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ORIGINAL ARTICLE

Stability During Frying of *Moringa oleifera* Seed Oil Variety "Periyakulam 1"

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The frying performance of the *Moringa oleifera* seed oil variety Periyakulam 1 (PKM 1) from India, extracted using cold press (CP) and *n*-hexane (H), during frying of potatoes and cod was studied especially as regards repeated frying operations. The oils were used for intermittent frying of potato slices and cod filets at a temperature of $175 \pm 5^{\circ}C$ for 5 consecutive days. The chemical changes occurring in the oils were evaluated. Free fatty acid content, peroxide value, specific extinction at 232 nm, polar compounds colour and viscosity of the oils all increased, whereas the iodine values, smoke points, polyunsaturated fatty acid content, induction period and tocopherol concentration decreased. The effect of the oils on the organoleptic quality of these fried foods was also determined by expert panellists. The analytical and sensory data showed that the lowest deterioration occurred in cold pressure produced oil and the highest in *n*-hexane extracted oil. Therefore, cold pressure oil appears to be the most appropriate for frying. Potatoes and cod were also fried in virgin olive oil in order to have a direct comparison between the different oils. The results clearly indicated that virgin olive oil has the highest resistance to thermal deterioration during frying compared with the other two oils.

Key Words: Moringa oleifera; PKM 1; deep-frying; frying stability; potatoes; cod.

INTRODUCTION

Deep-fried food and especially fried potatoes and cod (the most common foods fried in homes and restaurants) are becoming more and more popular among the inhabitants of the European Union. Deep-frying is also a very important method of cooking in the food services industry as it enhances the sensory properties of foods.

Repeated use of frying oils produces undesirable constituents that may pose health hazards (Tyagi and Vasishtha, 1996). During deep-frying, fats and oils are repeatedly

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used at elevated temperatures in the presence of air and moisture. This causes partial conversion of fats and oils to volatile chain-scission products, nonvolatile oxidized derivatives, and dimeric, polymeric, or cyclic substances (Chang *et al*., 1978). In view of this, the use of oil that can resist oxidation as much as possible is very important. Virgin olive oil has proven to be one of the most suitable oils for frying (Romero *et al*., 1999). Its oxidative stability is related to some extent to the presence of α-tocopherol (Kiritsakis, 1988) and phenolic compounds (Kiritsakis and Min, 1989). However, its applications in food industry are limited due to its high cost. The use of an oil with characteristics similar to olive oil but equal or increased resistance to oxidation during frying would be most appreciated. Our work tries to investigate the physical and chemical changes that occur in oils produced from the seeds of *Moringa oleifera* PKM 1, with cold press and solvent extraction with *n*-hexane during frying of potatoes and cod. The possible relevance of minor compounds in the frying life of the oils will be discussed. Fryings were also carried out with virgin olive oil for comparison.

MATERIALS AND METHODS

Materials

Frying oils were produced from the seeds of *Moringa oleifera* var. PKM 1 with cold press (CP) and solvent extracted using *n*-hexane (H) according to the method described by Tsaknis *et al*. (1999a). They were used for frying potatoes and cod. Fryings were also carried out with commercially obtained virgin olive oil ''Horio'' (MINERVA S.A., Athens, 14452, Greece). Potatoes (variety Lady Rosetta) and cod fillets (*Gadus morhua*) were purchased at the local market.

Reagents

All the reagents (analytical and HPLC grade) were obtained from Sigma Chemical Company Co. (St Louis, MO, U.S.A.) and the standard solutions for the determination of tocopherols were purchased from Merck Ltd (Darmstadt, Germany) (DL-α-tocopherol) or Sigma (δ-tocopherol). Fatty acid methylester standards were purchased from British Greyhound Chromatography and Allied Chemicals (Birkenhead, U.K.).

Methods

Physical and chemical characteristics. The method used for the determination of density and refractive index (at 40°C) was adapted from AOAC (method number 969.18) (1990). Colour was measured with a Lovibond Tintometer (The Tintometer Ltd., Salisbury, U.K.). Smoke point was determined according to British Standards Methods of Analysis (1976) (BS 684: Section 1.8). Free fatty acids were measured according to IUPAC (method number 2.201) (1987), saponification value according to AOCS (method Cd 3-25) as described by Allen and Marvin (1982), and iodine value according to the Wijs method by Pearsons (1981).

Determination of the fatty acid composition. Fatty acid composition was determined by gas–liquid chromatography (GLC) according to the method of

Tsaknis *et al*. (1999a). Analysis was performed on a Varian 3600 gas chromatograph (Varian, Palo Alto, CA, U.S.A.) equipped with a Supelcowax 10 (Supelco, INC., Supelco Park, Bellefonte, PA) fused silica capillary column $30 \times 0.32\,mm^2$ i.d., 0.25-μm film thickness. The temperature program was 60°C for 10 min and then 2°C/min up to 220°C. Injector and FID temperatures were set at 160 and 280°C, respectively, sample volume was 0.2 μL, the carrier gas was N_2 at a flow rate of 30 mL/min, chart speed was set at 0.5 cm/min and the attenuation at $10^{-10} \times 32$. The internal standard used was nonadecanoic acid. Methyl esters were identified and quantified by comparing the retention times and peak area of the unknowns with known FAME standard mixtures. Samples were prepared and measured separately in triplicate.

Tocopherol composition. Tocopherols were determined using a modified method of Carpenter (1979) and a Waters 600E HPLC pump (Millipore Corporation, Waters Chromatography Division, Massachusetts, MA, U.S.A.) equipped with a Waters μ-Polarsil, 125 Å, 10 μm, $3.9 \times 300\,mm^2$ column and a Waters 486 Tunable Absorbance Detector. One gram of oil was accurately weighed in a 5 mL sample vial wrapped in foil paper to prevent oxidation. The oil was dissolved in 5 mL *n*-hexane before injection. A 20 μL sample was injected into the HPLC. The detector was set at 295 nm. *Iso*-propanol: *n*-hexane: absolute ethanol (2:97.5:0.5) at 1 mL/min was used as mobile phase. A total of 10 min was enough to assay the tocopherols. Integration was done with Waters Baseline 815 software running on a computer. The samples were prepared and measured separately in triplicate.

Oxidative state and susceptibility to oxidation (Rancimat method). Peroxide value was measured using the method of Lea (1952). Specific extinction ($E^{1\%}_{1cm}$ at 232 nm) was determined using the method of IUPAC (method number 2.505, 1987) and a Hitachi U-3210 Spectrophotometer (Hitachi Ltd. Tokyo, Japan). The determination of the susceptibility to oxidation (Rancimat method) was carried out using the method described by Tsaknis *et al*. (1999a). The temperature was set at 120°C and the airflow at 15 L/h.

Frying. The frying method was adapted from Tsaknis *et al*. (1999b). Potatoes and skinless cod fillets were deep-fried independently, each in 2 L of oil. The potatoes were peeled and washed about 1 h before use, and sliced into discs 0.5 cm thick and 2.5 cm diameter, using a mechanical slicer. The skinless cod fillets were cut into square pieces ($3\,cm \times 3\,cm \times 1.5\,cm$) and coated with wheat flour. When the temperature of the oil reached 175°C a batch of 100 g of each was fried in separate oil samples. During 5 consecutive days, for 2 h and 30 min/day, five discontinuous fryings were carried out. The frying time was 8 min for cod fillets and 6 min for potato slices. At the end of the fryings each day, 50 g samples of oil were removed from each fryer and stored at 0°C. The fryers were then cupped with their lid and the fryings were continued the following day. Fresh oil was never added to the frying pans.

Polar compounds. They were determined using the IUPAC (1987) method. A chromatographic glass column with stopcock was filled with about 30 mL of the elution solvent, a mixture of light petroleum (b.p. 40–60°C)–diethylether (87:13). A

slurry of 25 g silica gel in about 80 mL of the elution solvent was prepared and poured into the column. Sea sand was added. The supernatant elution solvent was drained off as far as the sand layer. About 2.5 g of the sample was prepared in a 50 mL volumetric flask and then dissolved in about 20 mL of the elution solvent while warming slightly. After cooling to room temperature, the flask was filled up to the mark with the elution solvent. Twenty milliliters of the solution were introduced, with the aid of a volumetric pipette, onto the chromatography column. Two 250 mL flasks were dried in the oven and weighed accurately to within 0.001 g. One of them was placed under the outlet of the column. The sample solution was drained off to the level of the sand layer. The nonpolar compounds were eluted with 150 mL of the elution solvent using a dropping funnel. The flow rate was adjusted so that 150 mL passed through the column within 60–70 min. After the completion of the elution, any substance adhering to the outlet of the column was washed in the flask with the elution solvent. The solvent was removed from the flask with the aid of a rotary evaporator using a water bath at a temperature no higher than 60°C. Shortly before the end of distillation, nitrogen was introduced into the system. The flask was weighed. The content of polar compounds, in per cent (wt/wt), was given by the formula

$$\frac{m - m_1}{m} \times 100$$

where m_1 is the mass (in g) of the nonpolar fractions, m is the mass (in g) of the sample contained in 20 mL of the solution added to the column.

