_{G}$	$0.75R^{b}{}_{G}$	$0.80R^{a}{}_{G}$	$0.70R^{c}{}_{G}$
	1	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$
	2	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{F}$	$1.10R^{a}{}_{E}$
	3	$1.25R^{a}{}_{E}$	$1.20R^{b}{}_{E}$	$1.20R^{b}{}_{E}$	$1.20R^{b}{}_{E}$	$1.10R^{c}{}_{E}$
	4	$1.30R^{a}{}_{D}$	$1.30R^{a}{}_{D}$	$1.30R^{a}{}_{D}$	$1.25R^{b}{}_{D}$	$1.20R^{c}{}_{D}$
	5	$1.50R^{a}{}_{C}$	$1.40R^{b}{}_{C}$	$1.47R^{c}{}_{C}$	$1.35R^{d}{}_{C}$	$1.25R^{e}{}_{C}$
	6	$1.65R^{b}{}_{B}$	$1.65R^{a}{}_{B}$	$1.73R^{a}{}_{B}$	$1.55R^{c}{}_{B}$	$1.30R^{d}{}_{B}$
	7	$2.20R^{a}{}_{A}$	$2.10R^{a,b}{}_{A}$	$2.15R^{c}{}_{A}$	$1.80R^{d}{}_{A}$	$1.80R^{d}{}_{A}$
Color (yellow units)[b]	0	$6.05Y^{e}{}_{H}$	$8.25Y^{a}{}_{H}$	$6.50Y^{d}{}_{H}$	$7.65Y^{b}{}_{H}$	$7.30Y^{c}{}_{H}$
	1	$11.10Y^{a}{}_{G}$	$10.55Y^{b}{}_{G}$	$11.00Y^{a}{}_{G}$	$10.75Y^{a,b}{}_{G}$	$10.05Y^{a}{}_{G}$
	2	$11.40Y^{a}{}_{F}$	$11.00Y^{b,c}{}_{F}$	$11.15Y^{b}{}_{F}$	$11.00Y^{b,c}{}_{F}$	$10.90Y^{c}{}_{F}$
	3	$11.75Y^{b}{}_{E}$	$12.20Y^{a}{}_{E}$	$12.30Y^{a}{}_{E}$	$11.75Y^{c}{}_{E}$	$11.10Y^{d}{}_{E}$
	4	$13.45Y^{a}{}_{D}$	$12.50Y^{b}{}_{D}$	$12.55Y^{b}{}_{D}$	$11.90Y^{c}{}_{D}$	$12.40Y^{b}{}_{D}$
	5	$15.25Y^{a}{}_{C}$	$14.45Y^{b}{}_{C}$	$14.15Y^{c}{}_{C}$	$13.15Y^{e}{}_{C}$	$13.30Y^{d}{}_{C}$
	6	$17.30Y^{b}{}_{B}$	$18.60Y^{a}{}_{B}$	$18.50Y^{a}{}_{B}$	$14.40Y^{d}{}_{B}$	$16.40Y^{c}{}_{B}$
	7	$20.90Y^{a}{}_{A}$	$20.65Y^{a,b}{}_{A}$	$20.65Y^{a}{}_{A}$	$19.55Y^{c}{}_{A}$	$20.50Y^{b}{}_{A}$

[a]Each value in the table represents the mean ± standard deviation of 6 analyses from 2 replications. Means within each row with different superscripts are significantly ($P < 0.05$) different. Means within each column with different subscripts are significantly ($P < 0.05$) different. See Tables 1 and 2 for abbreviations.
[b]The mean standard deviation in Lovibond color measurements was less than 0.05R and 0.60Y.

that the rate of polymer formation was faster in the oil system without antioxidants than in oil systems with antioxidants. The polymer content in Systems II and III were not significantly ($P > 0.05$) different from each other. Within oil systems with antioxidants, Systems IV and V showed significantly ($P < 0.05$) slower formation of polymers than Systems II and III. System IV showed significantly ($P < 0.05$) less formation of polymers compared to the four other systems. Therefore, the oleoresin rosemary had the strongest effect in retarding formation of polymers during frying, followed by sage extract, the two synthetic antioxidants (BHA and BHT), and the control.

