Food Sci. Technol. Res., **7** (4), 265–279, 2001

Review

Frying of Nutritious Foods: Obstacles and Feasibility

Dina DANA and I. Sam SAGUY*

Institute of Biochemistry, Food Science and Nutrition, Faculty of Agricultural, Food and Environmental Quality Sciences, The Hebrew University of Jerusalem, PO Box 12 Rehovot 76100, Israel

Received October 18, 2001; Accepted October 22, 2001

Frying is an important cooking process due to the unique palatability and sensory characteristics of fried foods. Fried foods contain a considerable amount of fat, and have a negative perceived image due to their high caloric value and increased consumer awareness of the relationship between food, nutrition, and health. Oil consumption and especially saturated fat, is considered as one of the principal factors increasing health risks of heart disease, cancer, diabetes, and hypertension. The mechanism of oil uptake during frying is complex and affected by numerous factors, such as product and oil composition, surface-active agents, etc. Frying oil undergoes three main deleterious reactions: oxidation, hydrolysis and thermal decomposition, resulting in the formation of numerous constituents. The latter affect the organoleptic characteristics of the fried product, and could pose health risks. Frying has a significant role in the overall nutritional value of the product. Compared to other cooking methods, retention of water-soluble vitamins and vitamin E could be higher after frying. Due to the deterioration of oil after prolonged frying, regulations on the maximum levels of polar compounds and polymer concentration have been utilized. Nevertheless, an alarming number of oil samples collected from restaurants and fast food outlets in Europe failed to comply with regulations. Frying has only a marginal affect on the concentration of trans fatty acids. Yet, due to their possible connection with heart disease, the initial concentration of hydrogenated fats (that could reach 50%) should be considered. The relationships between frying and carcinogenesis and mutagenesis are inconclusive. Cyclic fatty acid monomers, which can be formed during frying, were proven harmful only in some studies. Exposure to malondialdehyde (MDA) during typical consumption of fried food constituted no actual health hazard, although MDA is known to be a very potent mutagen and carcinogen. Heterocyclic amines, formed during fish and meat frying, were related to higher cancer incidence, but only in concentrations which were higher by several orders of magnitude than those formed in typical frying. It is concluded that based on information to date, and using good manufacturing practices, fried foods pose no significant health hazard in a balanced diet.

Keywords: oil uptake, quality, regulation, carcinogenesis, mutagenesis, health

Frying is a common and extensively used process in the food industry because of the large-scale sales and vast variety of fried products. From the consumer's standpoint, the high palatability of fried foods is related to unique organoleptic and sensory characteristics, including flavor, texture, and appearance. Deep-fried food sales were estimated as $75 billion in the USA alone, and double this figure for the rest of the world (Blumenthal, 1996). This figure has probably doubled, considering the recent phenomenal growth in fast foods. In 1995, consumption of fats and oils per capita was 30.5 kg in the USA, while over a third (11.2 kg) originated from baking and frying fats (Moreira *et al.*, 1999). In Israel, during the Hanukkah holiday, it is estimated that over 32 million doughnuts are consumed, leading to an increased oil consumption of about one million liters. Over the past years, increased awareness of the western consumer to the relationship between food, nutrition and health is evident, emphasizing the need to limit consumption of oil, calories originating from fat and cholesterol, among others. Oil consumption, especially saturated fat, is recognized as one of the major factors playing a significant adverse role in health hazards (e.g., heart disease, cancer, diabetes, hypertension).

A recent article (Weisburger, 2000) highlights a direct correlation between nutrition and death caused by cancer. Fried food was noted as one of the sources related to a higher incidence of nutritionally linked cancers, especially of the breast, distal colon, prostate, pancreas, ovaries, and endometrium. It also reported that, in 1999, high fat and fried food consumption and low intake of fibers and vegetables comprised about 35% of all main causes of deaths in the USA. This clear and strong message, if accurate, could be extremely alarming as it indicates that consumption of fried foods is hazardous to the health and well-being of those who consume these products.

The aim of this paper is to examine this categorical statement by reviewing the association between health, nutrition, and fried foods. Our approach focused on reviewing pertinent aspects of the frying process (emphasizing technological aspects and the mechanisms of oil uptake) and highlighting changes in oil quality. The effect of deep fat frying on nutritive value, the relationship between fried foods and health, and the use of special oils are highlighted as well as the use of olive oil. The review is limited to topics we have chosen while many other aspects of frying are omitted.

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*To whom correspondence should be addressed.
E-mail: ssaguy@agri.huji.ac.il

Oil uptake

Frying is the immersion and cooking of food in hot oil. The purposes of frying are fast cooking and the formation of a unique crust, color, flavor, and texture. Frying also prevents migration of flavor and nutritive components from the product. It is difficult to indicate when frying with oil began, however, there is evidence that food was first fried around the sixth century BC (Morton, 1998). Since then, it has been frequently utilized by consumers and the food industry. The frying process is complex and involves many factors, some of which are dependent on the process itself and others on the food and type of fat used. Basically, the frying process is a dehydration process with three distinctive characteristics (Saguy & Pinthus, 1995; Saguy *et al*., 1998):

- The high temperature of the oil (around 180°C) allows rapid heat transfer and short cooking time (from a few seconds to several minutes).
- The temperature within the product does not exceed 100°C.
- The process does not involve water (other than its evaporation from the fried food), hence, the leaching of water-soluble compounds is minimal. Some of the evaporated water is replaced by the frying oil, which is absorbed into the product. Water evaporation could play a significant role in oil deterioration.

The majority of fried foods initially contain low levels of fat. The mechanism of oil uptake has been studied primarily to understand the phenomenon and to develop the know-how and means to reduce the final oil content. However, in spite of all these efforts, fried food products still contain significant amounts of fat, exceeding 30% in some cases (Table 1).

Oil uptake is affected by many factors, including the quality of the oil, product composition and shape, and the frying process. Oil absorption depends more on the quality than on the type of frying oil/fat (Dobarganes *et al*., 2000). Oil composition has a pronounced effect on fat uptake, and a high content of surface-active agents, produced by oxidation, significantly increases absorption (Blumenthal, 1991, 1996; Stier, 2000). The influence of surface-active compounds is also related to the interfacial tension between the oil and the food, which decreases with repeated frying and results in higher oil absorption (Pinthus & Saguy 1994). Most studies claim that oil uptake increases with higher initial moisture content, however, some found no such relationship. Crust development affects not only crispness, but also has a marked influence on oil uptake, which is restricted mainly to the surface (Lamberg *et al*., 1990; Saguy *et al*., 1997; Aguilera & Gloria, 2000). Crust temperature closely follows that of the oil, however, the internal temperature of the fried product does not exceed 100°C. Oil absorption increases with higher surface area and roughness (Rubnov & Saguy, 1997). Many fried foods are coated with batter and/or breading. Coatings contribute significantly to the added product value, its holding capabilities, and its crispness. They can also reduce fat intake and maintain higher moisture content (Khalil, 1999; Rayner *et al*., 2000; Shih *et al*., 2001). These unique attributes make coating very popular among fast food outlets where take-away is a significant part of the business. Blanching can also affect oil absorption. For example, blanching of potatoes and a short dehydration period, prior to deep fat frying, can reduce oil uptake (Selman & Hopkins, 1989). Possible explanations are related to the reduced overall and, in particular, surface moisture content, surface smoothing, and structural changes. A higher frying temperature usually reduces oil absorption by allowing the frying time to be shortened. This reduction can also be attributed to the enhanced crust formation, which simultaneously acts as a physical barrier to oil absorption and increases resistance to water evaporation (Pinthus *et al*., 1995b). However, according to some studies, the effect of temperature on oil uptake is not significant (Gamble *et al*., 1987; Pravisani & Calvelo, 1986). Oil temperature and thickness of potato strips were found to have a significant effect on oil uptake and moisture loss of French fries. The frying temperatures tested were 150, 170, and 190°C. An increased frying temperature decreased moisture content for the same frying time. The moisture content was higher for thicker potato strips. Higher frying temperatures increased the oil content of potato strips. Oil uptake was higher for thinner potato strips (Krokida *et al*., 2000). Low frying temperatures may result in excess oil absorption (Dobarganes *et al*., 2000).

Table 1. Typical mean oil content of selected fried foods (Saguy *et al*., 1998).

Food item	Mean oil content (g/100 g edible portion)
Potato chips	34.6
Corn chips	33.4
Tortilla chips	26.2
Doughnuts (plain)	22.9
Onion rings	18.7
Chicken breast-breaded	18.1
Fish fillet–battered or breaded	12.9
French fries/parfried	14.8/7.6

Oil uptake of commercial frozen parfried potatoes was assessed after frying in colza oil and a short post-frying immersion in hot coconut fat. Immediate transfer of potato samples to the coconut fat bath resulted in replacement of most of the colza oil by coconut fat after 10 s, meaning that the absorbed colza oil was located mainly in the crust structure. Cooling samples for up to 60 s before transferring them into hot coconut fat showed partial replacement of the colza oil. Seventy to 80% of the total oil uptake was oil wetting the sample surface at the end of the frying. Oil migration into the cellular spaces within the crust was enabled only after the formation of a crust (frying time > 1 min; Aguilera & Gloria, 2000). The latter is additional confirmation of the phenomenon reported previously (Ufheil & Escher, 1996).