Sensory evaluation. The organoleptic quality of the fried potatoes and cod was evaluated using eight panellists, members of the sensory panel. Fish and potatoes were kept for 10 min at room temperature before testing. First, the panellists were trained to use the triangular test in order to distinguish the difference in the organoleptic properties (colour, off-flavour) of the fried products. The samples used had been fried either with fresh oil or with oil previously used for 10 separate fryings beforehand. Assessment was conducted in natural white light in a specially designed taste panel room at T.E.I. of Athens. A taste panel score sheet with a numerical scale of rating was developed, using descriptive terms against each quality parameter as follows: colour (only for fried potatoes because the panellists were not able to detect any difference in colour of these samples during training sessions) scale of 1–4, an increasing score corresponding to decreasing quality, and a score of 4 represented extremely undesirable colour. Off-flavour, scale of 1–4, a score of 1 represented "no rancid off-flavour" and a score of 4 represented "strong rancid off-flavour". In the overall acceptance scale of 1–9, the two extreme ends represent conditions of quality, either extremely good (9) or totally undesirable (1). The panellists were provided with the score sheets and were asked to rate samples according to the descriptive scale. One sample from each frying pan (potatoes and cod) was represented at one session to each panellist. The hot samples were served in shallow disposable polystyrene food dishes with a code symbol for identification inscribed on the dish against each sample. In order to avoid transfer (carry over) of flavour components from one sample to the next, the panellists rinsed their mouths with water between tastings. Each day the panellists tasted the 30 products (3 oils × 2 products × 5 fryings) fried in three

different oils (Moringa PKM 1 cold press, Moringa PKM 1 *n*-hexane and Virgin olive oil).

Statistical Analysis

Results are representing the average and the standard deviation (S.D.) (in parenthesis) of three simultaneous assays carried out in all methods. Changes in polar compound content were adjusted to linear ($Y = a + bX$) adjustment equation by analysis of variance (ANOVA) ($P < 0.05$), where Y is the polar compounds and X the number of frying uses. Linear adjustment equations of three different oils were compared by analysis of covariance (ANCOVA), taking into account their slopes and intercepts. Using the linear equation and having 25% of polar compounds as a limit, the theoretical number of frying operations possible before having to discard the oil was calculated.

RESULTS AND DISCUSSION

Free Fatty Acid (FFA) Content

No significant increases were observed after 5 days of frying in all the oils at the 95% level of significance (Tables 1, 3, 5, 8, 10 and 12). The oil produced with cold pressure showed the lowest increase and the *n*-hexane oil the highest. The steady rise in the formation of FFA can be attributed partly to the hydrolysis and partly to the carboxylic groups present in polymeric products of frying (Tyagi and Vasishtha, 1996). The free fatty acids were mainly formed by hydrolysis of triglycerides, which was promoted by the presence of food moisture, and by oxidation or reaction of oil with moisture formed during other deterioration reactions (Al-Harbi and Al-Kabtani, 1993). In cod frying, the same trend was observed, although cod was found to cause a more rapid increase in the free fatty acid content. Virgin olive oil showed a lower increase in free fatty acid content in comparison to the other two oils.

Peroxide Value

Cold pressure and *n*-hexane extracted oils showed an increase at the initial stages of frying followed by a decrease in PV (Tables 1, 3, 5, 8, 10 and 12). Further frying resulted in a new increase in PV. Virgin olive oil showed a continuous increase during the frying process. All the used oils showed a significant increase ($P < 0.05$) in PV after 25 batches of frying. Peroxides under the heating conditions used are unstable, and react to form secondary oxidation products. An increase in the initial stage of frying would be expected to be followed by a decrease with further frying, because the hydroperoxides tend to decompose at 180°C to form secondary oxidation products (Perkins, 1967). The overall increase in peroxide value is connected with the cooling period of the oil. The length of time required to cool the oils at room temperature (28°C) was more than 4 h. During the cooling period, the oils were exposed to air at high temperature and hydroperoxides were formed again (Augustin and Berry, 1983). In view of these factors, peroxide value is not to be recommended for measuring heating oil deterioration. The oils used for frying cod seemed to follow the same trend with the only exception of cold pressure oil that showed a continuous increase of PV. Olive oil showed a higher increase in peroxide value in comparison to the other two oils.

Iodine Value

The results showed that there were no significant changes ($P<0.05$) between the fresh and used PKM 1 oils after 25 fryings (Tables 1, 3, 5, 8, 10 and 12). The decrease of iodine value correlated well with the decrease of unsaturated fatty acids ($r=0.992$). Cod was found to cause a more rapid decrease in the iodine value. Virgin olive oil showed a lower decrease in iodine value in comparison to the other two oils.

Viscosity

As the oxidation accelerated by heat proceeded, the values of viscosity progressively increased (Tyagi and Vasishtha, 1996). Cold press oil showed the lowest change in viscosity after 10 fryings, while *n*-hexane oil showed much higher changes (Tables 1, 3, 5, 8, 10 and 12). Virgin olive oil showed a higher increase in viscosity in comparison to the other two oils. The results showed that there were no significant changes ($P<0.05$) between the fresh and used PKM 1 oils after 25 fryings, while the virgin olive oil showed a significant increase ($P<0.05$). These results clearly indicate the higher deteriorative effect of oxidation and polymerization of *n*-hexane oil compared to cold pressure oil. The increase in viscosity of frying oils was due to polymerization which resulted in the formation of higher molecular weight compounds (carbon-to-carbon and/or carbon-to-oxygen-to-carbon bridges) between fatty acids (Al-Harbi and Al-Kabtani, 1993). The oils used for frying cod seemed to follow the same trend although cod was found to cause a more rapid increase in viscosity.

Smoke Point

As expected a decrease of smoke point of the oils was observed (Tables 1, 3, 5, 8, 10 and 12). The *n*-hexane oil showed a significant ($P<0.05$) decrease in smoke point after 25 fryings, while the cold pressure oil and virgin olive oil showed no significant increase after 25 fryings. Morton and Chidley (1988) reported that the amount of smoke emanating from a cup is directly proportional to the concentration of low molecular weight decomposition products in the oil. The free fatty acids and other volatile substances leaving the fat as gases, will not appear as smoke until their concentration is great enough to permit aggregation to colloidal sized particles. The oils used for frying cod seemed to follow the same trend although cod was found to cause a higher decrease in the smoke point.

Polar Compounds

The results demonstrated that cold pressure oil exhibited the lowest increase in polar compounds, and the *n*-hexane oil the highest (Tables 1, 3, 5, 8, 10 and 12). The *n*-hexane oil showed a significant ($P<0.05$) increase in polar compounds after 20 fryings, while the cold pressure oil and virgin olive oil showed significant increase after 25 fryings.

Fritch (1981) reported that the analysis of percentage polar compounds is considered to be one of the more reliable indicators of the state of the oil deterioration. This latter statement is supported by those of other researchers (Gere, 1982). As indicated by Romero *et al.* (1999), a number of European countries have passed specific laws and regulations concerning culinary oil used in frying. Many countries have set polar compounds' maximum level at 25% while others have established a polar compound cut point between 20 and

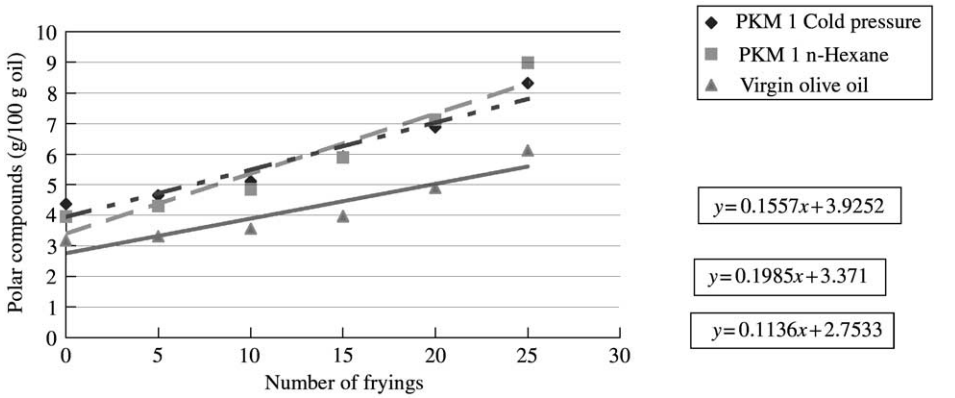

FIGURE 1. Linear adjustment ($Y = a + bX$) of polar content versus number of fryings of potatoes.