There was a noteworthy increase in viscosity with increase in days of frying (Table 4). The significant ($P < 0.05$) changes in viscosity over 7 d of frying were 37.50, 34.59, 32.50, 31.50, and 33.91 centipoise for Systems I, II, III, IV, and V, respectively. The observed increases in viscosity were due to polymerization, which resulted in formation of higher molecular weight compounds, i.e., carbon-to-carbon and/or carbon-to-oxygen-to-carbon bridges between fatty acids (30). The control had a consistently higher level of viscosity among the five systems during frying, and other systems in order of the size of viscosity increase were BHT > sage extract > BHA > oleoresin rosemary.

The red and yellow color of oil systems increased significantly ($P < 0.05$) throughout the seven consecutive days of frying (Table 4). The color of frying oil darkens during frying, as a result of oxidation and formation of browning pigments from the potato chips (12,18). At the end of the frying period, the red (R) and yellow (Y) color units were 2.20R, 20.90Y; 2.10R, 20.65Y; 2.15R, 20.65Y; 1.80R, 19.55Y; and 1.80R, 20.80Y for Systems I, II, III, IV, and V, respectively. The results showed that System IV (200 ppm oleoresin rosemary) was significantly ($P < 0.05$) darkened at a less rapid rate than the four other systems. This can be explained by the lower polymer content and viscosity across the seven consecutive days of frying.

Augustin *et al.* (29) reported that darkening of palm olein

TABLE 5
Changes in $E^{1\%}_{1\ cm}$ at 232 and 238 nm and Ratio of $C_{18:2}/C_{16:0}$ of RBD Palm Olein During Frying[a]