Frying involves heat and mass transfer and interaction between the food and the frying media. Oil uptake can be described by two mechanisms: (i) continuous fat absorption as a part of an exchange between the oil and the evaporated water; and (ii) an absorption process, taking place mainly after frying is completed.

- **Moisture replacement**—changes in the cellular structure (e.g., Pedreschi *et al*., 2001) of the food product and the formation of pores due to water evaporation allow oil to penetrate into the created voids. For instance, in potato products, starch granules disappear within the product after 10 s of frying, gelatinize in about 60 s and disappear thereafter. Starch, protein and lipids interact to form a continuous phase that becomes firm upon further frying. The oil adheres to the surface as water turns into steam and leaves the potato, leaving behind a uniform sponge-like network. The oil is drawn into these tunnels and the majority is absorbed during the first 20 s of frying (McDonough *et al*., 1993; Moreira *et al*., 1977).

This mechanism provides partial explanation since it has been proven that oil uptake occurs mainly during the cooling phase (Ufheil & Escher, 1996).

- **Oil absorption during the cooling phase**—during frying, water evaporates and its concentration at the surface decreases rapidly, allowing the creation of the crust. The moisture inside the food is converted to steam, causing a pressure gradient. The steam escapes through capillaries and channels in the cellular structure. The oil that adhered to the food surface or penetrated some of the voids left by the water is literally pushed out. The movement of steam out prevents the oil from filling the voids. Once the product cools, the decrease in the internal pressure caused by cooling and vapor condensation creates a 'vacuum effect', resulting in a driving force which sucks the oil into the product (Ufheil & Escher, 1996). It was hypothesized that oil that entered the food capillaries could also play a role in preventing some structure shrinkage and collapse. Therefore oil uptake could play a role in enhancing moisture loss (Saguy & Pinthus, 1995).

As long as steam is generated during food frying, oil uptake movement can be described as an advance and retreat process, depending mainly on the steam pressure and the nature of the capillaries. However, during cooling, oil penetration is no longer affected by this mechanism. Therefore, some industrial processes reduce oil uptake by hot air impinging, which maintains the product temperature and prevents cooling, thus partially preventing vacuum creation. The hot air stream also physically removes the oil from the product's surface. The high temperature maintains low oil viscosity, enhancing oil dripping back into the fryer. In household frying, simply wiping with an absorbent paper can reduce oil uptake up to 35%. In products with a high volume to surface area ratio, oil concentrates in the crust area. It tends to concentrate in corners, edges, and broken 'slots' of the fried product. Porosity affects oil absorption and the oil penetration depth is limited to approximately 1 mm (Pinthus *et al*., 1995a, Saguy *et al*., 1997).

In spite of the wide knowledge base, oil uptake is a dynamic and complex process. The mechanisms described above comprise only a partial explanation, highlighting the need for further studies.

Oil quality

During frying, a variety of reactions cause a spectrum of physical and chemical changes. In the presence of oxygen from either the air or the product, food moisture, and high temperature, oil undergoes mainly three deleterious reactions: hydrolysis caused by water, oxidation and thermal alterations caused by oxygen, and heat, respectively (Nawar, 2000). Triglycerides comprise 96–99% of fresh oil. In the course of frying, the oil is exposed to high temperatures, typically ranging from 160 to 180°C (frying at lower temperatures, e.g., of oriental noodles, is possible but of lesser applicability), which causes chemical reactions in the oil that change its composition and characteristics. These reactions are extremely complex and cause the formation of numerous decomposition and polymerization products, of which over 400 have been identified (Paul & Mittal, 1997). Decomposition products are also formed as a result of reactions between food ingredients (proteins, carbohydrates, oil, and fat). In this case, using GC/MS, over 140 different compounds were identified. Worth noting are: 1-pentanol, hexanal, furfuryl alcohol, octanal, 2-pentylfuran, (*E*)-2-noneal and hexadecanoic acid, playing a significant role in taste, flavor and shelf-life (Takeoka *et al*., 1996).

The influence of the frying process on oil quality can be described as the effect of two simultaneous reactions affected discretely or jointly by both the food and the oil. During frying, leaching fat or oil from the food can have a significant effect on the decomposition reactions (e.g., frying of fish). Oil absorption and leaching from the food leads to migration of various food components, including water, fat, amino acids, and surface-active agents, which increase the oil's polarity and foaming tendency, and lead to color, viscosity, and numerous other changes. Other reactions are related to the chemical alterations in the oil, which depend mostly on fatty acid composition. Oil deterioration can be classified into three major groups: hydrolysis, oxidation and thermal polymerization.

- **Hydrolysis**—de-esterification reaction leads to cleavage of bonds between glycerol and fatty acids. This occurs mainly due to water evaporating from the food during frying. The high temperature promotes hydrolysis and the resulting formation of diglycerides, monoglycerides, free fatty acids, and glycerol (O'Brien, 1998). Free fatty acids are more volatile and decrease the oil's smoke point. Mono and diglycerides are polar and increase the oil's tendency to foam. The use of oil containing long-chain fatty acids may diminish this problem. For instance, coconut oil contains high concentrations of lauric acid, a short chain fatty acid, and its smoking point is relatively low. During the frying of peanuts, due to their low moisture content, the oil is very stable. Determination of free fatty acid (FFA or acid value) concentration is often used as a criterion for oil quality during frying and some countries are implementing it as an upper measure for oil acceptability for frying. For instance, in Japan an acid value of 2.5 mg/g is the upper limit in the frying oil (Japanese Ministry of Health and Welfare, 1979, Fujisaki *et al*., 2001). The upper limit seems to be quite a low level compared to 5 to 25 mg/g normally applied in frying operations, depending on the product fried. It is interesting to note that when no food is fried and the fryer is maintained idle at 180°C, hydrolysis of triglycerides does not occur without oxidation. External spraying of the frying oil with water remarkably increased the acid value (Fujisaki *et al*., 2001).
- **Oxidation**—is usually the limiting factor for oil quality and fried products. The majority of reactions affecting flavor, aroma, color, nutrition, and health related properties of the oil are affected by oxidation. It can be described as comprising three sub-processes, which produce a variety of decomposition compounds known as: primary, secondary and tertiary oxidation.
- **Primary oxidation**—caused by the reaction of oxygen with oil at high temperatures, leading to the formation of hydroperoxides bound to a double bond of an unsaturated fatty acid. High temperature accelerates oxidation. Peroxide value is a simple common test to determine the quality of fresh oil, but quite meaningless for frying processes, since peroxides are volatile at high temperatures. Peroxide value indicates oxidative reactions occurring after frying and characterizes the sampling rather than the oil quality during the process.
- **Secondary oxidation**—fission of hydroperoxides at high

temperatures leads to the formation of secondary decomposition products, alcohols, carbonyls, and acids. Unsaturated aldehydes can undergo autoxidation giving rise to dialdehydes such as malondialdehyde (MDA). Formation of MDA was the basis for the thiobarbituric acid (TBA) method used for measuring fat oxidation. A common method for measuring aldehyde concentration is the *p*-Anisidine value, which enables colorimetric determination of aldehyde concentration. It also provides a criterion that could be correlated with the organoleptic quality of the fried product and thus is used as a routine test. Decomposition of fatty acids from triglycerides results in the formation of small and large molecules. Small molecules are generally volatile, VDP (volatile decomposition products), and large are generally non-volatile molecules, NVDP (nonvolatile decomposition products). VDP composition is responsible for the unique and characteristic taste of fried products.

- **Tertiary oxidation**—polymerization of secondary oxidation products. This process increases oil viscosity, the color turns darker and brown layers appear on the surface. Polymerization is abundant mainly in oils rich in free unsaturated fatty acids, such as soybean oil.

Oil oxidation is inevitable. Since it involves oxidation of double bonds, the degree of unsaturation, concentration of polyunsaturated fatty acids, oxygen concentration, and level of free radicals affect the oxidation rate. Hence, the use of oil high in saturated fatty acids and/or monounsaturated oil lowers oxidation. On the other hand, hydrogenation and saturation of the oil may create health concerns due to high concentrations of trans fatty acids (described herewith). Atmospheric conditions in the fryer are of utmost importance, and the rate of oxidative deterioration in oil held in an idle fryer (no food) at 180°C was nearly proportional to the atmospheric oxygen concentration (Fujisaki *et al.*, 2000). It should be noted, however, that these data were measured under conditions where no food was fried. A nitrogen atmosphere, "steam blanket," or vacuum frying could have a similar protective effect.