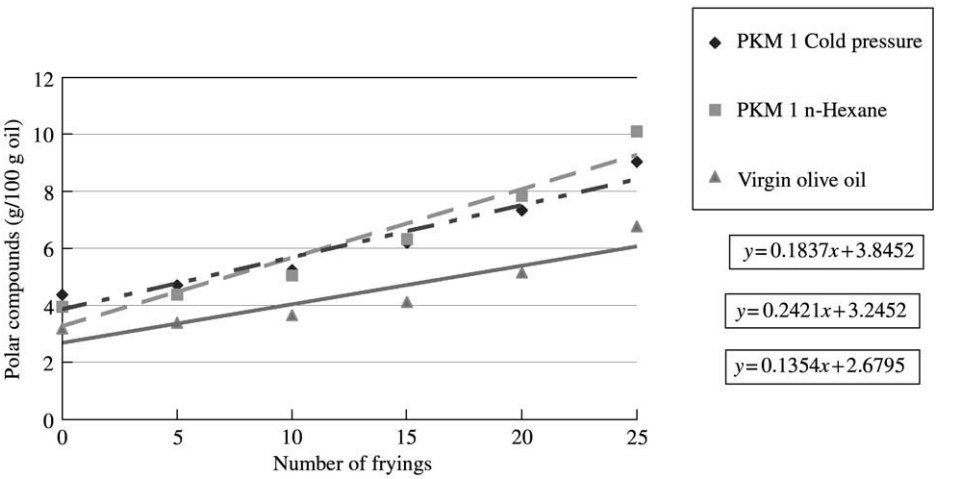

FIGURE 2. Linear adjustment ($Y = a + bX$) of polar content versus number of fryings of cod.

27%. Romero *et al*. (1999), in their work, used three different equations, namely linear, logarithmic and power, to estimate the number of frying operations before the critical quantity of polar compounds was reached during frying (frying oil was frequently replenished with fresh oil at a quantity lost during operations). Logarithmic and power equations appeared to define the changes more accurately because polar compounds tended to stabilize after a certain number of fryings. In our work, linear equation seemed to be more adequate because there was no replenishment with fresh oil and the polar compounds kept increasing until the end of fryings.

The linear adjustments of polar compound changes are shown in Table 15. The linear equation showed that the critical level of 25% of polar compounds would be reached after 196 ± 18 (potatoes) or 165 ± 21 (cod) fryings of olive oil, after 135 ± 26 (potatoes) or 115 ± 11 (cod) fryings of PKM 1 cold pressure and after 109 ± 8

TABLE 1

Changes in the quality characteristics of PKM 1 *Moringa oleifera* oil extracted with cold pressure during potato frying at 175°C

Determination	Number of fryings						
	0	5	10	15	20	25	*P*
Free fatty acids	1.94	1.99	2.11	2.28	2.63	3.05	−
(% as oleic acid)	(0.21)	(0.14)	(0.24)	(0.16)	(0.30)	(0.44)	
Peroxide value	0.11	0.76	1.62	1.35	2.95	3.86	+
(meq O_2/kg of oil)	(0.10)	(0.24)	(0.55)	(0.39)	(0.67)	(0.97)	
Iodine value	65.73	65.62	65.47	65.26	65.01	64.42	−
(g of I_2/100 g of oil)	(0.49)	(0.78)	(0.59)	(0.81)	(0.37)	(0.94)	
Viscosity	80.00	80.12	80.28	80.59	80.96	81.54	−
(mPa s)	(0.92)	(1.58)	(1.12)	(1.67)	(1.27)	(0.76)	
Smoke point	203	202	200	199	198	195	−
(°C)	(2.5)	(2.0)	(1.5)	(1.5)	(2.5)	(1.0)	
Polar compounds	4.37	4.65	5.10	5.91	6.88	8.32	+
(g/100 g oil)	(0.76)	(0.93)	(1.08)	(0.57)	(0.44)	(0.76)	
$E^{1\%}_{1cm}$ at 232 nm	0.982	1.114	1.347	1.762	2.443	3.467	+
	(0.13)	(0.17)	(0.21)	(0.17)	(0.24)	(0.25)	
Induction period (h)	16.20	15.95	15.58	15.06	14.28	13.08	+
	(0.80)	(1.14)	(0.97)	(1.26)	(0.85)	(1.06)	
α-Tocopherol	5.06	4.81	4.44	3.92	3.14	2.01	+
(mg/kg oil)	(0.67)	(0.44)	(0.36)	(0.52)	(0.41)	(0.29)	
γ-Tocopherol	25.40	24.60	22.68	19.49	14.16	7.46	+
(mg/kg oil)	(1.16)	(0.97)	(1.06)	(0.76)	(0.93)	(0.90)	
δ-Tocopherol	3.55	3.42	3.26	2.96	2.42	1.67	+
(mg/kg oil)	(0.45)	(0.38)	(0.77)	(0.69)	(0.36)	(0.47)	
Colour	1.90/30.00	2.09/30.00	2.39/30.15	2.76/30.43	3.93/30.64	5.59/30.88	−/+
red/yellow	(0.10)/(2.40)	(0.45)/(1.30)	(0.76)/(1.65)	(0.84)/(0.95)	(0.47)/(1.30)	(0.36)/(0.77)	

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference.

TABLE 2

Fatty acid composition of PKM 1 *Moringa oleifera* oil extracted with cold pressure during potato frying at 175°C

Fatty acid	Number of fryings						
	0	5	10	15	20	25	*P*
8:0	0.04 (0.01)	0.05 (0.02)	0.06 (0.02)	0.09 (0.03)	0.12 (0.04)	0.08 (0.02)	−
14:0	0.13 (0.08)	0.15 (0.06)	0.17 (0.04)	0.14 (0.06)	0.18 (0.05)	0.20 (0.07)	−
16:0	6.34 (0.41)	6.34 (0.28)	6.36 (0.15)	6.38 (0.42)	6.41 (0.39)	6.40 (0.30)	−
16:1 *n*-9	0.10 (0.06)	0.09 (0.02)	0.08 (0.03)	0.06 (0.04)	0.07 (0.03)	0.04 (0.02)	−
16:1 *n*-7	1.28 (0.87)	1.26 (0.43)	1.24 (0.22)	1.23 (0.36)	1.20 (0.15)	1.17 (0.19)	−
17:0	0.08 (0.02)	0.10 (0.03)	0.11 (0.02)	0.09 (0.02)	0.12 (0.04)	0.14 (0.06)	−
18:0	5.70 (0.21)	5.71 (0.44)	5.72 (0.26)	5.76 (0.33)	5.88 (0.45)	6.12 (0.53)	−
18:1	71.60 (0.73)	71.56 (0.50)	71.58 (0.66)	71.56 (0.48)	71.52 (0.26)	71.44 (0.40)	−
18:2	0.77 (0.38)	0.75 (0.26)	0.71 (0.33)	0.67 (0.20)	0.62 (0.17)	0.55 (0.13)	+
18:3	0.20 (0.03)	0.18 (0.06)	0.15 (0.05)	0.12 (0.08)	0.08 (0.02)	0.03 (0.01)	+
20:0	3.52 (0.29)	3.53 (0.28)	3.55 (0.17)	3.56 (0.33)	3.58 (0.15)	3.61 (0.16)	−
20:1	2.24 (0.25)	2.24 (0.28)	2.23 (0.25)	2.21 (0.36)	2.18 (0.19)	2.15 (0.38)	−
22:0	6.21 (0.48)	6.22 (0.38)	6.24 (0.17)	6.26 (0.29)	6.29 (0.30)	6.33 (0.40)	−
22:1	0.12 (0.06)	0.11 (0.04)	0.11 (0.04)	0.09 (0.04)	0.07 (0.03)	0.05 (0.02)	−
26:0	1.21 (0.15)	1.21 (0.16)	1.19 (0.18)	1.16 (0.12)	1.12 (0.14)	1.08 (0.07)	−

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference.