Characteristic	Day	System I (control)	System II (BHT)	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
$E^{1\%}_{1\ cm}$ at 232 nm[b]	0	$1.63 \pm 0.03^{a}_{E}$	$1.60 \pm 0.08^{a}_{G}$	$1.64 \pm 0.11^{a}_{G}$	$1.65 \pm 0.14^{a}_{G}$	$1.62 \pm 0.08^{a}_{G}$
	1	$3.94 \pm 0.10^{a}_{D}$	$2.88 \pm 0.17^{c}_{F}$	$2.36 \pm 0.04^{d}_{F}$	$3.42 \pm 0.71^{b}_{F}$	$3.37 \pm 0.12^{b}_{F}$
	2	$9.38 \pm 0.22^{a}_{C}$	$6.92 \pm 0.21^{b}_{E}$	$5.22 \pm 0.15^{e}_{E}$	$4.76 \pm 0.16^{d}_{E}$	$6.43 \pm 0.19^{c}_{E}$
	3	$16.63 \pm 0.25^{a}_{B}$	$10.79 \pm 0.31^{b}_{D}$	$10.33 \pm 0.04^{c}_{D}$	$8.99 \pm 0.21^{d}_{D}$	$10.78 \pm 0.23^{b}_{D}$
	4	$16.70 \pm 0.41^{a}_{B}$	$11.15 \pm 0.49^{b}_{C}$	$10.43 \pm 0.29^{c}_{D}$	$10.19 \pm 0.22^{c}_{C}$	$11.11 \pm 0.18^{b}_{C}$
	5	$16.58 \pm 0.48^{a}_{B}$	$11.13 \pm 0.27^{b}_{C}$	$10.79 \pm 0.14^{c}_{C}$	$10.31 \pm 0.08^{d}_{C}$	$11.12 \pm 0.17^{c}_{C}$
	6	$16.72 \pm 0.23^{a}_{B}$	$11.86 \pm 0.19^{b}_{B}$	$11.03 \pm 0.16^{d}_{B}$	$10.72 \pm 0.23^{e}_{B}$	$11.45 \pm 0.09^{c}_{B}$
	7	$17.23 \pm 0.27^{a}_{A}$	$12.85 \pm 0.19^{b}_{A}$	$11.35 \pm 0.11^{d}_{A}$	$11.08 \pm 0.11^{e}_{A}$	$12.43 \pm 0.13^{c}_{A}$
$E^{1\%}_{1\ cm}$ at 268 nm[b]	0	$0.40 \pm 0.04^{a}_{G}$	$0.40 \pm 0.07^{a}_{G}$	$0.40 \pm 0.05^{a}_{H}$	$0.37 \pm 0.03^{a}_{H}$	$0.38 \pm 0.02^{a}_{F}$
	1	$1.80 \pm 0.10^{a}_{F}$	$0.84 \pm 0.08^{c}_{F}$	$0.68 \pm 0.08^{d}_{G}$	$0.76 \pm 0.07^{c,d}_{G}$	$1.15 \pm 0.05^{b}_{E}$
	2	$1.85 \pm 0.12^{a}_{F}$	$1.46 \pm 0.05^{b}_{E}$	$1.00 \pm 0.07^{d}_{F}$	$0.82 \pm 0.01^{e}_{F}$	$1.29 \pm 0.11^{c}_{D,E}$
	3	$2.94 \pm 0.19^{a}_{E}$	$1.59 \pm 0.09^{b}_{D,E}$	$1.23 \pm 0.05^{d}_{E}$	$0.92 \pm 0.03^{e}_{E}$	$1.42 \pm 0.19^{c}_{C,D}$
	4	$3.33 \pm 0.20^{a}_{D}$	$1.62 \pm 0.05^{b}_{D}$	$1.34 \pm 0.04^{c}_{D}$	$1.33 \pm 0.06^{c}_{D}$	$1.46 \pm 0.19^{b}_{C}$
	5	$3.64 \pm 0.27^{a}_{C}$	$1.83 \pm 0.06^{c}_{C}$	$1.77 \pm 0.03^{c}_{C}$	$1.46 \pm 0.03^{d}_{C}$	$2.33 \pm 0.07^{b}_{B}$
	6	$3.85 \pm 0.21^{a}_{B}$	$2.83 \pm 0.13^{b}_{B}$	$2.05 \pm 0.10^{d}_{B}$	$1.63 \pm 0.03^{e}_{B}$	$2.36 \pm 0.10^{c}_{B}$
	7	$4.26 \pm 0.19^{a}_{A}$	$3.53 \pm 0.27^{b}_{A}$	$3.08 \pm 0.12^{c}_{A}$	$1.93 \pm 0.11^{d}_{A}$	$3.02 \pm 0.17^{c}_{A}$
$C_{18:2}/C_{16:0}$ ratio	0	$0.243 \pm 0.003^{b}_{A}$	$0.245 \pm 0.012^{b}_{A}$	$0.240 \pm 0.003^{b}_{A}$	$0.237 \pm 0.005^{b}_{A}$	$0.255 \pm 0.001^{a}_{A}$
	1	$0.206 \pm 0.003^{c}_{B}$	$0.219 \pm 0.001^{b}_{B}$	$0.232 \pm 0.005^{a}_{B}$	$0.233 \pm 0.006^{a}_{A,B}$	$0.226 \pm 0.011^{a,b}_{B}$
	2	$0.181 \pm 0.003^{d}_{C}$	$0.199 \pm 0.003^{c}_{C}$	$0.213 \pm 0.005^{b}_{C}$	$0.227 \pm 0.008^{a}_{B}$	$0.193 \pm 0.009^{c}_{C}$
	3	$0.149 \pm 0.005^{c}_{D}$	$0.185 \pm 0.013^{b}_{D}$	$0.196 \pm 0.003^{a}_{D}$	$0.199 \pm 0.005^{a}_{C}$	$0.190 \pm 0.001^{a,b}_{C}$
	4	$0.136 \pm 0.002^{d}_{E}$	$0.177 \pm 0.004^{b}_{D}$	$0.173 \pm 0.002^{c}_{E}$	$0.187 \pm 0.001^{a}_{D}$	$0.180 \pm 0.002^{b}_{D}$
	5	$0.097 \pm 0.001^{c}_{F}$	$0.158 \pm 0.007^{b}_{E}$	$0.162 \pm 0.003^{a,b}_{F}$	$0.168 \pm 0.000^{a}_{E}$	$0.163 \pm 0.006^{a}_{E}$
	6	$0.081 \pm 0.006^{d}_{G}$	$0.155 \pm 0.003^{b}_{E}$	$0.148 \pm 0.002^{c}_{G}$	$0.165 \pm 0.000^{a}_{E}$	$0.149 \pm 0.004^{c}_{F}$
	7	$0.061 \pm 0.001^{c}_{H}$	$0.138 \pm 0.008^{a}_{F}$	$0.129 \pm 0.007^{b}_{H}$	$0.137 \pm 0.001^{a}_{F}$	$0.132 \pm 0.004^{a,b}_{G}$

[a]Each value in the table represents the mean ± standard deviation of six analyses from two replications. Means within each row with different superscripts are significantly ($P < 0.05$) different. Means within each column with different subscripts are significantly ($P < 0.05$) different. See Tables 1 and 2 for abbreviation.
[b]Not corrected for triglyceride absorption.

could not be solely linked to oxidative deterioration of oil. Although the darkening of oil is an undesirable characteristic, care must be exercised when relating color development in RBD palm olein to oxidative deterioration of the oil. Therefore, it is not accurate to evaluate the oil quality by monitoring the changes in color alone.