- **Thermal polymerization**—is similar to tertiary oxidation, but is not related to oxidation. At elevated temperatures, when the oxygen supply is rather limited (as in the case of a "steam blanket" generated on the oil surface by water which evaporated from the fried food), the main reactions lead to polymerization rather than oxidation (Gertz *et al.*, 2000). Polymerization results in brown residues near the heating elements. Thermal changes lead to the formation of cyclic monomers, dimers and polymers in a non-radical mechanism. The polymerization mechanism is complex and not completely understood. Polymerized triglyceride formation is proportional to the temperature and frying time and less dependent on fatty acid composition. Saturated fatty acids are more stable than unsaturated counterparts but at temperatures over 150°C they decompose to carboxylic acids and a large variety of aldehydes, ketones, and other carbons. Oxygen accelerates this process. Cyclic fatty acid monomers (CFAM), formed from linoleic and linolenic acid due to oil exposure to high temperatures, are of great importance. When originated from linoleic acid, CFAM contain a five-member ring, while those originated from linolenic acid contain a five or six member ring (Sebedio & Chardigny, 1996, Gertz *et al.*, 2000).

Oxidation is of great financial importance due to the development of rancid flavors that damage the organoleptic value of the product, and the formation of oxidation products that may comprise a health hazard (e.g., mutagenic, carcinogenic). In comparison with frying oil, selective absorption may take place, enriching the food product with breakdown oil compounds (Pokorny, 1998).

Hydrolysis, oxidation, and thermal alterations are interrelated. Free fatty acids can be formed mainly by hydrolysis and, also, by oxidation and cleavage of double bonds. Fatty acids can be oxidized and/or undergo thermal breakdown. Polymers cause foaming that holds steam bubbles in the oil for a longer period of time and hastens hydrolysis. On the other hand, when the bubbles burst, they facilitate the introduction of oxygen into the hot oil, effecting oxidation. Food can leach fat during frying (for example, fish or chicken), resulting in a different mixture stability compared to the original frying oil. The presence of food crumbs and batter residues contributes to color changes. In the course of frying, increases in oil viscosity, foaming tendency, and free fatty acid content are observed, coinciding with the development of dark color and decreases in the smoke point, the unsaturation degree and interfacial tension (Nawar, 2000).

Uptake removes oil from the fryer and, to maintain a constant level, fresh oil is added. The food removes some of the formed breakdown products, including polar compounds, polymers, free fatty acids, and triglycerides. Indications are that some of these material concentrations are higher in the food due to preference absorption (Pokorny, 1998). This oil is replaced by practically pure triglycerides. Hence, replenishment contributes to maintaining oil quality. The size of the fryer should fit the food throughput. For quantifying the appropriate ratio, oil turnover is defined as the ratio between the amount of oil in the fryer and the amount of oil consumed per hour. Typical industrial frying is continuous and the turnover is below 8 h, considered acceptable. As fried food products and fryers are quite different, turnover times could vary significantly. However, it is recommended that it be as short as possible and no longer than 8 h. In fast-food outlets, the frying process is typically a batch process with idle periods; the turnover could range from 30 to 100 h. Higher values are also known

Table 2. Effect of typical food ingredients on an oleic based vegetable oil frying oil life (Blumenthal, 2001).

Ingredient	Fry life reduction[a](%)
Rendered chicken fat	15–20
Meat protein residues	25–30
Cheese protein residues	30–35
Beer batter protein residues	30–35
Hydrocolloid gums	25–30
Salt	15–20
Sea salt	20–30
Yeast leavening	20–25
Baking soda	30–35
Iron salt (10 ppm)	30–50
Phosphate residues	35–50
Catalyst residues (10 ppm)	10–40
Soap (30 ppm)	15–20
Excess antioxidants	20–25

[a] Soybean, cottonseed, sunflower and canola oil.
For tallow based oils, the figures are lower by about 10%.
For palmitic based oils, the figures are lower by about 5%.
For lauric based oils, the figures are lower by about 5–7%.

Table 3. Retention of vitamin C in various cooking methods of frozen French fries (Fillion and Henry, 1998).

Processing operation	Vitamin C retention (%)			
	Large fries		Small fries	
	Absolute[a]	Apparent[b]	Absolute	Apparent
Blanching	70	70	68	68
Par-frying	96	127	82	138
Deep frying	83	123	65	106
Oven baking	71	140	57	102

[a] Absolute retention–dry weight fat free basis (ratio between cooked to raw).

[b] Apparent retention–wet weight basis (ratio between cooked to raw).

(Lawson, 1995; Stauffer, 1996). This fact has significant ramifications on the high deterioration of oil in restaurants, canteens, and fast-food outlets. Foods and their composition and ingredients have different effects on reducing the fry life of the oils used during frying (Table 2).

The majority of decomposition products concentrate in the polar fraction of the oil. This fraction contains compounds with a lower molecular weight than triglycerides. Weight percent of the polar compounds is determined after the removal of the non-polar fraction by extraction (Moreira *et al.*, 1999; Nawar, 2000).

Effect of frying on nutritive value

Although frying is considered an inexpensive, fast, and efficient method for cooking and sterilizing food surfaces, fried foods have a negative image in the Western diet. In the following section the frying process is compared with other cooking methods, focusing on the nutritional value.

Temperature and the duration of the heat treatment have a significant effect on nutritional losses. Surprisingly, deep fat frying has two significant advantages over other cooking methods:

- The temperature within the product (aside from the crust region) does not exceed 100°C as long as the product contains water.
- Frying time is usually very short and ranges from a few seconds to several minutes.

Therefore, the frying process is expected to cause less deterioration to heat-sensitive vitamins (e.g., C and thiamine) than baking or boiling. Another advantage is the insolubility of water-soluble vitamins in oil. For instance, retention of vitamin C in potato products was found to be high in French fries and quite similar to the initial concentration in the raw potato (Table 3).

Assessment of various heat treatments (stir frying, microwave, and boiling) on vitamin C retention in broccoli and green beans showed that the highest retention was in broccoli, fried or cooked in a small amount of water. However, in green beans, high retention was observed only after boiling in a small amount of water (Table 4).

It is interesting to note the comparison between vitamin C concentration of fresh apples, French fries and potato chips. Quite surprisingly, French fries and potato chips (without salt) contain a higher concentration (11.6 and 41.6, respectively, in contrast to 5.7 mg/100 g in raw apples with skin; http://www.rahul.net/cgi-bin/fatfree/usda/usda.cgi). Obviously, this is merely one aspect, and should not be interpreted as a recommendation to replace apples with French fries or chips.

The picture for lipid soluble vitamins is more complex. Vitamin A retention in boiled vegetables was higher than in fried (86 and 76%, respectively). Moreover, deep fat frying caused twice as much loss of the vitamin than stir-frying. These findings are not surprising, considering the solubility of vitamin A in oil. In contrast, all vegetable oils used for frying contain vitamin E at a concentration of 15–49 mg α-tocopherol equivalents/100 g (Holland *et al.*, 1991). Therefore, fried foods are enriched with considerable amounts of vitamin E. The RDA for vitamin E is 10 mg α-tocopherol equivalents (http://www.nalusda.gov/fnic/dga/rda.pdf). A portion of 100 g homemade French fries provides up to 50% of this RDA (Table 5). Naturally, oil quality and the number of frying cycles are of crucial significance in the determination of the final vitamin concentration.

Another aspect that is not often considered is the minuscule decrease in mineral content during frying. For instance, fried fish

Table 4. Vitamin C retention of broccoli and green beans prepared by various methods (Eheart and Gott, 1965).

Cooking method	Vitamin C retention (%)	
	Broccoli	Green beans
Stir frying	76.6	57.5
Microwave	56.8	58.9
Boiling (large amount of water)	44.8	59.6
Boiling (small amount of water)	74.2	76.0

Table 5. Vitamin E in 100 g fried potato product (Holland *et al.*, 1991).

Potato products	Vitamin E (% of RDA)
Raw potatoes	0.6
Retail French fries (vegetable oil)	3.9
French fries, frozen (corn oil)	32.7
Home-made French fries (corn oil)	49.0

Table 6. European regulations of maximum levels allowed in frying oil (Dobarganes, 1998; Ollé, 1998).

Country	Polar compounds (%wt)	Polymers (%wt)	Max. frying temperature (°C)	Acid value (%)	Smoke point (°C)
Austria	27	—	180	2.5	>170
Belgium	25	10	180	2.5	—
France	25	—	—	—	—
Germany	24	—	—	2.5	>170
Italy	25	—	180	—	—
Spain	25	—	—	—	—
Netherlands	—	16	—	—	—
Hungary	30	—	—	—	—
Portugal	25	—	180	—	—
Switzerland	27	—	—	—	—

and potatoes showed negligible mineral losses when compared to boiling or baking (Fillion & Henry, 1998).