(potatoes) or 90 ± 10 (cod) fryings of PKM 1 *n*-hexane. Figures 1 and 2 represent estimation on the frying life (before having to discard) of the three oils by using a linear equation.

Colour

Darkening is attributed to the presence of unsaturated carbonyl compounds or to non-polar compounds of foodstuff solubilized in the oil (Gutierrez *et al*., 1988). The results indicated that there was an increase in red units of the colour measurement of frying oils, while yellow units showed only minor changes (Tables 1, 3, 5, 8, 10 and 12). The colour change was a result of the diffusion of pigments into the oil during frying. *n*-Hexane oil showed the highest increase in colour while cold pressure oil showed the lowest. The *n*-hexane oil showed a significant ($P<0.05$) increase in red units of colour after 20 fryings, and the cold pressure oil after 25 fryings. Virgin olive oil showed no significant increase after 25 fryings. All the used oils showed no significant difference in yellow

TABLE 3

Changes in the quality characteristics of PKM 1 *Moringa oleifera* oil extracted with *n*-hexane during potato frying at 175°C

Determination	Number of fryings						
	0	5	10	15	20	25	*P*
Free fatty acids	1.12	1.19	1.35	1.57	2.01	2.57	−
(% as oleic acid)	(0.20)	(0.38)	(0.49)	(0.54)	(0.59)	(0.56)	
Peroxide value	1.83	2.15	3.48	3.25	4.37	5.36	+
(meq O_2/kg of oil)	(0.19)	(0.89)	(0.95)	(1.20)	(1.10)	(0.94)	
Iodine value	65.58	65.44	65.25	64.98	64.62	63.89	−
(g of I_2/100 g of oil)	(0.48)	(0.88)	(0.67)	(0.94)	(0.69)	(0.74)	
Viscosity	45.00	45.15	45.36	45.76	46.23	46.96	−
(mPa s)	(0.13)	(0.52)	(0.41)	(0.33)	(0.60)	(0.58)	
Smoke point	200	199	197	195	193	190	+
(°C)	(2.0)	(1.5)	(2.5)	(2.0)	(1.0)	(1.5)	
Polar compounds	3.95	4.30	4.85	5.89	7.13	8.99	+
(g/100 g oil)	(1.03)	(0.80)	(0.48)	(0.56)	(0.36)	(0.63)	
$E^{1\%}_{1cm}$ at 232 nm	3.001	3.244	3.611	4.161	5.211	6.481	+
	(0.86)	(0.59)	(0.44)	(0.55)	(0.37)	(0.48)	
Induction period	8.70	8.38	8.01	7.35	6.36	4.72	+
(h)	(0.90)	(1.04)	(0.76)	(0.81)	(0.66)	(0.65)	
α-Tocopherol	15.38	14.96	14.21	12.98	11.08	7.93	+
(mg/kg oil)	(0.68)	(0.97)	(0.62)	(0.55)	(0.51)	(0.74)	
γ-Tocopherol	4.47	4.22	3.90	3.46	2.88	1.89	+
(mg/kg oil)	(0.87)	(0.38)	(0.46)	(0.71)	(1.89)	(0.36)	
δ-Tocopherol	15.51	15.30	14.90	13.85	11.05	8.90	+
(mg/kg oil)	(0.99)	(0.60)	(0.39)	(0.66)	(0.48)	(0.44)	
Colour	0.80/35.00	1.06/35.16	1.40/35.24	1.83/35.44	3.27/35.65	5.58/35.94	−/+
red/yellow	(0.20)/(3.14)	(0.40)/(2.17)	(0.33)/(1.94)	(0.49)/(2.76)	(0.59)/(2.14)	(0.84)/(1.46)	

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference.

TABLE 4

Fatty acid composition of the PKM 1 *Moringa oleifera* oil extracted with *n*-hexane during potato frying at 175°C

Fatty acid	Number of fryings						
	0	5	10	15	20	25	*P*
8:0	0.03 (0.01)	0.05 (0.02)	0.08 (0.03)	0.12 (0.05)	0.17 (0.06)	0.23 (0.09)	−
14:0	0.13 (0.08)	0.18 (0.06)	0.24 (0.08)	0.31 (0.09)	0.36 (0.11)	0.40 (0.07)	−
16:0	6.46 (0.32)	6.48 (0.22)	6.51 (0.31)	6.54 (0.37)	6.57 (0.21)	6.60 (0.40)	−
16:1 *n*-9	0.09 (0.04)	0.08 (0.04)	0.06 (0.03)	0.05 (0.04)	0.03 (0.02)	0.03 (0.01)	−
16:1 *n*-7	1.36 (0.84)	1.35 (0.17)	1.33 (0.26)	1.30 (0.18)	1.27 (0.25)	1.23 (0.31)	−
17:0	0.08 (0.02)	0.10 (0.07)	0.12 (0.08)	0.14 (0.06)	0.15 (0.07)	0.16 (0.08)	−
18:0	5.88 (0.23)	5.91 (0.26)	5.93 (0.34)	5.97 (0.19)	6.17 (0.24)	6.56 (0.36)	−
18:1	71.21 (0.69)	71.14 (0.46)	71.12 (0.50)	71.09 (0.41)	71.03 (0.52)	70.94 (0.26)	−
18:2	0.65 (0.32)	0.62 (0.28)	0.58 (0.36)	0.51 (0.21)	0.44 (0.15)	0.36 (0.16)	+
18:3	0.18 (0.05)	0.16 (0.08)	0.15 (0.07)	0.13 (0.09)	0.09 (0.04)	0.03 (0.02)	+
20:0	3.62 (0.33)	3.64 (0.27)	3.66 (0.18)	3.67 (0.33)	3.69 (0.12)	3.73 (0.16)	−
20:1	2.22 (0.26)	2.20 (0.35)	2.18 (0.29)	2.16 (0.21)	2.14 (0.33)	2.11 (0.28)	−
22:0	6.41 (0.46)	6.43 (0.19)	6.45 (0.33)	6.47 (0.40)	6.50 (0.22)	6.56 (0.38)	−
22:1	0.12 (0.07)	0.12 (0.05)	0.11 (0.06)	0.09 (0.04)	0.07 (0.05)	0.03 (0.02)	−
26:0	1.18 (0.20)	1.16 (0.24)	1.14 (0.36)	1.11 (0.44)	1.07 (0.30)	1.01 (0.44)	−

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference.

units after 25 fryings. Cod was found to cause less increase in red units of colour. The higher increase of oil colour during frying of potatoes than that during oil frying of cod is due to the fact that reactions between the aldehyde group of sugar and amino acids give brown products (Maillard reaction). Burton (1989) reported that the α and β unsaturated carbonyl compounds, derived from the sugars are the first formed intermediates that react with substances containing α-amino groups to give carbonyl-nitrogen compounds which conjugate to form brown products.

FAME Analysis by Gas–Liquid Chromatography

It was observed that there was a decrease in polyunsaturated fatty acids and a resulting increase in the saturated acids content (Tables 2, 4, 6, 9, 11 and 13). However, the changes in monounsaturated and saturated fatty acids were not statistically significant ($P<0.05$), whereas the polyunsaturated fatty acids ($C_{18:2}$ and $C_{18:3}$) showed significant decrease after 25 fryings. Changes in fatty acid profile of all

TABLE 5

Changes in the quality characteristics of virgin olive oil during potato frying at 175°C

Determination	Number of fryings						
	0	5	10	15	20	25	*P*
Free fatty acids	0.98	0.98	0.99	1.02	1.06	1.12	−
(% as oleic acid)	(0.11)	(0.55)	(0.44)	(0.35)	(0.66)	(0.28)	
Peroxide value	0.76	0.89	1.10	1.53	2.46	4.57	+
(meq O_2/ kg of oil)	(0.85)	(0.90)	(0.80)	(1.10)	(1.30)	(1.37)	
Iodine value	80.01	79.96	79.83	79.64	79.39	79.04	−
(g of I_2/100 g of oil)	(0.71)	(0.62)	(0.42)	(0.51)	(0.75)	(1.16)	
Viscosity	74.01	74.10	74.24	75.03	76.07	77.42	+
(mPa s)	(0.17)	(0.42)	(0.87)	(0.98)	(0.76)	(0.89)	
Smoke point	190	190	189	188	187	185	−
(°C)	(1.9)	(2.0)	(1.0)	(1.5)	(1.0)	(1.0)	
Polar compounds	3.18	3.31	3.56	3.97	4.90	6.12	+
(g/100 g oil)	(0.46)	(0.57)	(0.68)	(0.42)	(0.62)	(0.57)	
$E^{1\%}_{1cm}$ at 232 nm	2.011	2.115	2.297	2.622	3.155	3.961	+
	(0.391)	(0.103)	(0.053)	(0.076)	(0.095)	(0.086)	
Induction period (h)	7.88	7.75	7.38	7.01	6.60	5.78	+
	(0.53)	(0.44)	(0.90)	(0.85)	(0.65)	(0.56)	
α-Tocopherol	130.10	125.34	118.48	106.35	90.17	70.43	+
(mg/kg oil)	(2.32)	(1.17)	(1.49)	(0.98)	(1.52)	(1.28)	
γ-Tocopherol	9.90	9.65	9.30	8.70	7.55	6.01	+
(mg/kg oil)	(1.65)	(0.80)	(1.05)	(0.78)	(1.12)	(0.97)	
δ-Tocopherol	1.60	1.56	1.49	1.38	1.25	1.06	+
(mg/kg oil)	(0.86)	(0.44)	(0.34)	(0.56)	(0.19)	(0.36)	
Colour	2.50/36.00	2.60/36.30	2.90/36.60	3.10/36.90	3.40/37.50	3.80/38.90	−/−
red/yellow	(0.32)/(0.23)	(0.40)/(0.35)	(0.20)/(0.38)	(0.12)/(0.30)	(0.55)/(0.15)	(0.19)/(0.64)	