Changes in $E^{1\%}_{1\ cm}$ at 232 and 238 nm. The changes in $E^{1\%}_{1\ cm}$ at 232 and 268 nm across seven consecutive days of frying are shown in Table 5. Oxidation of polyunsaturated fatty acids is accompanied by increased ultraviolet absorption. The magnitude of change is not readily related to the degree of oxidation, because the effects upon the various unsaturated fatty acids vary in quality and magnitude. However, the changes in $E^{1\%}_{1\ cm}$ at 232 and 268 nm of a given substance can be used as a relative measurement of oxidation (30). Unlike the peroxide value, $E^{1\%}_{1\ cm}$ at 232 nm—which also measures the degree of primary oxidation—shows a trend of increasing diene content with progress in frying times for all systems. The change in the $E^{1\%}_{1\ cm}$ at 232 nm during the first 3 d of frying showed that a large amount of conjugated dienes was formed. After 4–7 d of frying there was, however, only a negligible increase in the content of conjugated dienes in the oil systems; this can be explained by an equilibrium between the rate of formation of conjugated dienes and the rate at which those compounds formed polymers (12). Moreover, the data obtained for the oil's viscosity and content of polymers support for the same periods of frying this assumption (Table 4). In this study, the oil systems with antioxidants showed significantly ($P < 0.05$) less formation of conjugated dienes compared to the oil system without antioxidants (control). The $E^{1\%}_{1\ cm}$ at 232 nm of the oil after 7 d of frying was lowest in System IV. The lower $E^{1\%}_{1\ cm}$ at 232 nm may be related to the corresponding lower increase in viscosity and polymer content in System IV. Within Systems II, III, and V, System III showed significantly ($P < 0.05$) less formation of conjugated diene, followed by Systems V and II.

The $E^{1\%}_{1\ cm}$ at 268 nm, which is an indicator of the formation of conjugated triene, increased significantly ($P < 0.05$) across the 7 d of frying in all systems (Table 5). At the end of the frying period, changes in $E^{1\%}_{1\ cm}$ at 268 nm were 4.26, 3.53, 3.08, 1.93, and 3.02 for Systems I, II, III, IV, and V, respectively. The changes in the $E^{1\%}_{1\ cm}$ at 268 nm paralleled the changes in $E^{1\%}_{1\ cm}$ at 232 nm. According to Peled *et al.* (12), besides dienes, trienes could also form polymers during frying. These results, like those for peroxide values and $E^{1\%}_{1\ cm}$ at 232 nm, indicate that the stabilizing effect of antioxidants on RBD palm olein was in the order: oleoresin rosemary > sage extract ≈ BHA > BHT.

Changes in fatty acid composition and $C_{18:2}/C_{16:0}$. The changes in fatty acid composition of oil systems across 7 d of frying are given in Table 6. It was found that there was a decrease in both linolenic acid ($C_{18:3}$) and linoleic acid ($C_{18:2}$),