With the increased importance of fibers, it is interesting to note that deep fat frying of French fries was found to decrease digestible starch concentration, and increase the dietary fiber content. Therefore, consumption of French fries contributes to fiber uptake (Thed & Phillips, 1995). Although the change was quite small, it could have some importance in light of the possible contribution of dietary fibers to prevention of diseases such as colon cancer, heart disease, and diabetes. The aforementioned data is not conclusive. For instance, the total dietary fiber content of chickpeas fried in vegetable oil decreased 3.6%, compared to the raw product, and the insoluble dietary fiber content was not affected by frying (Perez-Hidalgo *et al.*, 1997).

It can be concluded that the frying process has no significant effects on the nutritional value (excluding oil content and calories) of foods. In some cases, nutritional losses are lower in frying compared to other cooking methods. Furthermore, frying enriches the product with vitamin E and, to a lesser extent, increases the dietary fiber content in potato products. Hence, fried foods could have a place in a balanced diet. Moreover, in developing countries, the contribution of fried foods is of great importance due to possible deficiencies of nutritional components.

Control and regulations of frying oil quality

Most European countries are concerned by the changes that occur in the oil during frying. Consequently, the concentration of total polar compounds was chosen as one criterion of oil quality, and its value was limited to 25%. In addition, two countries have also limited the polymer content to 10 and 16% (Table 6). An international conference held in Germany in March 2000 discussed deep fat frying, and several recommendations were published (http://www.dgfett.de/news/recomm.htm) Accordingly, evaluation of the quality of frying oils to determine when to replace oil in the fryer should be based on two principal criteria: the maximum concentrations of total polar compounds and polymer content, which were specified as 24 and 12%, respectively.

The National Food Administration of Sweden published guidelines for deep fat frying and the tests for assessing oil quality are: organoleptic evaluation, Fritest (carbonyl compounds), peroxide value, free fatty acids, foam formation, etc. (Paul & Mittal, 1997). In Israel, there are no regulations for the use of frying oils or definition of deteriorated oil. Nevertheless, the Israeli Food Control Service at the Ministry of Health follows the Swedish recommendations. Before Hanukkah (a Jewish holiday in which a large amount of doughnuts is consumed), the Israeli Ministry of Health published a memo on oils used to fry doughnuts, falafel, and similar food products, recommending canola or cotton oil. In addition, it recommended testing the oil prior to frying and maintaining the level of total polar materials below 25%. A turnover time of up to 8 h, temperature below 180°C, and filtration of oil are also recommended. However, these well-thought guidelines (Shapira, 2000) could be utopian, as no legal measures, sampling or monitoring of oil quality were enforced. According to the Japanese Ministry of Health and Welfare (1979), which is still in effect (Mizuno, 2001). Frying oil should comply with the following limits: 1. Smoking point higher than 170°C; 2. Acid value less than 2.5 mg/g and 3. Carbonyl value less than 50.

Industrial, restaurant, and fast food frying

During the frying process in restaurants and fast-food outlets, the frying oil is exposed to high temperatures for long periods of time, while quite often the fryer is idle. In industrial frying, the turnover time is usually below 8 h. A higher turnover time is often observed in restaurants and fast-food chains, strongly affecting oil quality. During industrial frying, food particles,

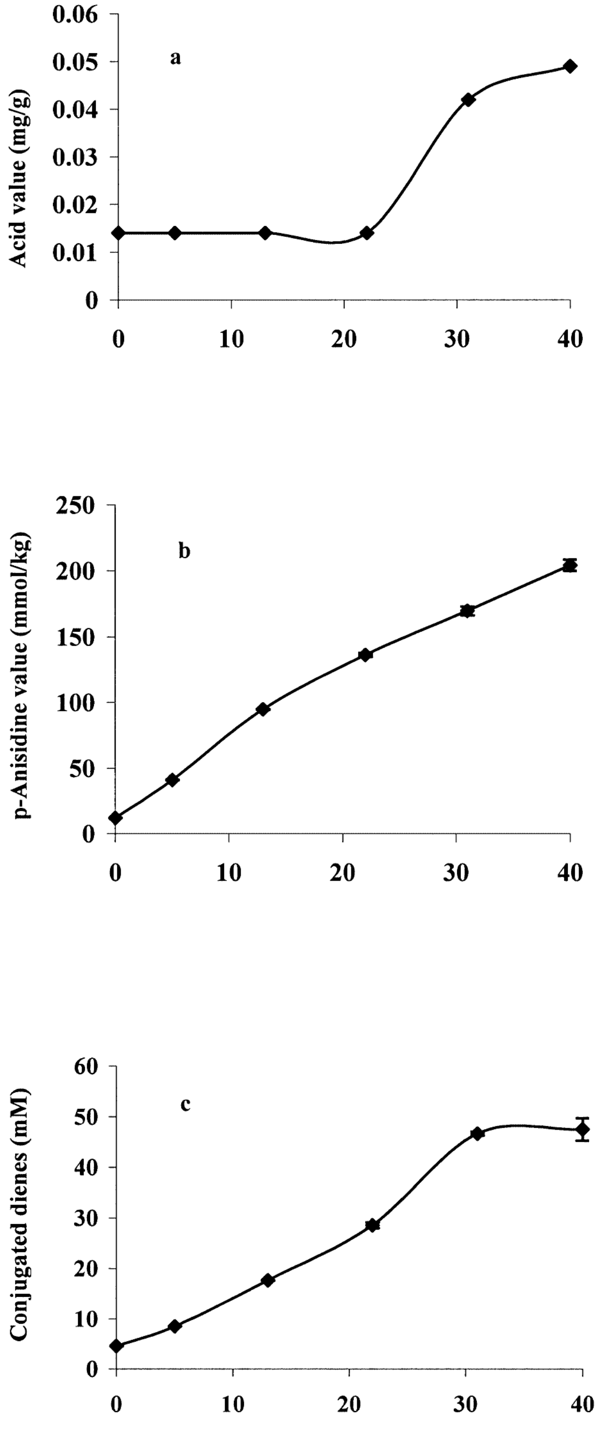

Fig. 1. Effect of frying time at 170°C on corn oil quality. a, acid values; b, *p*-anisidine values; c, conjugated dienes (adopted from Dana and Saguy, 2001).

crumbs, and batter or breaded compounds are continuously removed, preventing some of the formation of black burnt particles which create dark to black spots on the food. These particles are a source of generating free radicals.

To demonstrate the impact of a long frying period (up to 40 h), data on corn oil at 170°C, measured in our lab, are shown in Figs. 1a–c. The data include acid and *p*-Anisidine values, and conjugated dienes concentration.

The changes in typical oil characteristics of various oils utilized for frying for 30 h were significant (Table 7). The increase in oil viscosity formed extensive foaming. Color changes ranged from brown in corn oil to dark brown in soybean oil and palm olein. Free fatty acid levels were slightly higher in palm olein than in soybean and corn oil. Under these conditions, it is worth noting that although soybean oil is considered the least stable oil, vitamin E retention was higher than in palm olein (Fig. 2).

In industrial frying, oil uptake follows continuous production; hence, oil is replenished continuously, as can be derived from the low turnover value. Continuous replenishing of fresh oil maintains oil quality and enables prolonged frying (Romero *et al.*, 1999). In contrast, restaurant and fast-food fryers typically are idle some of the time or operate at partial capacity. Therefore, a high turnover time (in some cases exceeding 100 h) is not surprising. The significant difference between continuous frying of chips, doughnuts, and fish, and the batch type frying in restaurants, fast-food outlets, and households is clearly manifested by oil quality (Table 8).

These data indicate that most of the unacceptably high values were found in restaurants and fast-food outlets. For instance, 37.5% of the examined restaurants exceeded the regulation which limits polar compound concentration to 25% (Dobarganes, 1998). These values and others (Table 9) clearly demonstrate that, in batch frying, oil deterioration was higher due to the need to keep the fryer idle at high temperatures and to fry different types of products in the same oil, and the low oil replenishment rate. These values are not restricted to Europe. Similar data were collected in over 3000 tests carried out in South Africa (Kock *et al.*, 1999). These data highlight the need for enforcing strict legal regulations to maintain oil quality.

Table 7. Effect of frying for 30 h at 185°C on typical oil characteristics (Simonne and Eitenmiller, 1998).

Oil	Viscosity (cP)	Color $L^{a)}$	Free fatty acids (%)
Soybean oil	+63.7	–5.9	+0.59
Corn oil	+26.2	–3.2	+0.52
Palm olein	+34.6	–6.0	+0.87

$^{a)}$Hunter lightness values

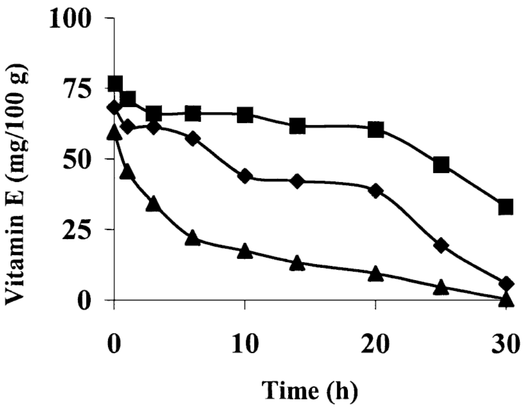

Fig. 2. Effect of frying for 30 h at 185°C on total vitamin E (adopted from Simonne and Eitenmiller, 1998). ◆, soybean oil; ■, corn oil; ▲, palmolein.