Note: Values are means of triplicate determinations and standard deviation are given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference

TABLE 6

Fatty acid composition of virgin olive oil during potato frying at 175°C

Fatty acid	Number of fryings						
	0	5	10	15	20	25	*P*
14:0	<0.01	–	–	–	–	–	–
	–						
16:0	11.20	11.29	11.33	11.36	11.50	11.67	–
	(0.66)	(0.43)	(0.19)	(0.72)	(0.28)	(0.30)	
16:1 *n*-9	1.22	1.26	1.24	1.28	1.25	1.23	–
	(0.09)	(0.31)	(0.29)	(0.42)	(0.53)	(0.17)	
17:0	<0.01	–	–	–	–	–	–
	–						
18:0	2.80	2.80	2.99	3.17	3.18	3.38	–
	(0.12)	(0.48)	(0.26)	(0.29)	(0.37)	(0.40)	
18:1	74.53	74.34	74.50	74.65	74.69	74.55	–
	(0.78)	(0.64)	(0.36)	(0.20)	(0.50)	(0.60)	
18:2	8.82	8.71	8.58	8.42	8.17	7.85	+
	(0.49)	(0.44)	(0.29)	(0.45)	(0.22)	(0.59)	
18:3	1.12	1.07	1.04	1.02	0.99	0.96	+
	(0.10)	(0.38)	(0.60)	(0.12)	(0.39)	(0.30)	
20:0	<0.01	–	–	–	–	–	–
	–						
20:1	<0.01	–	–	–	–	–	–
	–						
22:0	<0.01	–	–	–	–	–	–
	–						

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while – indicates no significant difference.

oils during frying are basically among the unsaturated fatty acids, whereas the saturated fatty acids (palmitic and stearic) were slightly increased (Tyagi and Vasishtha, 1996).

HPLC of Tocopherols

The relative decomposition rates after 25 fryings were $\delta > \gamma > \alpha$ (Tables 1, 3, 5, 8, 10 and 12). The results are in agreement with those of Sonntag (1979), who reported that the decomposition rates of tocopherols, after 10 h frying, were $\gamma > \alpha$. In contrast, Miyagawa *et al*. (1991), in their experiments, using a mixture of soybean and rapeseed oils to fry potatoes, found that, after 32 batches of frying, the decomposition rates of tocopherols were $\gamma > \delta > \alpha$. Carlson and Tabacch (1986) who came to the same conclusion, reported that the decomposition rates of tocopherols in fried soybean oil with French fries were $\gamma > \delta > \alpha$. Also, Lea (1960) showed that the order of antioxidant activity changed with the oil used for the experiment.

Specific Extinction ($E^{1\%}_{1cm}$) at 232 nm

The specific extinction at 232 nm which measures the degree of the primary oxidation products increased during frying time and was significant after the fifth frying in all the used oils (Tables 1, 3, 5, 8, 10 and 12).

TABLE 7

Sensory evaluation (taste panel scores) of fried potatoes

Number of fryings	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Colour																									
PKM 1 cold press	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.3	1.4	1.7	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.4	2.5	2.6	2.7
PKM 1 *n*-hexane	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.2	1.4	1.6	1.8	1.9	1.9	2.1	2.2	2.4	2.6	2.6	2.7	2.7	2.8	2.9	2.9	3.0
Virgin olive oil	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.6	1.7	1.9	1.9	2.0	2.1	2.3	2.5	2.5	2.6
Off-flavour																									
PKM 1 cold press	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.3	1.5	1.6	1.6	1.6	1.7	1.7	1.7
PKM 1 *n*-hexane	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.5	1.5	1.7	1.8	1.9	1.9
Virgin olive oil	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.3	1.5	1.5	1.6	1.7	1.9	2.0	2.0	2.1
Overall acceptance																									
PKM 1 cold press	8.9	8.8	8.6	8.4	8.3	8.2	8.1	8.0	8.0	7.9	7.9	7.9	7.8	7.8	7.8	7.8	7.8	7.7	7.7	7.7	7.5	7.4	7.2	7.1	7.1
PKM 1 *n*-hexane	8.8	8.7	8.2	8.1	8.0	8.0	8.0	7.9	7.9	7.9	7.8	7.8	7.7	7.7	7.7	7.7	7.5	7.4	7.3	7.3	7.3	7.2	7.1	7.1	7.0
Virgin olive oil	9.0	8.8	8.4	8.3	8.0	8.0	7.9	7.9	7.8	7.8	7.8	7.8	7.7	7.7	7.7	7.7	7.6	7.6	7.6	7.6	7.6	7.5	7.4	7.4	7.4

Note: Colour scale of 1–4 (1 represents desirable and 4 extremely undesirable colour), Off-flavour scale of 1–4 (1 represents "no rancid off-flavour" and 4 "strong rancid off-flavour") and overall acceptance scale of 1–9 (9 represents extremely good and 1 totally undesirable).

TABLE 8

Changes in the quality characteristics of PKM 1 *Moringa oleifera* oil extracted with cold pressure during cod frying at 175°C

Determination	Number of fryings						
	0	5	10	15	20	25	*P*
Free fatty acids	1.94	2.00	2.14	2.34	2.75	3.25	−
(% as oleic acid)	(0.21)	(0.55)	(0.48)	(0.72)	(0.50)	(0.66)	
Peroxide value	0.11	0.94	1.77	2.93	2.70	4.35	+
(meq O_2/kg of oil)	(0.10)	(0.55)	(0.71)	(0.89)	(0.46)	(0.92)	
Iodine value	65.73	65.60	65.39	65.14	64.85	64.18	−
(g of I_2/100 g of oil)	(0.49)	(0.37)	(0.48)	(0.33)	(0.43)	(0.73)	
Viscosity	80.00	80.14	80.33	80.70	81.13	81.82	−
(mPa s)	(0.92)	(1.02)	(0.79)	(0.95)	(0.47)	(0.97)	
Smoke point	203	202	200	198	196	193	−
(°C)	(2.5)	(2.0)	(2.5)	(1.5)	(2.0)	(1.5)	
Polar compounds (g/100 g oil)	4.37	4.70	5.23	6.19	7.33	9.03	+
	(0.76)	(0.46)	(1.07)	(0.63)	(0.81)	(0.54)	
$E^{1\%}_{1cm}$ at 232 nm	0.982	1.443	1.425	1.931	2.761	4.012	+
	(0.13)	(0.15)	(0.19)	(0.22)	(0.11)	(0.37)	
Induction period (h)	16.20	15.91	15.47	14.86	13.94	12.52	+
	(0.80)	(0.70)	(0.97)	(1.11)	(0.65)	(0.80)	
α-Tocopherol	5.06	4.77	4.33	3.72	2.80	1.46	+
(mg/kg oil)	(0.67)	(0.24)	(0.57)	(0.44)	(0.74)	(0.18)	
γ-Tocopherol	25.40	24.46	3.16	2.84	2.28	1.49	+
(mg/kg oil)	(1.16)	(0.94)	(0.58)	(0.76)	(0.44)	(0.85)	
δ-Tocopherol	3.55	3.44	3.16	2.84	2.28	1.49	+
(mg/kg oil)	(0.45)	(0.60)	(0.58)	(0.76)	(0.44)	(0.85)	
Colour	1.90/30.00	2.06/30.00	2.31/30.30	2.62/30.40	3.61/30.50	5.03/30.70	−/+
red/yellow	(0.10)/(2.40)	(0.22)/(1.90)	(0.16)/(2.10)	(0.18)/(1.50)	(0.33)/(1.20)	(0.25)/(2.15)	