TABLE 6
Fatty Acid Composition for Systems I, II, III, IV and V during Frying

System	Days of frying	Fatty Acids (%)[a]						
		$C_{12:0}$	$C_{14:0}$	$C_{16:0}$	$C_{18:0}$	$C_{18:1}$	$C_{18:2}$	$C_{18:3}$
I	0	0.29	1.18	41.14	3.90	43.24	10.00	0.25
(control)	1	0.39	1.43	42.33	3.91	43.06	8.72	0.16
	2	0.31	1.28	42.50	3.94	44.20	7.68	0.10
	3	0.35	1.16	43.54	4.32	44.10	6.50	0.02
	4	0.26	1.21	43.80	4.82	43.96	5.94	—
	5	0.37	1.52	46.88	4.50	42.24	4.48	—
	6	0.38	1.38	46.27	4.77	43.43	3.76	—
	7	0.41	1.43	48.19	4.49	42.55	2.93	
II	0	0.25	1.06	40.22	4.18	44.23	9.83	0.23
(BHT)	1	0.27	1.14	41.48	4.16	43.67	9.09	0.19
200 ppm	2	0.35	1.27	42.98	4.10	42.58	8.57	0.14
	3	0.41	1.41	43.94	4.07	41.92	8.10	0.15
	4	0.31	1.29	42.98	4.19	43.51	7.59	0.12
	5	0.46	1.50	45.62	4.23	41.05	7.07	0.09
	6	0.32	1.33	43.78	4.20	43.47	6.90	—
	7	0.36	1.34	45.44	4.26	42.34	6.25	—
III	0	0.39	1.33	41.74	3.82	42.60	10.12	0.26
(BHA)	1	0.28	1.10	40.64	3.98	44.36	9.44	0.20
200 ppm	2	0.28	1.17	41.45	3.85	44.25	8.85	0.16
	3	0.29	1.14	42.03	4.03	44.17	8.23	0.12
	4	0.28	1.23	42.98	4.01	43.99	7.44	0.08
	5	0.30	1.26	43.08	4.40	43.94	6.96	0.07
	6	0.28	1.24	43.63	4.41	43.97	6.46	—
	7	0.40	1.51	46.39	4.27	41.45	5.89	—
IV	0	0.34	1.29	41.61	4.01	42.64	9.88	0.23
(oleoresin	1	0.31	1.19	41.08	3.91	43.74	9.56	0.21
rosemary)	2	0.26	1.12	41.00	3.80	44.32	9.31	0.18
200 ppm	3	0.36	1.27	42.27	4.27	42.75	8.49	0.14
	4	0.32	1.27	43.19	4.00	43.02	8.09	0.11
	5	0.35	1.36	45.39	4.04	41.27	7.50	0.09
	6	0.27	1.17	43.25	4.21	43.96	7.14	—
	7	0.56	1.53	45.64	4.15	41.87	6.25	—
V	0	0.25	1.17	39.77	4.10	44.34	10.14	0.24
(sage extract)	1	0.28	1.13	41.03	4.30	43.90	9.26	0.20
200 ppm	2	0.29	1.25	42.97	4.07	42.97	8.29	0.17
	3	0.30	1.27	42.09	4.52	43.71	7.98	0.13
	4	0.28	1.17	43.17	4.26	43.21	7.78	0.12
	5	0.34	1.30	44.76	4.31	41.93	7.28	0.10
	6	0.29	1.21	44.41	4.39	43.07	6.63	—
	7	0.36	1.44	46.26	4.47	41.36	6.11	—

[a]Mean of four analyses from two replications. See Tables 1 and 2 for abbreviations.

whereas palmitic acid ($C_{16:0}$) increased with frying time. From Table 6, the decreases in $C_{18:2}$ across seven consecutive days of frying were 7.07, 3.57, 4.23, 3.63, and 4.03% for Systems I, II, III, IV, and V, respectively. The results showed that the decrease in $C_{18:2}$ was higher in System I as compared to the four other systems. The decrease in $C_{18:2}$ was mainly due to the oxidation of unsaturated fatty acid into primary and secondary oxidation products, which decreased the percentage of unsaturated fatty acid composition.

Linoleic acid and palmitic acid are usually used as indicators of the extent of fat deterioration because linoleic acid is more susceptible to oxidation, whereas palmitic acid is more stable toward oxidation. Therefore, the ratio of $C_{18:2}/C_{16:0}$ was also used to indicate the degree of oxidative deterioration of frying oil. The ratios of $C_{18:2}/C_{16:0}$ are presented in Table 5. In all of the oil systems, these ratios declined rapidly across the 7 d of frying. These results showed that the overall rate of oxidation of $C_{18:2}$ was reduced in the presence of antioxidants.

Sensory evaluation of fried potato chips. The results of sensory evaluation of potato chips are given in Table 7. The sensory results showed that there were no significant ($P > 0.05$) differences in organoleptic qualities of potato chips fried in five different systems. These sensory results showed that, although the natural flavors of oleoresin rosemary, and sage extract are not compatible with the chips' flavor profile, it must be subliminal to be pleasant at low usage level (200 ppm). Sensory evaluation was employed to assess the effect of an an-

TABLE 7
Sensory Scores of Fried Potato Chips Prior to Storage[a]

Sensory attributes	System I (control)	System II (BHT)[b]	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
Flavor	3.89[a]	3.68[a]	4.24[a]	3.90[a]	4.10[a]
Odor	3.89[a]	3.68[a]	3.78[a]	3.49[a]	3.78[a]
Texture	3.95[a]	3.49[a]	3.76[a]	3.49[a]	3.93[a]
Overall acceptability	4.37[a]	3.68[ab]	4.12[ab]	3.49[b]	3.80[ab]

[a]Mean of 40 observations. Means within each row with the different superscripts are significantly ($P < 0.05$) different. Evaluation scale: 1 (like extremely) to 9 (dislike extremely).
[b]See Tables 1 and 2 for abbreviations.