Health and frying

The assumption that changes which occur in the oil and in the food during frying are undesirable can be misleading, since some of the changes are essential to obtain the unique palatability and sensory characteristics of fried foods. Frying in fresh oil results in light colored products, poor taste and increased oil uptake (Blumenthal, 1991). On the other hand, prolonged frying or frying without adequate control can lead to nutritional losses, lower sensory attributes and even, or more importantly, health risks.

There are only a few extreme incidents of direct correlation between oil quality and health hazards. In 1938, several people became ill in South Africa due to the consumption of contaminated oil. In 1984, more than 20,000 people became ill and 600 died in Spain after consuming unlabelled, contaminated rapeseed oil (Kock *et al.*, 1999). However, these events are not related to deterioration of quality caused by frying.

Oxidized oil may comprise a health hazard as a result of the presence of peroxides, aldehydes, ketones, hydroperoxides, polymers, etc. Vitamin E in body membranes is destroyed by peroxides or subsequent free radical reaction. Similarly, polyunsaturated compounds promote oxidation, lowering the tocopherol level. Moreover, polymers formed during deep fat frying have an adverse effect on digestibility (Paul & Mittal, 1997).

Table 8. Polar compounds and polymer concentration range in frying oils from different European sources (Dobarganes, 1998).

Fryer type	Polar compounds (%)	Polymer content (%)
Continuous (industrial)	4.2–27.3	1.1–11.2
Batch (fast food, restaurant)	3.1–61.4	0.2–47.6

Table 9. Polar compound and polymer content in fast-food restaurants in several European countries.

Country	Number of samples	Polar compounds (PC) range (%)	Polymer content range (%)	Samples (%) with PC>25%	Reference
Sweden	100	1.0–55.0	—	38.0	Croon *et al.* (1986)
Germany	125	5.8–57.7	1.7–35.0	35.2	Gertz (1986)
France	31	8.2–54.6	0.8–39.5	48.4	Sebedio *et al.* (1987)
Spain	174	3.1–61.4	0.2–47.6	34.5	Dobarganes and Marquez (1995)
Finland	20	7.7–55.8	—	60.0	Skrokki (1995)

Rats were fed for six months a diet containing 15% thermoxidized palm oil (TPO) collected from oil heated five times to a temperature of 300°C and used to fry different products for 20 min each time. This experiment included the offspring generation. The TPO diet reduced lung and kidney mass in male rats, but did not affect the females. The hearts of the filial generation of both males and females were enlarged and the liver, kidneys, and lungs were reduced in females. These organs are highly membranous and thus lipid-rich and, as such, they comprise a target to free radical oxidation from the thermoxidized oil (Isong *et al*., 2000). It is worth noting that the frying temperature of 300°C is beyond the acceptable frying temperatures.

Calcium absorption in rats consuming olive oil or sunflower oil which was not used or was used for repeated frying of potatoes until the oils reached the 25% polar compound limit was examined recently. During a 28 day period, five groups of rats were fed diets containing 8% unused olive oil, olive oil used in 48 or 69 potato-frying operations, unused sunflower oil, and sunflower oil used 48 times to fry potatoes. No significant differences in food intake, body weight, or food efficiency were observed. Both sunflower oil diets increased the calcium absorption efficiency without modifying the calcium balance, urinary calcium, blood-serum calcium, or calcium in the carcasses. The intake of oils used for frying did not induce any significant changes. Sunflower oil enhanced calcium bioavailability slightly, but oil used for frying did not produce any additional effect (Perez-Granados *et al*., 2000).

The digestion of thermoxidized oil containing 26.4% polar compounds formed in degradation fried products in Wistar rats was 30% lower, testing breakdown products such as polymers and dimers. These data supported the hypothesis that the body has a controlling mechanism that can deal with oil oxidized in prolonged frying (Gonzalez-Munoz *et al*., 1998).

To investigate the effect of a dietary oxidized oil on the thyroid hormone status and circulating cholesterol, a study was conducted with 16 male miniature pigs fed a nutritionally adequate diet with 15% of either fresh or thermoxidized oil for 35 days (*n*=8/group). The thermoxidized oil was prepared by heating sunflower oil at 110°C for 48 h. The fresh oil consisted of a mixture of sunflower oil and lard (94 : 6, v/v) which had a fatty acid composition similar to the thermoxidized oil. At the end of the study, there were no differences in body weight gains and plasma clinicochemical variables between groups, suggesting that the thermoxidized oil did not induce general toxic symptoms. However, it was also found that there was a close relationship between alterations of thyroid hormone status and cholesterol metabolism in pigs fed the thermoxidized oil, and dietary oxidized fats should be considered in thyroid hormone disorders (Eder & Stangl, 2000).

As can be seen from the above typical examples, conflicting data on frying and health have been widely documented. Our objective, however, is also to review a number of additional findings concerning consumption of fried foods containing compounds formed during frying that could have an adverse effect on health.

Trans fatty acids

Since the negative effect of trans fatty acids (TFA) on serum lipoproteins (Katan *et al*., 1984) and increased risk of heart disease (Willett & Ascherio, 1994) are widely accepted, there is an understandable tendency to reduce the TFA concentration in margarine and edible oils. Frying oils undergo partial hydrogenation to improve their stability, which could significantly raise the TFA concentration (Aro *et al*., 1998). The absorption of various TFA in the digestive system is extremely high (>98.8%) and, in fact, is identical to the absorption of the cis fatty acids. Trans-isomers of essential C18 fatty acids are found in the blood and can therefore participate in different metabolic routes, but further research is needed to determine whether these isomers are integrated in lipid metabolism in humans (Sebedio & Chardigny, 1996).

A recent study conducted in Europe indicated that even when the concentration of TFA is below 1% in non-hydrogenated oil, its level in frying oils could reach up to 50% (Table 10) due to hydrogenation (Aro *et al*., 1998). Only Denmark has regulation on the maximum allowed TFA (15%) in unused frying oil (Fox, 2001).

Repeated use of frying oils may increase the TFA concentration due to the exchange of fatty acids between the fried food and the oil and as a result of the high temperature and prolonged frying process. For instance, an increased concentration of trans-isomers of C18:1 was found in various vegetable oils used for beef frying. In addition, repeated frying of sunflower oil resulted in an increased concentration of the TFA isomer C18:2 (Aro *et al*., 1998). These findings are of great importance due to their implications of a possible link with the frequency of heart disease. To estimate the exposure to TFA due to the consumption of fried foods, the TFA concentration was measured in a potato product, which was pre-fried, frozen and refried. Extra virgin olive oil, sunflower oil, and high oleic sunflower oil were used. The product was fried for 8 min at 180°C without or with frequent replenishment of oil (after each frying, for a total of 20 frying cycles). The resultant TFA concentrations in the fried potatoes (Table 11) indicate that during frying, the formation of TFA did not exceed 5 mg/g oil and the consumption of one portion of fried potatoes (approximately 140 g) is an insignificant contributor to the intake of TFA (i.e., lower than 0.13 g; Romero *et al*., 2000). A typical Western diet contains 100 g of fat with a concentration of 10% TFA, mainly from baked products. The consumption of 4% TFA in the diet did not seem to have adverse effects (Nestel *et al*., 1992). These data highlight the need to reduce TFA concentration due to hydrogenation, while the frying process has only a miniscule effect.

Table 10. Trans fatty acid (TFA) concentration in frying oils in some European countries (Aro *et al*., 1998).

Country	TFA concentration (%)
Belgium	35.34
Denmark	20.16
England	4.67
Finland	15.92
France	0.51
Germany	7.75
Iceland	39.09
Italy	0.30
Netherlands	50.19
Norway	28.65
Portugal	5.58

Table 11. Total TFA concentration (mg/140 g par-fried frozen potatoes) fried in various oils (Romero *et al*., 2000).