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference

TABLE 9

Fatty acid composition of the PKM 1 *Moringa oleifera* oil extracted with cold pressure during cod frying at 175°C

Fatty acid	Number of fryings						
	0	5	10	15	20	25	*P*
8:0	0.04 (0.01)	0.06 (0.04)	0.07 (0.04)	0.10 (0.07)	0.11 (0.04)	0.12 (0.08)	−
14:0	0.13 (0.08)	0.14 (0.08)	0.16 (0.07)	0.17 (0.06)	0.19 (0.08)	0.21 (0.05)	−
16:0	6.34 (0.41)	6.35 (0.19)	6.37 (0.28)	6.39 (0.33)	6.40 (0.44)	6.41 (0.36)	−
16:1 n-9	0.10 (0.06)	0.10 (0.08)	0.09 (0.07)	0.07 (0.04)	0.05 (0.04)	0.03 (0.01)	−
16:1 n-7	1.28 (0.87)	1.27 (0.26)	1.25 (0.28)	1.22 (0.42)	1.19 (0.24)	1.16 (0.36)	−
17:0	0.08 (0.02)	0.09 (0.06)	0.10 (0.05)	0.08 (0.04)	0.11 (0.08)	0.13 (0.04)	−
18:0	5.70 (0.21)	5.72 (0.36)	5.73 (0.46)	5.77 (0.52)	5.94 (0.37)	6.15 (0.21)	−
18:1	71.60 (0.73)	71.55 (0.47)	71.53 (0.70)	71.50 (0.26)	71.46 (0.30)	71.40 (0.51)	−
18:2	0.77 (0.38)	0.74 (0.50)	0.70 (0.28)	0.64 (0.36)	0.59 (0.39)	0.51 (0.19)	+
18:3	0.20 (0.03)	0.19 (0.11)	0.15 (0.09)	0.13 (0.06)	0.09 (0.05)	0.02 (0.01)	+
20:0	3.52 (0.29)	3.54 (0.43)	3.56 (0.29)	3.58 (0.52)	3.60 (0.47)	3.63 (0.45)	−
20:1	2.24 (0.25)	2.23 (0.60)	2.21 (0.35)	2.19 (0.60)	2.16 (0.17)	2.13 (0.31)	−
22:0	6.21 (0.48)	6.23 (0.46)	6.25 (0.27)	6.28 (0.40)	6.30 (0.51)	6.35 (0.63)	−
22:1	0.12 (0.06)	0.10 (0.07)	0.09 (0.07)	0.08 (0.06)	0.06 (0.05)	0.04 (0.03)	−
26:0	1.21 (0.15)	1.20 (0.35)	1.17 (0.24)	1.13 (0.24)	1.10 (0.45)	1.06 (0.17)	−

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference.

Induction Period

The results showed that cold pressure oil had the longest induction period followed by *n*-hexane oil and virgin olive oil (Tables 1, 3, 5, 8, 10 and 12). The cold pressure and *n*-hexane oil showed a significant ($P<0.05$) decrease in induction period after 20 fryings, while the virgin olive oil showed significant decrease after 25 fryings. Induction period measurements were carried out on frying oils in order to provide a quick indication of the trends in resistance to oxidative rancidity of the heated oils. The induction period determined via accelerated oxidation methods on the original oil cannot guarantee or predict the actual frying performance of the oil as other factors will be introduced once frying starts (e.g., a badly operated fryer or heat exchanger will ruin even the best quality oil). Nevertheless, it is considered that the ''Rancimat'' induction period can be useful to act as a ''screening'' test and eliminate the possibility of introducing lower stability oils into the production area with all the attendant consequences (Morton and Chidley, 1988). The oils used for frying cod

TABLE 10

Changes of the quality characteristics of PKM 1 *Moringa oleifera* oil extracted with *n*-hexane during cod frying at 175°C

Determination	Number of fryings						
	0	5	10	15	20	25	*P*
Free fatty acids	1.12	1.21	1.40	1.67	2.21	2.89	−
(% as oleic acid)	(0.20)	(0.35)	(0.48)	(0.64)	(0.73)	(0.57)	
Peroxide value	1.83	3.20	2.70	3.56	4.70	6.04	+
(meq O_2/ kg of oil)	(0.19)	(1.13)	(0.74)	(0.95)	(1.05)	(0.88)	
Iodine value	65.58	65.41	65.18	64.78	64.34	63.53	−
(g of I_2/100 g of oil)	(0.48)	(0.76)	(0.84)	(0.51)	(0.68)	(0.49)	
Viscosity	45.00	45.18	45.44	45.93	45.36	47.39	−
(mPa s)	(0.13)	(0.44)	(0.77)	(0.48)	(0.69)	(0.56)	
Smoke point	200	198	196	194	192	188	+
(°C)	(2.0)	(2.5)	(3.0)	(2.0)	(1.5)	(1.0)	
Polar compounds	3.95	4.38	5.05	6.32	7.83	10.10	+
(g/100 g oil)	(1.03)	(0.76)	(0.36)	(0.55)	(0.59)	(0.58)	
$E^{1\%}_{1cm}$ at 232 nm	3.001	3.252	3.623	4.176	5.232	6.559	+
	(0.86)	(0.44)	(0.33)	(0.52)	(0.21)	(0.29)	
Induction period (h)	8.70	8.31	7.86	7.05	5.84	3.84	+
	(0.90)	(0.98)	(0.84)	(0.69)	(1.07)	(0.77)	
α-Tocopherol	15.38	14.87	13.96	12.46	10.14	6.29	+
(mg/kg oil)	(0.68)	(0.89)	(0.57)	(0.48)	(0.76)	(0.54)	
γ-Tocopherol	4.47	4.16	3.76	3.29	2.75	1.53	+
(mg/kg oil)	(0.87)	(0.56)	(0.94)	(0.66)	(0.70)	(0.49)	
δ-Tocopherol	15.51	15.25	14.76	13.48	10.06	7.45	+
(mg/kg oil)	(0.99)	(0.65)	(0.74)	(0.89)	(0.58)	(0.60)	
Colour	0.80/35.00	1.01/35.14	1.33/35.25	1.69/35.41	2.96/35.62	4.72/35.89	−/+
red/yellow	(0.20)/(3.14)	(0.37)/(2.80)	(0.56)/(1.72)	(0.40)/(12.6)	(0.50)/(3.17)	(0.45)/(2.36)	

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference

TABLE 11

Fatty acid composition of PKM 1 *Moringa oleifera* oil extracted with *n*-hexane during cod frying at 175°C

Fatty acid	Number of fryings						
	0	5	10	15	20	25	*P*
8:0	0.03	0.06	0.09	0.13	0.18	0.25	–
	(0.01)	(0.09)	(0.06)	(0.09)	(0.11)	(0.12)	
14:0	0.13	0.17	0.23	0.34	0.38	0.42	–
	(0.08)	(0.12)	(0.14)	(0.16)	(0.19)	(0.14)	
16:0	6.46	6.49	6.52	6.55	6.58	6.62	–
	(0.32)	(0.11)	(0.26)	(0.40)	(0.24)	(0.27)	
16:1 *n*-9	0.09	0.07	0.05	0.05	0.04	0.02	–
	(0.04)	(0.05)	(0.04)	(0.03)	(0.03)	(0.01)	
16:1 *n*-7	1.36	1.34	1.32	1.29	1.26	1.22	–
	(0.84)	(0.22)	(0.34)	(0.11)	(0.25)	(0.28)	
17:0	0.08	0.09	0.11	0.15	0.16	0.17	–
	(0.02)	(0.07)	(0.06)	(0.08)	(0.11)	(0.31)	
18:0	5.88	5.92	5.94	5.98	6.21	6.59	–
	(0.23)	(0.30)	(0.27)	(0.21)	(0.18)	(0.22)	
18:1	71.21	71.15	71.11	71.06	71.01	70.91	–
	(0.69)	(0.53)	(0.41)	(0.33)	(0.42)	(0.37)	
18:2	0.65	0.61	0.56	0.49	0.41	0.30	+
	(0.32)	(0.18)	(0.21)	(0.28)	(0.26)	(0.16)	
18:3	0.18	0.17	0.14	0.12	0.08	0.02	+
	(0.05)	(0.08)	(0.10)	(0.08)	(0.05)	(0.01)	
20:0	3.62	3.65	3.68	3.69	3.72	3.75	–
	(0.33)	(0.28)	(0.13)	(0.14)	(0.16)	(0.15)	
20:1	2.22	2.21	2.17	2.15	2.12	2.09	–
	(0.26)	(0.25)	(0.31)	(0.38)	(0.18)	(0.19)	
22:0	6.41	6.42	6.46	6.49	6.54	6.59	–
	(0.46)	(0.29)	(0.42)	(0.23)	(0.18)	(0.35)	
22:1	0.12	0.11	0.10	0.08	0.06	0.02	–
	(0.07)	(0.08)	(0.06)	(0.06)	(0.04)	(0.01)	
26:0	1.18	1.15	1.13	1.09	1.05	0.97	–
	(0.20)	(0.36)	(0.30)	(0.17)	(0.19)	(0.34)	

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while – indicates no significant difference.

seemed to follow the same trend although cod was found to cause a higher decrease in induction period.