TABLE 8
TBA Value of Fried Potato Chips During Storage Study

	TBA values (μmoles malonaldehyde/kg sample)[a]				
Storage period (wk)	System I (control)	System II (BHT)	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
0	$13.25 \pm 0.57^{a}_{H}$	$12.35 \pm 0.61^{b}_{H}$	$13.22 \pm 0.73^{a}_{H}$	$12.39 \pm 0.46^{b}_{H}$	$12.93 \pm 0.81^{ab}_{H}$
2	$25.60 \pm 0.65^{a}_{G}$	$20.82 \pm 0.71^{b}_{G}$	$18.56 \pm 0.48^{c}_{G}$	$15.45 \pm 0.59^{d}_{G}$	$18.99 \pm 1.11^{c}_{G}$
4	$33.95 \pm 0.65^{a}_{F}$	$24.12 \pm 0.34^{b}_{F}$	$22.50 \pm 0.31^{c}_{F}$	$21.38 \pm 1.16^{d}_{F}$	$24.05 \pm 1.18^{b}_{F}$
6	$35.46 \pm 0.78^{a}_{E}$	$28.85 \pm 0.62^{b}_{E}$	$25.49 \pm 0.75^{d}_{E}$	$25.21 \pm 1.02^{d}_{E}$	$27.34 \pm 0.30^{c}_{E}$
8	$40.30 \pm 0.44^{a}_{D}$	$33.62 \pm 0.46^{b}_{D}$	$29.14 \pm 2.42^{c}_{D}$	$27.58 \pm 0.65^{d}_{D}$	$33.22 \pm 0.59^{b}_{D}$
10	$57.52 \pm 0.89^{a}_{C}$	$35.97 \pm 0.59^{b}_{C}$	$33.40 \pm 0.39^{c}_{C}$	$31.78 \pm 1.21^{d}_{C}$	$35.14 \pm 1.03^{b}_{C}$
12	$71.14 \pm 1.27^{a}_{B}$	$38.78 \pm 1.05^{c}_{B}$	$38.64 \pm 0.83^{c}_{B}$	$36.87 \pm 0.94^{d}_{B}$	$41.20 \pm 0.99^{b}_{B}$
14	$85.04 \pm 0.94^{a}_{A}$	$56.05 \pm 0.74^{b}_{A}$	$50.56 \pm 1.54^{d}_{A}$	$44.05 \pm 0.49^{e}_{A}$	$53.59 \pm 0.78^{c}_{A}$

[a]Mean of three analyses. Means within each row with the different superscripts are significantly ($P < 0.05$) different. Means within each column with the different subscripts are significantly ($P < 0.05$) different. See Tables 1 and 2 for abbreviations.

tioxidant on the flavor, odor, texture, and overall acceptability of fried potato chips. Although somewhat subjective, sensory evaluation remains the ultimate measure of rancidity, as no combination of chemical or physical tests is currently capable of assessing the composite sensory attributes of a food (15).

Oxidative stability of fried potato chips during storage. Potato chips were analyzed for oxidation using TBA test and rancid odor evaluation. In the study, statistical analysis of TBA values and sensory scores for rancid odor both showed significant ($P < 0.05$) effects of treatments and storage times. The changes in TBA values of fried potato chips stored under ambient temperature are presented in Table 8. Results indicated that the TBA value of all systems increased significantly ($P < 0.05$) after only 2 wk of storage. As shown in Table 8, all systems with antioxidants yielded lower TBA values than did the control throughout the storage period. Although each antioxidant offered protection, the oleoresin rosemary was most effective ($P < 0.05$) in retarding oxidation, followed by BHA, sage extract, and BHT.

Results of rancid odor evaluation of potato chips during storage at ambient temperature are presented in Table 9. Generally, changes of sensory scores for rancid odor over time agreed with changes in TBA values for all oil systems. However, there was no significant ($P > 0.05$) difference in sensory scores within the five systems during storage periods. This may due to the strong flavor of fried potato chips, which may have prevented the panel from accurately assessing varying degrees of oxidation among storage periods.

When sensory panel data were compared with chemical measurements of oxidation, it was observed that the panel did not detect the presence of rancid notes although TBA values indicated that there was a rapid increase in oxidation. The absence of rancidity notes and the lack of correlation between TBA values and sensory panel data have been observed in other studies in which TBA was the major method of measuring oxidation (31).