Oil	Frequently replenished	Par-fried frozen	8-cycles	20-cycles
Extra virgin olive oil	+	45.2	56.9	124.3
Extra virgin olive oil	–	45.2	64.4	110.8
High oleic sunflower oil	+	20.8	38.7	86.4
High oleic sunflower oil	–	20.8	38.9	96.5
Sunflower oil	+	45.2	68.6	113.0
Sunflower oil	–	45.2	71.3	129.0

Cyclic monomers and polar compounds

Cyclic fatty acid monomers (CFAM) are formed mainly from linoleic and linolenic acids during heating of vegetable oils at a temperature of 200°C. This temperature is reached in some frying processes and during oil refining. The mechanisms of CFAM formation are not completely clear and require further study, but free radicals are probably involved (Christie & Dobson, 2000). CFAM are absorbed in the digestive system and, as shown in rats, they reach various tissues containing phospholipids and neutral lipids. A diet containing 1% CFAM fed to rats lowered food intake and offspring weights significantly, even compared with the group not exposed to CFAM but fed a restricted diet similar to that of the tested group. This indicates that the lower offspring weight was a result of a specific effect of CFAM and not only the reduced food intake. During the first three days, 98% of the offsprings died; the rest died after two additional days (Sebedio & Chardigny, 1996).

Several studies indicated that cyclic monomers, which are highly absorbed in the digestive and lymph systems (91–96%), are very harmful. Their formation was directly related to oil in saturation and time of exposure to high temperatures. The amount of CFAM in oxidized oils is relatively small (about 0.5%), but their high absorption in the body may increase the possible harmful effect when food fried in oil with a high CFAM content is consumed (Paul & Mittal, 1997). Penetration of CFAM into pig endothelial cell membranes in tissue cultures caused alterations in biochemical and physical parameters. The absorption of CFAM was higher in five-member than in six-member ring in polar and non-polar lipid fractions. Retarded growth and morphological changes in tissue cultures were observed at two different CFAM concentrations. CFAM in the growth media caused physical changes of cell membranes and alteration of biological routes related to culture homeostasis. The increased CFAM concentration caused a decreased ratio of cellular lipids/protein, which may contribute to the reduced order of membrane lipids observed. Hence, prolonged CFAM presence in the diet might affect endothelium injury and degeneration *in vitro* (Flickinger *et al*., 1997). However, CFAM concentration in oxidized oil of poor quality is less than 0.5%, hence, the actual consumed concentration is rather low.

Rats fed a diet containing 20% oils heated at 200°C for 48 h showed retarded growth and enlarged livers. The negative effect was related to a fraction containing CFAM, was harmful to histological development of the heart, liver, and kidney tissues. A fraction containing 1% CFAM injected into the digestive system of the rats caused the death of all the animals after eight days. Evidence was found for increased oxidation stress expressed by higher enzyme activity (i.e., cytochrome 450 and superoxide dismutase), and increased metabolic activity due to the feeding with oxidized oils (Sebedio & Chardigny, 1996). On the other hand, three generations of rats were fed a diet containing 10% soybean oil and hydrogenated walnut oil heated for 96 h at 175°C with or without fried food. No deleterious effect was found after ten years. Moreover, the incidence of tumors was lower than in the control group. Although this study was conducted more than 20 years ago, its conclusions are probably valid to date, namely, frying oil maintained at adequate conditions should not be harmful to the health of laboratory animals (Lang *et al*., 1978).

Some recent studies showed that even frying oils of fine quality caused diarrhea, weight loss, and, in some cases, sudden death of the experiment animals. In most cases, the reasons for these alarming data are unbalanced diets, lack of essential fatty acids and vitamin E, fats and oils as a sole nutrient, feeding of large amounts with a stomach tube, and determination of the lethal dose LD_{50} of fats and oils. Evaluation of such experiments requires special attention. For instance, in the aforementioned study, which lasted for 10 years (Lang *et al*., 1978), the maximum recommended daily intake of frying oil was not found since the concentrations used were below the levels that produce negative effects (Billek, 2000). A sequential study used the polar fraction that contains the oxidation products. Sunflower oil used in industrial frying of fish fingers was separated into polar and non-polar fractions and compared with fresh oil used in the control feeding group. The oil or oil fraction comprised 20% of the rats' diet for 1.5 years. The control group had the highest weight gain. The rats fed the polar fraction gained significantly less, and the weights of their livers and kidneys were higher, indicating a possible direct effect on these organs. Also, activity of the enzymes glutamic pyruvic transaminase (GPT) and glutamic oxaloacetic transaminase (GOT; responsible for removing ammonia and thus related to detoxification mechanisms) was 20% higher. Other tested measures were normal and histological investigations indicated no changes, leading to the conclusion that the rats would have recovered if they had been returned to a balanced diet. The rats fed the non-polar fraction differed slightly from the control group and had a lower weight increase (Billek & Guhr, 1979). This difference was later associated with CFAM in the non-polar fraction which were bound to triglycerides and, thus, unable to pass to the polar fraction (Grandgirard & Juillard, 1984).

These inconclusive findings could not unequivocally demonstrate negative effects of frying oils and their fractions on health. Recent studies resulted in determination of the various CFAM structures (Christie & Dobson, 2000), opening new ways to investigate their impact in nutritional studies and, hopefully, quantify their possible effects on human nutrition, which remain to be elucidated.

Frying, mutagenesis and carcinogenesis

Several studies indicate that products generated through oil oxidation can be carcinogenic. Some volatile oxidation products were found to be mutagenic in vapor inhalation during frying (Marquez-Ruiz & Dobarganes, 1996). A recently published study showed a relationship between lung cancer in women and vapor released during fish frying in China and Taiwan (Yang *et al.*, 2000; Seow *et al.*, 2001). Food frying in restaurants and institutional feeding may constitute a problem due to long exposure of the oil to extreme conditions and the lack of adequate oil replenishment and replacement. For example, a fraction of polar compounds separated from frying oils in restaurants showed mutagenic activity in Ames test in Salmonella. A positive correlation was found with TBARS (thiobarbituric acid reactive substances), formed from fatty acids with three or more double bonds. This fraction contains MDA, which was found to be mutagenic in many other studies (Esterbauer, 1993; Hageman *et al.*, 1988; Basu & Marnett, 1983; Shamberger *et al.*, 1974). Mutagenic activity was positively correlated with MDA concentrations (Hageman *et al.*, 1988). Prolonged frying caused a substantial rise in MDA concentration (Fig. 3).

MDA was found to cause skin cancer in rats and creates cross-linking with amino groups of DNA solution. Ames test indicated that MDA is a mutagen causing DNA alterations and reacting mainly with guanine and cytidine by a depletion of this base pair (Mukai & Goldstein, 1976). MDA can damage proteins and phospholipids by covalent bonding and cross-linking. Rats fed a diet containing MDA suffered retarded growth, irregular intestinal activities, enlarged liver and kidneys, anemia, and low serum and liver vitamin E (Esterbauer, 1993). Since a considerable amount of oil is absorbed in the product during frying (10–40%), frying in oil that carries mutagens could lead to consumption of foods containing hazardous compounds. Usually the concentration of mutagens in the oil is low, but high oil uptake may have health implications (Hageman *et al.*, 1988). It is also possible that a higher concentration could be absorbed in the food due to preferential uptake. It is worth noting that the concentrations used in the aforementioned experiments on rats are twice as high as the average human consumption of MDA (Esterbauer, 1993). Hence, the increase in MDA during frying should be studied further as it is not typically monitored during deep fat frying.

As low mutagenesis was found in oils exposed to severe frying conditions, which are uncommon in typical industry or household operations, and no mutagenic activity was found in oil used for repeated frying of potatoes, onion rings, or fish fillet (Taylor *et al.*, 1983), it can be assumed that, under controlled conditions, the level of exposure to mutagenic compounds should not constitute a health hazard.

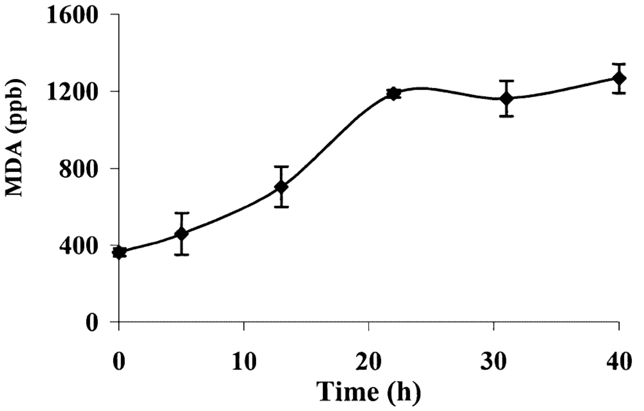

Fig. 3. Effect of frying time at 170°C on MDA concentration in corn oil (adopted from Dana and Saguy, 2001).

Heterocyclic amines (HAs)

Pan-fried or roasted meat, although not deep-fried, is classified a fried product. Due to the importance of meat product consumption and the implication of frying on the formation of health-affecting compounds (Felton *et al.*, 1997), this subject is partially covered in this article. Mutagenic activity was found in beef cooked in regular domestic conditions in the 1970s. Since then, about 20 HAs of high mutagenesis have been isolated and identified, mainly from protein-rich foods. MeIQx (2-amino-3,8-dimethyl-imidazo[4,5-f]quinoxaline) and PhIP (2-amino-1-methyl-6-phenyl-imidazo[4,5-b] pyridine) compose about 48% of all HAs formed in meat. Several long-term studies in mice, rats, and other mammals showed a correlation between HAs and cancer (Skog *et al.*, 1998). Further, epidemiological studies found a relationship between high consumption of meat and fish and various types of human cancers (e.g., pancreas, colon, rectum, bladder). Due to the accumulation of evidence concerning HAs as a risk factor for colon and other cancer types, intense research efforts have been devoted to studying their formation in foods, absorption, carcinogenesis, and their significance in human cancer development (Murkovic & Pfannhauser, 2000).

