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Effect of Processing on Chemical and Nutritional Changes in Food Lipids

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ABSTRACT

Commercial processing of fats and oil into edible products is done to remove the impurities from the oil. Unless the oil is hydrogenated, very few chemical changes occur during this process to alter the nutritional quality of the oils. Trans fatty acids that are formed during hydrogenation have limited nutritional and metabolic effects if consumed with an adequate supply of essential fatty acids. When lipids or foods containing lipids are heated in the presence of oxygen, they undergo oxidation, which causes degradation of the fatty acids. The free radicals produced in these oxidation reactions may react with proteins, vitamins, or other food constituents and reduce the nutritive quality of the food. However, destruction of flavor or color by these reactions is often noticed before major nutritional damage can occur.

Lipids are consumed in different quantities throughout the world. In the U.S., we may consume 100-150 g of fat a day, which is 40-45% of our total caloric intake (*65*). Approximately 60% of this fat is hidden within our food and we consume it without realizing how much we have eaten.

The lipids in our food play an important role in our well being. They are a concentrated source of energy providing 9 Kcal per g, which is approximately twice the calories provided by proteins and carbohydrates. They are normal constituents of cellular structure and cell membrane functions. They provide essential fatty acids and are vehicles for lipid soluble vitamins, carotenoids and sterols. Metabolically, lipids are needed for many functions such as enzyme reactions, transmission of nerve impulses, memory storage and hormone synthesis (*65*). Perhaps the reason why we really eat fat is that it makes food taste better and has a high satiety value. Food is dry, tasteless and unappealing without fat.

In the processing of foods, fats and oils are used as a heat exchange medium and to contribute to the color and flavor of fried foods. The functional properties of fats are used in the production of shortening and margarines, which are used in baked goods and for table spreads. Various monoglycerides, diglycerides and phospholipids are used as emulsifiers or act as staling inhibitors in bakery products.

As fats and oils or foods containing lipids are processed, chemical and physical changes may take place which alter their nutritional or functional role in our diet. The first part of this review will cover briefly the changes which occur when fats and oils are processed into edible products. The second part of this review will cover the chemical and nutritional changes that occur in lipids when foods are processed.

OIL PROCESSING

Vegetable oils such as peanut, coconut, rapeseed, palm, olive and sesame seed oil are used in a clean but unrefined form in many parts of the world (*46*). With the exception of hydrolytic and oxidative reaction products, these oils are unchanged and contain the components naturally present in the oil seeds. The art of refining and processing crude oils to finished food products has developed over the last 50 years to such an extent that it is expected and demanded by consumers worldwide. The major factors responsible for development of refined and processed oils are flavor and stability characteristics of oils and preparation of hardened products, such as margarines and shortenings from liquid oils.

Separation of the oil from the oil-rich source is the first step in the processing operation. The method of oil extraction varies and depends on the type of oil being extracted. The oil is usually expelled by pressing or extracting with a solvent such as hexane. The crude oil contains the triglycerides, phospholipids, free fatty acids and small amounts of other substances which contribute to color, flavor, odor and instability of the oil (*29*). The following refining steps are designed to remove these unwanted contaminants and have very little effect on the nutritional properties of the oils.

Degumming

The degumming procedure usually involves mixing the oil with 1 to 3% water for 30 min at 30-60°C (*10*). The hydrated gums and phospholipids are separated from the oil by settling or centrifuging.

Crude oils are degummed to remove phospholipid and mucilagenous gums from the oil since these substances can

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hydrate and settle out during shipment and storage. These substances also act as emulsifying agents during other refining steps and lead to the loss of neutral oil. Phospholipids can also interfere with hydrogenation of the oil at a later processing stage (*14,21*). Commercial lecithin is made from phospholipids which are isolated during the degumming of licithin-rich oils such as soybean oil. Degumming has little or no effect on the fatty acid composition of oils, and causes very little loss of tocopherols (*26,60*).

Alkali refining

Alkali refining involves treatment of oils with sufficient NaOH solution (12-15%) to neutralize the free fatty acids and give the desired color to the oil. The oil-alkali mixture is heated to 75-80°C and the aqueous phase containing fatty acid soaps and other soluble constituents is removed by centrifugation (*10*). The refined oil is washed with water (10-20%) at 90°C to remove most of the soaps from the oil.

Alkali refining of crude oils removes undesirable components, such as free fatty acids, phospholipids, gums, color pigments and other insoluble unsaponifiable material. Also 14 to 20% of the total tocopherol is removed from the oil by the alkali treatment. (*26*).

Bleaching

The bleaching process usually involves mixing the oil with 0.5-1.5% acid-activated earth at 90-95°c for 15-30 min at a vacuum of 26-28 in. of Hg followed by filtration.

Refined oils are bleached to remove entrained soaps and color pigments. Bleaching of the oil also removes 10-15% of the tocopherols (*26*), and improves the oxidative stability of the oil by removing oxidation products.

Deodorization

Deodorization is the final step in processing edible oils. This is done to improve the taste, odor, color and stability of the oil by removing color pigments, flavor compounds, oxidation products and other volatile constituents. Approximately 12% of the total tocopherol is lost during the deodorization stage (*26*). The high temperatures used in this processing step can cause limited geometric isomerization of polyunsaturated fatty acids (*1*). Deodorization consists of bubbling steam through oil under partial vacuum.

Hydrogenation

The purpose of hydrogenating edible oils is to improve their stability, resistance to oxidation or to change their physical characteristics for use in various foods.