The results of this study have shown that the addition of antioxidants to RBD palm olein improves its oxidative stability

TABLE 9
Sensory Scores for Rancid Odor of Fried Potato Chips Stored Under Ambient Temperature[a]

Storage period (wk)	System I (control)	System II (BHT)	System III (BHA)	System IV (oleoresin rosemary)	System V (sage extract)
0	0.20^{a}_{C}	0.20^{a}_{F}	0.10^{a}_{C}	0.00^{a}_{E}	0.10^{a}_{C}
2	0.60^{a}_{C}	$0.40^{a}_{E,F}$	0.40^{a}_{C}	$0.20^{a}_{D,E}$	0.40^{a}_{C}
4	1.80^{a}_{B}	$0.90^{b}_{E,F}$	$1.40^{a,b}_{B}$	$0.80^{b}_{C,D}$	$1.00^{b}_{B,C}$
6	1.90^{a}_{B}	$1.20^{a}_{D,E,F}$	$1.50^{a}_{A,B}$	$1.30^{a}_{B,C}$	$1.70^{a}_{A,B}$
8	2.10^{a}_{B}	$1.60^{a}_{B,C,D}$	$1.60^{a}_{A,B}$	$1.40^{a}_{A,B,C}$	$1.80^{a}_{A,B}$
10	$2.50^{a}_{A,B}$	$1.90^{a}_{B,C}$	$2.00^{a}_{A,B}$	$1.80^{a}_{A,B}$	2.30^{a}_{A}
12	3.20^{a}_{A}	$2.30^{a,b}_{A,B}$	$2.10^{a,b}_{A,B}$	$1.90^{b}_{A,B}$	$2.40^{a,b}_{A}$
14	3.30^{a}_{A}	$2.90^{a,b}_{A}$	$2.30^{a,b}_{A}$	2.10^{b}_{A}	$2.60^{a,b}_{A}$

[a]Mean of 10 observations. Means within each row with the different superscripts are significantly ($P < 0.05$) different. Means within each column with the different subscripts are significantly ($P < 0.05$) different. Odor score: 0 (bland) to 6 (markedly disagreeable off-flavor, very rancid) See Table 2 for abbreviations.

when used as a deep-fat frying oil. The order of activity found for antioxidants in RBD palm olein during deep-fat frying of potato chips was oleoresin rosemary > BHA > sage extract > BHT, although some variation from this order was found depending on the method of assessment. The storage study of fried potato chips carried out at ambient temperature showed the same order in relative activity of antioxidants. The results indicated that oleoresin rosemary and sage extracts could replace those synthetic antioxidants which have been questioned due to possible undesirable side effects.

ACKNOWLEDGMENT

This is a contribution of IRPA Project No. 03-02-04-003 of Universiti Putra Malaysia.