Sensory Evaluation

Eight panellists were chosen to taste potatoes and cod for the overall characterization of the organoleptic properties (appearance, colour, flavour and texture) after each batch had been fried. A taste panel score sheet with a numerical scale of rating was developed, using descriptive terms against each numerical score for each quality parameter. Throughout the frying time, the overall acceptance scores showed a significant difference in overall acceptance of fried potatoes with cold pressure oil after 5 days of frying, while this difference was significant after 4 days of frying with *n*-hexane oil (Tables 7 and 14). The overall acceptance scores showed that fried cod was unacceptable after being fried in oil for 5 days in cold pressure oil and after 3 days in *n*-hexane oil. Olive oil showed no significant difference in overall acceptance scores after 5 days of frying potatoes and cod. The panel scores confirmed that olive oil and cold pressure oil are more suitable oils for repeated frying of potatoes and cod.

TABLE 12

Changes in the quality characteristics of virgin olive oil during cod frying at 175°C

Determination	Number of fryings						
	0	5	10	15	20	25	*P*
Free fatty acids	0.98	0.99	1.01	1.03	1.08	1.15	−
(% as oleic acid)	(0.11)	(0.46)	(0.65)	(0.40)	(0.72)	(0.52)	
Peroxide value	0.76	0.94	1.69	2.55	3.66	5.30	+
(meq O_2/kg of oil)	(0.85)	(0.86)	(1.02)	(1.16)	(1.23)	(1.25)	
Iodine value	80.01	79.92	79.78	79.61	79.35	78.98	−
(g of I_2/100 g of oil)	(0.71)	(0.81)	(1.15)	(0.81)	(0.76)	(1.44)	
Viscosity	74.01	74.16	74.30	75.26	76.43	78.35	+
(mPa s)	(0.17)	(0.14)	(0.19)	(0.11)	(0.36)	(0.15)	
Smoke point	190	189	187	186	184	183	−
(°C)	(1.9)	(1.5)	(2.0)	(1.0)	(1.7)	(2.0)	
Polar compounds	3.18	3.38	3.65	4.11	5.14	6.77	+
(g/100 g oil)	(0.46)	(0.30)	(0.19)	(0.28)	(0.55)	(0.81)	
$E^{1\%}_{1cm}$ at 232 nm	2.011	2.134	2.349	2.733	3.362	4.312	+
	(0.391)	(0.019)	(0.033)	(0.045)	(0.058)	(0.014)	
Induction period (h)	7.88	7.70	7.28	6.92	6.49	5.61	+
	(0.53)	(0.36)	(0.76)	(0.44)	(0.94)	(0.68)	
α-Tocopherol	130.10	120.29	109.36	91.88	73.49	49.65	+
(mg/kg oil)	(2.32)	(1.46)	(1.49)	(0.47)	(1.08)	(1.53)	
γ-Tocopherol	9.90	9.60	9.22	8.51	7.42	5.12	+
(mg/kg oil)	(1.65)	(0.56)	(1.28)	(0.60)	(1.62)	(0.36)	
δ-Tocopherol	1.60	1.53	1.44	1.29	1.07	0.84	+
(mg/kg oil)	(0.86)	(0.80)	(0.62)	(0.75)	(0.52)	(0.17)	
Colour	2.50/36.00	2.50/36.20	2.70/36.40	2.80/36.60	2.90/37.10	3.30/38.50	−/−
red/yellow	(0.32)/(0.23)	(0.20)/(0.15)	(0.30)/(0.42)	(0.25)/(0.50)	(0.55)/(0.15)	(0.19)/(0.64)	

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while − indicates no significant difference.

TABLE 13

Fatty acid composition of virgin olive oil during cod frying at 175°C

Fatty acid	Number of fryings						
	0	5	10	15	20	25	*P*
14:0	<0.01	–	–	–	–	–	–
16:0	11.20 (0.66)	11.21 (0.34)	11.33 (0.29)	11.48 (0.38)	11.69 (0.43)	11.88 (0.28)	–
16:1 *n*-9	1.22 (0.09)	1.24 (0.18)	1.16 (0.40)	1.12 (0.14)	1.15 (0.38)	1.19 (0.20)	–
17:0	<0.01	–	–	–	–	–	–
18:0	2.80 (0.12)	2.80 (0.43)	2.87 (0.17)	2.95 (0.50)	3.08 (0.18)	3.23 (0.42)	–
18:1	74.53 (0.78)	74.40 (0.68)	74.60 (0.37)	74.65 (0.40)	74.88 (0.33)	74.55 (0.61)	–
18:2	8.82 (0.49)	8.74 (0.28)	8.61 (0.16)	8.39 (0.80)	8.10 (0.23)	7.76 (0.24)	+
18:3	1.12 (0.10)	1.11 (0.41)	1.05 (0.22)	0.98 (0.11)	0.96 (0.19)	0.90 (0.31)	+
20:0	<0.01	–	–	–	–	–	–
20:1	<0.01	–	–	–	–	–	–
22:0	<0.01	–	–	–	–	–	–

Note: Values are means of triplicate determinations and standard deviation is given in parenthesis. *P*: + indicates significant difference at $P<0.05$, while – indicates no significant difference.

The content of α-, γ- and δ-tocopherol and the lower degree of saturation of the *Moringa oleifera* PKM 1 seed oils could be partly attributed to its resistance to oxidation. The long induction period of Moringa oil might be explained by the presence of Δ^5-avenasterol (Tsaknis *et al*., 1999b). Hudson and Ghavami (1984) reported that although most sterols are ineffective as antioxidants, Δ^5-avenasterol, fucosterol and citrostadienol have been shown to exhibit antioxidant properties in oils heated at 170°C. It has been suggested that the donation of a hydrogen atom from the allylic methyl group in the side chain, followed by isomeration to a relatively stable tertiary allylic free radical represents the mode of action of the sterol antioxidants. Δ^5-avenasterol appears to be increased in concentration in a layer at the surface, and it is ineffective at room temperature. These findings suggest that avenasterol acts as a chemical antioxidant, its effectiveness arising from its concentration at the surface where oxidation occurs.

Fried cod induced higher changes to frying oils, compared with the same oils used for potato frying (with the exception of colour). Trace to measurable amounts of *n*-3 fatty acids appear in the oils when oily fish is fried and which are rapidly oxidized, although no polyunsaturated fatty acids were detected during FAME determination, possibly due to the relatively low amount of *n*-3 fatty acids in cod.

Virgin olive oil was more unsaturated (containing linoleic and linolenic acids, which more easily underwent oxidation and degradation than $C_{18:1}$, in a higher quantity than PKM 1 oils) and showed great stability during frying. The products (potatoes and cod) fried in it were highly acceptable by the panellists. Again, virgin olive oil has proven to be one of the most suitable oils for frying as indicated by others researchers (Romero *et al*., 1999; Aggelousis and Lalas, 1997).

TABLE 14

Sensory evaluation (taste panel scores) of fried cod

Number of fryings	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Off-flavour																									
PKM 1 cold press	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.3	1.4	1.5	1.6	1.6	1.6	1.7	1.7	1.7
PKM 1 *n*-hexane	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.5	1.6	1.7	1.8	1.9
Virgin olive oil	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.0	1.0	1.0	1.0	1.6	1.6	1.8	1.9	2.0	2.1
Overall acceptance																									
PKM 1 cold press	8.8	8.5	8.2	8.1	7.9	7.8	7.8	7.7	7.6	7.6	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.0	6.9	6.9	6.8	6.8	6.7	6.7
PKM 1 *n*-hexane	8.7	8.5	8.3	8.1	8.0	8.0	7.8	7.5	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.7	6.6	6.6	6.5	6.5
Virgin olive oil	8.9	8.8	8.5	8.2	8.2	8.1	8.1	8.0	7.9	7.8	7.7	7.7	7.6	7.6	7.6	7.5	7.5	7.4	7.4	7.4	7.2	7.0	6.9	6.8	6.8

Note: Off-flavour scale of 1–4 (1 represents ''no rancid off-flavour'' and 4 ''strong rancid off-flavour'') and overall acceptance scale of 1–9 (9 represents extremely good and 1 totally undesirable).