The Maillard reaction (non-enzymatic browning) plays an important role in the formation of HAs. Creatine, free amino acids, and carbohydrates found in fresh meat are precursors of HAs (Wong & Shibamoto, 1996). Temperature has a more marked effect on the formation of HAs than time, so frying temperatures below 200°C significantly reduce the amount of HAs formation. The cooking method and type of food also affect the formation of HAs. For instance, in oven roasting, fewer HAs are formed than in stir frying, and a few minutes of preliminary microwave treatment reduces the levels of HAs by destroying their precursors (Skog *et al.*, 1998). Meat spicing also influences HAs concentration. Spicing with thyme, rosemary, sage, garlic, or brine substantially decreased the amount of HAs in fried meat (Fig. 4). This protecting effect is related to the antioxidant activity of spices, which inhibits the Maillard reaction, an essential step in the formation of HAs. The inhibition includes scavenging free radicals that have an important role in HAs formation resulting from browning reactions. Hence, meat spicing is an effective method of reducing the formation of HAs and minimizing the health risk in consumption of fried meat (Murkovic *et al.*, 1998).

The concentrations used to test the relation between the development of cancer and HAs consumption in animals were several orders of magnitude higher (up to seven, in some cases) than the concentrations of HAs that may be found typically in foods. The average daily uptake of HAs is about 26 ng/kg body weight, so that a person weighing 70 kg consumes about 1.8 μg HAs daily. The average concentration in the feeding experiments was 10–400 mg/kg body weight, 10 million times higher than the average daily intake. In fact, the consumed levels are too low to furnish an explanation for the development of human cancer (Skog *et al.*, 1998). Furthermore, in an epidemiological study testing whether HAs are related to colon, bladder, and kidney cancer, an

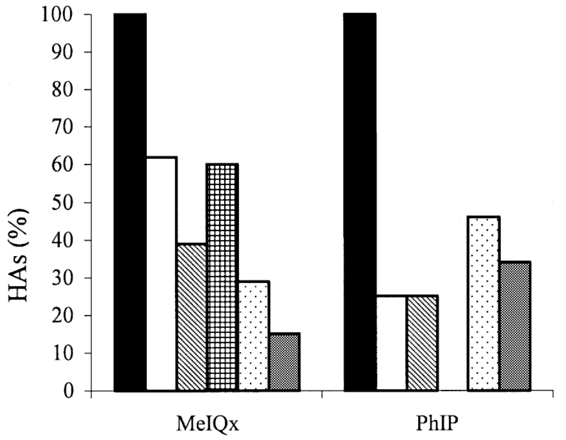

Fig. 4. Effect of several spices on the formation of Heterocyclic amines (HAs) in stir-fried beef. ■, No spices, □, rosemary, ▧, thyme, ⊞, sage, ⊡, garlic, ▩, brine (adopted from Murkovic *et al.*, 1998).

average daily consumption of up to 84 ng/kg body weight showed no raised incidence of these cancers (Augustsson *et al.*, 1999).

Special oils

There is a need to develop special oils, which have increased natural oxidation stability. Fatty acid composition is one of the main stability-affecting factors. The number of double bonds, their location and geometry, influence the oxidation rate. A large amount of double bonds increases the oxidation rate (Table 12), and cis bonds are more labile than trans-bonds (Nawar, 2000). Saturated fatty acids, such as palmitic or stearic acid, have high oxidative stability. Monounsaturated fatty acids, mainly oleic acid, are relatively stable against oxidation. Oleic acid is also considered a heart-healthy component in the diet. Polyunsaturated fatty acids (PUFA) have a good nutritional image but, during frying, high PUFA concentrations lead to increased oil degradation (Brinkmann, 2000). Partial or full hydrogenation or high oleic acid oils may significantly contribute to oil stability. High-oleic canola, sunflower or safflower oils, low linolenic acid or high-oleic soybean oil are successful developments of crop breeding technologies (Moreira *et al.*, 1999; Hazebroek, 2000). Such developments may reduce the need for hydrogenation of frying oils or even eliminate it.

Genetically modified (GM) or breeding selection of novel oils represent some of the most significant innovations for the oils and fats industry. Many of these novel oils posses fatty acid contents that are unique to the crop in which they have been developed. Modified oils fall into two main categories: the primary value of one group is enhanced oxidative stability, crucial for frying applications; the second general group is characterized by altered levels of saturated fatty acids. Modified oils have been developed using either breeding or gene modified via recent innovative biotechnology tools. In some cases, both techniques have been utilized to stack traits or enhance trait expression (Hazebroek, 2000). Consumers pressure to define GM as having ingredient or additive originating from GM crop, bowed the EC to establish the *de minimis* threshold at 1% of adventitious contamination, which states that for food from non-GM source, a 1% non-deliberate contamination is legal. The consequence for frying is the effective disappearance of soy and corn oils, unless identified as 'identify-preserved' (Fox, 2001). Consumers' objection to GM products will therefore determine the commercial success of the new oils.

Table 12. Relative oxidation rate of various C18 fatty acids (Nawar, 2000).

Fatty acid	Relative oxidation rate
Stearic (C18:0)	1
Oleic (C18:1)	10
Linoleic (C18:2)	100
Linolenic (C18:3)	200

The stability of frying oils was compared for high-oleic, regular and hydrogenated corn oil, and high-oleic sunflower oil. The level of polar compounds was significantly lower in high-oleic corn oil after 20 h of frying French fries at 190°C. This oil also was more stable in accelerated oxidation tests. In addition, organoleptic sensory acceptance tests showed that French fries fried in hydrogenated or high-oleic corn or sunflower oil were tastier than French fries fried in regular corn oil (Warner & Knowlton, 1997).

When heating various oils to 190°C for the period of time required to reach a polar compound content of 25%, the oxidation rate of corn oil (57.4% linoleic acid) was the fastest, reaching this level after seven days. Canola oil (21.2% linoleic acid and the highest linolenic acid concentration –10.1%) reached the same point after nine days. The oxidation rate of cotton oil (54.2% linoleic acid) was slightly higher than canola oil. Surprisingly, soybean oil, although containing high concentrations of linoleic acid (52.9%) and linolenic acid (8.0%), was fourth in the rate of polar compound formation. Since corn oil and cotton oil contain only traces of linolenic acid, its concentration cannot be the major factor in determining the stability of oils during frying (Takeoka *et al.*, 1997).

An important factor in the stability of the oil during frying is the type and concentration of the antioxidant present in the oil. Synthetic antioxidants tend to be more volatile than their naturally occurring counterparts (e.g., tocopherol) at frying temperatures. Most antioxidants lose their activity due to the high frying temperature and long exposure time. It is also possible that they are absorbed by the fried food (Moreira *et al.*, 1999). There is sufficient evidence that antioxidants (e.g., BHA, BHT, and TBHQ) provide oil protection but lose their ability to prevent significant degradation due to their diminishing concentration by steam distillation (Takeoka *et al.*, 1997). Hence, increasing and improving the natural antioxidant activity should be considered.

A typical example of specially designed oil for frying is Good-Fry®oil containing 76% oleic acid (http://www.goodfry.com). It is a mixture of sunflower, sesame, and rice bran oil. It is claimed that the oil was created for two main purposes; namely, to be as healthy as virgin olive oil and to be more or as stable as partially hydrogenated liquid oils and/or palm oil in industrial frying. The oil does not contain linolenic acid at all, which is known to be highly labile to oxidation. It is also stated that the oil contains tocopherols, other antioxidants and precursors of natural antioxidants, which are activated at high temperatures and thus protect the oil during frying. The oil has been approved as "dietetic" oil by the Federal Institute for the Health Protection of Consumers in Berlin, Germany (Kochhar, 2000). Other ingredients supplied by the same company contain a mixture of sesame oil and rice bran oil, which could decrease the deterioration rate of the frying oil (Fig. 5). These data requires additional verification by independent sources.

In addition to improved stability, a significant advantage of modified oils developed for deep-frying is their high content of monounsaturated fatty acids, mainly oleic acid, which is nutritionally beneficial. These oils are liquid at room temperature and, hence, convenient to use. Research concerning the development and use of modified oils is of great interest to both academia and industry, and will probably attract more attention in the future.