REFERENCES

1. Alexander, J.C., Biological Effects Due to Changes in Fats During Heating, *J. Am. Oil Chem. Soc. 55*:711–717 (1978).
2. Pearson, A.M., J.I. Gray, A.M. Wolzak, and N.A. Horenstein, Safety Implications of Oxidized Lipids in Muscle Foods, *Food Technol. 37*:121–127 (1983).
3. Wu, P.F., and W.W. Nawar, A Technique for Monitoring the Quality of Used Frying Oils, *J. Am. Oil Chem. Soc. 63*:1363–1367 (1986).
4. Houlihan, C.M., and C.T. Ho, Natural Antioxidants, in *Flavor Chemistry of Fats and Oils*, edited by D.B. Min and T.H. Smouse, American Oil Chemists' Society, Champaign, 1985, p. 117.
5. Zhang, K.Q., Y.D. Bao, P. Wu, R.T. Rosen, and C.T. Ho, Antioxidative Components of Tanshen (*Salvia miltiorrhiza* Bung), *J. Agric. Food Chem. 38*:1194–1197 (1990).
6. Kim, S.Y., J.H. Kim, S.K. Kim, M.J. Oh, and M.Y. Jung, Antioxidant Activities of Selected Oriental Herb Extracts, *J. Am. Oil Chem. Soc. 71*:633–640 (1994).
7. Chipault, G.R., J.M. Mizuno, J.M. Hawkins, and W.O. Lundberg, The Antioxidant Properties of Natural Spices, *Food Res. 17*:46–49 (1952).
8. Rasit, R., and M.A. Augustin, Effect of Tertiary-butylhydroquinone on the Stability of Fried Banana Chips, *Pertanika 5*:119–122 (1982).
9. *Standard Methods for the Analysis of Oils, Fats and Derivatives*, 6th edn., edited by C. Paquot, International Union of Pure and Applied Chemistry, Commission on Oils, Fats and Derivatives, 1979, pp. 138–139, 145–146.
10. *PORIM Test Methods*, Palm Oil Research Institute of Malaysia, Ministry of Primary Industries, Malaysia, 1995, pp. 72–75, 40–42, 92–101.
11. Ke, P.J., E. Cervantes, and C. Robles-Martinez, Determination of Thiobarbituric Acid Reactive Substances (TBARS) in Fish Tissue by an Improved Distillation-Spectrophotometric Method, *J. Sci. Food Agric. 35*:1248–1254 (1984).
12. Peled, M., T. Gutfinger, and A. Letan, Effect of Water and BHT on Stability of Cottonseed Oil During Frying, *Ibid. 26*:1655–1666 (1975).
13. Egan, H., R.S. Kirk, and R. Sawyer, *Pearson's Chemical Analysis of Foods*, Churchill-Livingstone, Edinburgh, 1981, p. 537.
14. Peryam, D.R., and F.J. Pilgrim, Hedonic Scale Method of Measuring Food Preferences, *Food Technol. 11*:9–14 (1957).
15. Robards, K., A.F. Kerr, and E. Patsalides, Rancidity and Its Measurement in Edible Oils and Snack Foods, *Analyst 113*:213–222 (1988).
16. *Statistical Analysis System User's Guide: Statistics*, SAS Institute Inc., Cary, 1989, pp. 125–154.
17. Tan, B.K., and F.C.H. Oh, Oleins and Stearins from Malaysian Palm Oil—Chemical and Physical Characteristics, in *PORIM Technology*, No. 4, Palm Oil Research Institute of Malaysia, Ministry of Primary Industries, Malaysia, 1981, pp. 1–6.
18. Fritsch, C.W., Measurements of Frying Fat Deterioration: A Brief Review, *J. Am. Oil Chem. Soc. 58*:272–274 (1981).
19. Gwo, Y.Y., G.J. Flick Jr., and H.P. Dupuy, Effect of Ascorbyl Palmitate on the Quality of Frying Fats for Deep Frying Operation, *Ibid. 62*:1666–1671 (1985).
20. Rady, A.H., and M.A. Madkour, Changes in Physical and Chemical Properties of Palm Olein During Heating, *Grasas Aceites 46*:270–275 (1995).
21. Perkins, E.G., Formation of Non-Volatile Decomposition Products in Heated Fats and Oils, *Food Technol. 21*:125–130 (1967).
22. Cuvelier, M.E., C. Berset, and H. Richard, Antioxidant Constituents in Sage (*Salvia officinalis*), *J. Agric. Food Chem. 42*:655–669 (1994).
23. Namiki, M., Antioxidants/Antimutagens in Food, *Crit. Rev. Food Sci. Nutr. 29*:273–300 (1990).
24. Gordon, M.H., The Mechanism of Antioxidant Action *in vitro*, in *Food Antioxidants*, edited by B.J.F. Hudson, Elsevier, New York, 1990, pp. 1–18.
25. Sherwin, E.R., Methods for Stability and Antioxidants Measurement, *J. Am. Oil Chem. Soc. 45*:632a–648a (1968).
26. Coppen, P.P., The Use of Antioxidants, in *Rancidity in Foods*, 2nd edn., edited by J.C. Allen, and R.J. Hamilton, Elsevier, London, 1989, pp. 83–104.
27. Yoon, S.H., S.K. Kim, M.G. Shin, and K.H. Kim, Comparative Study of Physical Methods for Lipid Oxidation Measurement in Oils, *J. Am. Oil Chem. Soc. 62*:1487–1489 (1985).
28. Landers, R.E., and D.M. Rathmann, Vegetable Oils: Effects of Processing, Storage, and Use on Nutritional Values, *Ibid. 58*:255–259 (1981).
29. Augustin, M.A., K.H. Lee, and K.T. Yan, Comparison of the Frying Performance of Market Samples of Palm Olein, Corn Oil and Soya Oil in Malaysia, *Pertanika 10*:295–304 (1987).
30. Gray, J.I., Measurement of Lipid Oxidation—A Review, *J. Am. Oil Chem. Soc. 55*:539–546 (1978).
31. Krevchenia, M., and O.R. Fennema, Effects of Cryoprotectants on Frozen Burbot Fillets and A Comparison with Whitefish Fillets, *J. Food Sci. 53*:1104–1108 (1988).

[Received April 27, 1998; accepted November 2, 1998]