TABLE 15

Linear adjustments of polar compounds changes

Equation	Oil	r	A	b	P	Oil versus oil
Potatoes						
Linear adjustment $Y = a + bX$	Cold pressure (CP)	0.9523	3.9252 ± 0.235	0.1557 ± 0.007	*	CP versus H + + +
	n-Hexane (H)	0.9328	3.3710 ± 0.253	0.1985 ± 0.009	*	CP versus VOO + + +
	Virgin olive oil (VOO)	0.9633	2.7533 ± 0.308	0.1136 ± 0.004	*	H versus VOO + + +
Cod						
Linear adjustment $Y = a + bX$	Cold pressure (CP)	0.9218	3.8452 ± 0.367	0.1837 ± 0.003	*	CP versus H + + +
	n-Hexane (H)	0.9455	3.2452 ± 0.188	0.2421 ± 0.005	*	CP versus VOO + + +
	Virgin olive oil (VOO)	0.9033	2.6795 ± 0.394	0.1354 ± 0.004	*	H versus VOO + + +

Note: r: regression coefficient, a: intercept ± S.E., b: slope ± S.E., Y: polar content, X: number of frying times, P: significant adjustment to a linear equation (asterisk (*) indicates $P<0.001$, ANOVA test). Significant differences between oils' adjustment equations: + $P<0.05$, $P<0.001$ (ANCOVA test).

CONCLUSION

The oil from the seeds of *Moringa oleifera* variety PKM 1 showed that it could be utilized successfully as frying oil, although not as well as virgin olive oil. It also contains high monounsaturated to saturated fatty acids ratio, and might be an acceptable substitute for highly monounsaturated oils such as olive oil. *Moringa oleifera* is a tree growing rapidly even in poor soil and is little affected by drought (Sengupta and Gupta, 1970; Morton, 1991) and can be easily grown in poor third world countries. The production of useful oil from its seeds could be of economic benefit to the native population of the areas where the tree is cultivated.

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REFERENCES

Aggelousis, G. and Lalas, S. (1997). Quality changes of selected vegetable oils during frying of doughnuts. *Riv. Ital. Sost. Gras.* **LXXIV,** 559–565.

Al-Harbi, M. M. and Al-Kabtani, H. A. (1993). Chemical and biological evaluation of discarded frying palm oil in commercial restaurants. *Food Chem.* **48,** 395–401.

Allen, R. R. and Marvin, F. W. (1982). Analytical methods. In *Bailey's Industrial Oil and Fat Products*, Vol. 2 (D. Swern and N.O.V. Sonntag, Eds.). John Wiley and Sons, New York/London.

AOAC (1990). In *Official Methods of Analysis of the Association of the Official Analytical Chemists* (D. Firestone, Ed.). Association of the Official Analytical Chemists Inc., VA, U.S.A.

Augustin, M. A. and Berry, S. K. (1983). Efficacy of the antioxidants BHA and BHT in palm olein during heating and frying. *J. Am. Oil Chem. Soc.* **60,** 1520–1522.

British Standards Methods of Analysis (1976). *Fats and Oils* (*Part 1*), *Physical Methods*, Section 1.8, British Standards Institution, London.

Burton, W. G. (1989). The cooking and processing of potatoes as food. In *The Potato*, 3rd edn., pp. 336–364. John Wiley and Sons, New York.

Carlson, B. L. and Tabacch, M. H. (1986). Frying oil deterioration and vitamin loss during foodservices operation. *J. Food Sci.* **51,** 218–221.

Carpenter, A. P. Jr. (1979). Determination of tocopherols in vegetable oil. *J. Am. Oils Chem. Soc.* **56,** 668–671.

Chang, S. S., Peterson, R. J., and Ho, C. T. (1978). Chemistry of deep fat frying. In *Lipids as a Source of Flavour* (M. K. Supran, Ed.). American Chemical Society, U.S.A.

Fritch, C. W. (1981). Measurements of frying fat deterioration: a brief review. *J. Am. Oil Chem. Soc.* **58,** 746–750.

Gere, A. (1982). Studies of the changes in edible fats during heating and frying. *Die Nahrung*. **26,** 923–932.

Gutierrez, R., Gonzalez, O., and Dobarganes, M. C. (1988). Analytical procedures for the evaluation of used frying fats. In: *Frying of Food: Principles, Changes, New Approaches* (G. Varela, A. E. Bender and I. D. Morton, Eds.), pp. 141–154. Ellis Horwood Series in Food Science and Technology, Chichester, U.K.

Hudson, B. J. F. and Ghavami, M. (1984). Phospholipids as antioxidant synergists for tocopherols in the autoxidation of edible oils. *Lebensmitten Wiss. Tech.* **17,** 19–24.

International Union of Pure and Applied Chemistry (IUPAC) (1987). In *Standard Method for the Analysis of Oils, Fats and Derivatives*, 7th edn. (C. Paquot and A. Hautfenne, Eds.). Blackwell Scientific Publications, London.

Kiritsakis, A. (1988). Tocopherols. *The Olive Oil*. Agricultural Cooperative Editions, Thessaloniki, Greece.

Kiritsakis, A. K. and Min, D. B. (1989). Flavour chemistry of olive oil. In *Flavour Chemistry of Lipid Foods*
(D. B. Min, Ed.). The American Oil Chemists' Society/Champlain, IL.

Lea, C. H. (1952). Methods for determination of peroxide in lipids. *J. Sci. Food Agric.* **3,** 566–594.

Lea, C. H. (1960). On the antioxidant activities of the tocopherols. II-Influence of substrate, temperature and level of oxidation. *J. Sci. Food Agric.* **11,** 212–215.

Miyagawa, K., Hirai, K., and Takezoe, R. (1991). Tocopherol and fluorescence levels in deep-frying oil and their measurement for oil assessment. *J. Am. Oil Chem. Soc.* **68,** 163–166.

Morton, J. F. (1991). The horse radish tree, *Moringa Pterigosperma* (Moringaceae)—a boon to arid lands? *Econ. Botany*. **45,** 318–333.

Morton, I. D. and Chidley, J. F. (1988). Methods and equipment in frying. In *Frying of Food: Principles, Changes, New Approaches* (G. Varela, A. E. Bender, and I. D. Morton, Eds.). Ellis Horwood Series in Food Science and Technology, Chichester, U.K.

Pearsons, D. (1981). In *Chemical Analysis of Foods*, 8th edn. (H. Egan, R. S. Kird, and R. Sawyer, Eds.), pp. 520–547. Churchill Livingstone, Edinburgh, U.K.

Perkins, E. G. (1967). Non-volatile decomposition products in heated fats and oils. *Food Tech.* **21,** 611–616.

Romero, A., Cuesta C. and Sanchez-Muniz, F. J. (1999). Does frequent replenishment with fresh monoenoic oil permit the frying of potatoes indefinitely? *J. Agric. Food Chem.* **47,** 1168–1173.

Sengupta, A. and Gupta, M. P. (1970). Studies on seed fat composition of Moringaceae family. *Fette Seifen. Anstrich.* **72,** 6–10.

Sonntag, N. O. V. (1979). Composition and characteristics of individual fats and oils. In *Bailey's Industrial Oil and Fat Products*, Vol. 11, 4th edn. (D. Swern, Ed.), pp. 389–398. John Wiley and Sons, New York.

Tsaknis, J., Spiliotis, V., Lalas, S., Gergis, V., and Dourtoglou, V. (1999a). Characterization of *Moringa oleifera* variety Mbololo seed oil of Kenya. *J. Agric. Food Chem.* **47,** 4495–4499.

Tsaknis, J., Spiliotis, V., Lalas, S., Gergis, V., and Dourtoglou, V. (1999b). Quality changes of *Moringa oleifera*, variety Mbololo of Kenya seed oil during frying. *Grasas Y Aceites*. **76** (1), 19–22.

Tyagi, V. K. and Vasishtha, A. K. (1996). Changes in characteristics and composition of oils during deep fat frying. *J. Am. Oil Chem. Soc.* **73,** 499–506.