Olive oil

The medical value of olive oil was recognized long ago. Recent nutritional and medicinal data on the utilization of olive oil show significant health benefits as well as the prevention of diet-related diseases (Kafatos & Comas, 1990). Olive oil is rich in oleic acid (monounsaturated fatty acid, C18:1 ω-9), which oxidizes less than polyunsaturated fatty acids. Oleic acid constitutes 56–84% of all the fatty acids in olive oil. The concentration of active vitamin E (α-tocopherol) in olive oil is relatively high and contributes to its antioxidant nature. Consumption of olive oil supplies the daily allowances of essential fatty acids and prevents vitamin E deficiency.

Olive oil was found to be a regulator of blood cholesterol levels, has a healing effect on stomach ulcers, and positively influences growth and development. In fact, the "Mediterranean diet," equated with high consumption of olive oil, has been widely studied for its relation to a low incidence of heart disease and certain types of cancer and long life span (Kafatos & Comas, 1990). A number of studies showed that high levels of lipoproteins enriched with triglycerides during lipid metabolism after meals (postprandial lipid metabolism) are related to the development of atherosclerosis. Typically, the Western diet contains a daily consumption of 50–100 g fat. Postprandial lipid metabolism can last up to eight hours, during which a significant increase in plasma triglycerides is observed. The mechanism is not entirely clear, but the longer it lasts, the higher is the incidence of atherosclerosis and heart disease. In the Mediterranean diet, lipid metabolism was found to be more effective, accompanied with a faster drop of plasma triglyceride levels. A diet enriched with olive oil led to a substantial decrease in plasma cholesterol levels. The complete biochemical mechanism of these effects is not entirely understood, but it is clear that olive oil plays a key role in preventing atherosclerosis and coronary heart disease. Possibly, the high consumption of olive oil explains the lower incidence of heart diseases in Mediterranean countries (Roche *et al.*, 2000).

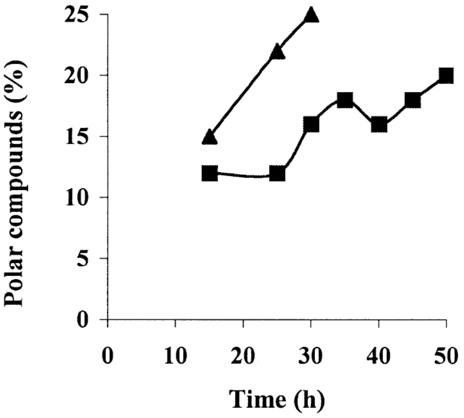

Fig. 5. Effect of added mixture of sesame oil and rice bran oil (HOSO–high-oleic sunflower oil+Good-fry) on the polar compounds content during frying (http://www.goodfry.com). ▲, Palmolein; ■, Hoso+Good-fry.

Table 13. Vitamin E concentration in various edible oils (http://www.rahul.net/cgi-bin/fatfree/usda/usda.cgi).

Oil type	Vitamin E (mg/100 g oil)
Soybean oil	18.0
Olive oil	12.4
Palm olein	21.7
Cotton oil	38.3
Sunflower oil	50.6
Safflower oil	43.0
High oleic safflower oil	34.4

Olive oil contains a variety of compounds, which compose 1–2% of the oil and contribute to its stability and unique taste. Following the oxidation of LDL (low density lipoprotein) cholesterol, foam cells are formed, leading eventually to atherosclerosis. Olive oil phenols were found to inhibit LDL oxidation. The phenol luteolin and its aglycone (a derivative without bound glucose) were found to be LDL oxidation inhibitors in a concentration of 10^{-5} M. The high contents of monounsaturated fatty acids and phenols probably play an important role in heart disease prevention. It is not known whether phenols are digested and absorbed *in vivo*, but experiments showed higher resistance to LDL oxidation in test animals fed a diet enriched with olive oil than in those fed a diet enriched with oleic acid (Visioli & Galli, 1998).

There are several advantages to using olive oil for frying. For instance, fat composition in lean or fat beef fried in olive oil showed that, after frying, the saturated fatty acid content de-

Table 14. Changes in fat composition of lean and fat beef fried in olive oil (Varela and Ruiz-Roso, 1998).

Composition	Fresh olive oil	Beef			
		Lean		Fat	
		Raw	Fried	Raw	Fried
Total fat (g/100 g food)	100.0	3.1	6.4	41.0	40.8
Saturated fatty acids (%)	15.7	41.2	28.6	43.8	42.0
Monounsaturated fatty acids (%)	74.4	43.2	61.5	49.5	52.0
Polyunsaturated fatty acids (%)	9.7	15.6	9.6	2.3	2.0

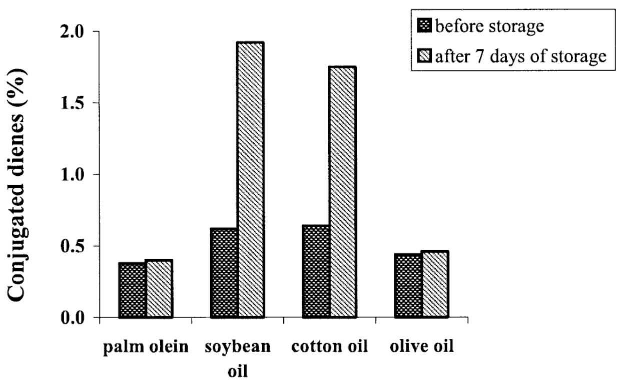

Fig. 6. Effect of storage on conjugated dienes concentrations in potato chips fried in different oils before and after 7 d at 63°C (adopted from Lolos *et al.*, 1999).

creased and the monounsaturated fatty acid content increased (Table 14). Hence, frying improved the quality of the beef. Olive oil is more stable than other vegetable oils due to its higher content of monounsaturated fatty acids (Varela & Ruiz-Roso, 1998). When compared to soybean, sunflower oil and palm olein, olive oil quality was maintained and highest even after 40 h (5 days) of potato frying (Pantzaris, 1998).

Oil used for frying affects the stability of the final product. Potato chips are typically consumed a few weeks after their production and, due to their high oil content (up to 40%), the type of oil used for frying affects their quality. Fried potato chips stored at accelerated condition of 63°C for 18 days in a typical package showed that olive oil and palm olein had a similar and better oxidation stability than cotton or soybean oil. The peroxide value was significantly lower (i.e., 20 for olive oil and palm olein vs. 60 and 75 mEq/kg for cotton and soybean oil after five days, respectively). Apparently, stability was not affected by the high concentration of oleic acid in the olive oil.

An additional criterion for oxidation is the conjugated dienes level. This test detects oxidation at its early stages. Comparing the conjugated dienes concentration in various frying oils prior to and after seven days storage (Fig. 6) showed that soybean and cotton oil were quite comparable, probably due to similar concentrations of total linoleic and linolenic acid. These data highlight the fact that the fatty acid composition of the frying oil affects not only the stability of the oil but also, and probably more important from the consumer point of view, the stability of the fried product during storage until consumption. Higher concentrations of oleic acid were not effective in improving stability. On the other hand, a higher content of linoleic or linolenic acid caused accelerated oxidation (Lolos *et al.*, 1999).

The common myth that olive oil is unsuitable for frying should be re-evaluated due to its high oxidative stability compared to other oils commonly used in frying processes. In addition, the use of olive oil enhances stability during storage. However, its high cost and characteristic and dominant virgin flavor mandates examining consumer acceptance of the unique flavor and willingness to pay a higher price for a probably healthier product. In any case, the myth that frying in olive oil should be avoided has no foundation.

Conclusions

In this study, the oil uptake mechanism, effect of frying on oil quality, association between frying and health, and nutritional value of fried foods and modified oils were reviewed. Main conclusions:

1. Oil uptake of the fried product increases with higher surface-active compound concentrations, roughness, area and others.
2. In the course of frying, a variety of chemical and physical changes occur due to hydrolysis, oxidation, and thermal decomposition. Water (released by the product), oxygen, high temperature, and the duration of the frying process are some of the key contributors to these changes.
3. Some of the compounds formed during frying in oil, especially at high temperatures, could pose a health hazard. However, the concentrations found in frying oils are quite low compared with those used in animal feeding experiments.
4. Data collected at some European restaurants highlight the need to enforce stricter legal regulations to control oil quality.
5. To date, there is no overall agreement concerning the relationship between frying and health risks.
6. The development of high stability oils is a promising research area, working towards improving the quality of frying oils and fried products. The possibility of using modified oils to reduce oil uptake should also be examined.
7. The development of novel technologies and frying techniques is needed to optimize product and food quality.
8. Development and additional studies focusing on biomonitoring techniques and markers are needed to assess possible DNA damage, toxicology and health risks.

As for fried food in general, in view of the information presented herewith, there is no sufficient justification for its negative perceived image. Aside from its high caloric value compared to other foods, the belief that fried foods are unhealthy is inaccurate and from a nutritional aspect could be misleading. Based on today's findings and knowledge, it can be concluded that fried foods pose no health risk in a balanced diet, when adequate frying technology and oil quality are maintained.

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