Hydrogenation is usually carried out in a batch process in which oil, hydrogen and nickel catalyst are mixed together in reactors (*3*). Since the reaction takes place in contact with each other on the surface of the catalyst, the reaction rate is controlled by factors such as agitation, temperature and hydrogen pressure, which influence the migration rate of the hydrogen to the catalyst. When hydrogenation is carried out at high pressure, low temperature, high agitation and low levels of catalyst, the surface of the catalyst is covered with hydrogen and there is limited formation of geometrical and positional isomers. High temperature, low agitation, low pressure and high catalyst levels produce incomplete hydrogen coverage of the catalyst surface, which results in high levels of positional and geometrical isomers (*3,16,19*). Figure 1 illustrates the mechanism by which geometrical and positional isomers are formed in the hydrogenation of oleate. The double bond of oleic acid is diadsorbed to the active sites (*) of the catalyst (A). This is followed by uptake of one hydrogen atom to give the monoadsorbed species (B) or two hydrogen atoms to give the saturated acid (C). If the catalyst surface is not completely covered with hydrogen, the reactions leading to the monoadsorbed species can be reversed to give the unsaturated acid. However, cis or trans isomers as well as positional isomers can be formed since hydrogen atom on either side of the active site in (B) can be removed as these reactions take place. Since many hydrogenation processes favor isomer formation, this processing treatment has the greatest effect on essential fatty acid levels of oils.

The amount of trans-acids found in commercially hydrogenated products ranges from 5 to 45% (*2,9*). It is estimated that the total intake of trans-acids in visible fats is approximately 8% (*35,44*).

The nutritional effect of consuming hydrogenated fats is not clear despite a great deal of research that has been conducted in this area. In a recent review, Applewhite (*4*) summarized and discussed the results of many of these studies. Consumption of trans fatty acids have been implicated in coronary heart disease and other circulatory disorders. A statistical analysis of dietary fat and cancer trends revealed that trans fatty acids could be positively correlated to increased cancer deaths (*20*). Kummerow and co-work-

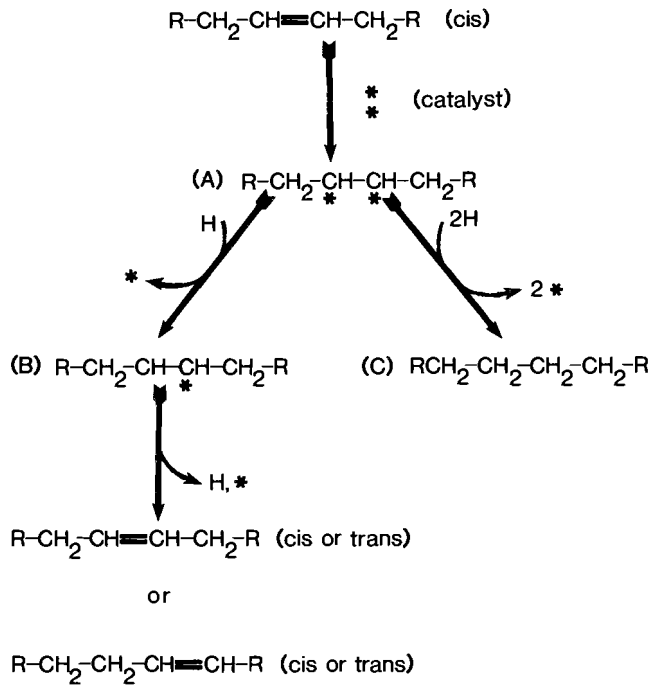

Figure 1. *Mechanism for the hydrogenation and isomerization of oleate* (15).

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ers (*35*) first reported that young pigs consuming hydrogenated fats with 50% trans-acids developed a higher increase of total lipids and cholesterol levels and a larger area of aortic atherosclerotic involvement than did pigs fed on other diets. However, it was suggested that these results could be caused by a high fat-to-protein ratio and borderline essential fatty acids (*4*). Studies (*18,31*) using proper dietary amount of fat, protein and essential fatty acids did not confirm Kummerow's earlier results. Applewhite (*4*), when reviewing this and other work, concluded that swine fed proper dietary amounts of protein, fats and essential fatty acids showed no unique effects of trans-isomers on the occurence of swine atherosclerosis. It has also been reported that trans fatty acids can affect membrane permeability and alter enzyme functions in animals (*13,28*). Applewhite (*4*) concluded that the diet in most of these studies contained minimal essential fatty acids and the trans effect could not be separated from the well known effects of essential fatty acid deficiency on cell functions. In studies where the essential fatty acid levels are adequately maintained, no effects of trans-acids have been noted (*2*).

FRYING FAT DETERIORATION

During deep fat frying, many complex changes take place that result in deterioration of the oil. As the food enters the hot oil, oxygen is introduced into the oil, which leads to oxidation. Oxidation products include hydroperoxides, aldehydes, ketones, acids, hydrocarbons and many polymeric compounds. As the food absorbs frying fat, the food lipids as well as color pigments are solubilized and released into the frying fat. Moisture is released from the frying food, which results in hydrolysis of triglycerides to form free fatty acids, diglycerides, monoglycerides and glycerol. The volatile degradation products are released from the oil with the steam as smoke. Heating the oil to high frying temperatures leads to formation of polymers as the reaction products condense. As these reactions take place, the sensory and nutritional qualities of the fat change, and the oil can no longer be used to produce high quality foods. At this time the frying fat is replaced with fresh fat even though the nutritional qualities may still be adequate (*37,50,58,66*).

Hydrolysis

Moisture in foods that are fried in fat can cause the release of free fatty acids from the triglycerides. Concentrations of at least 2% free fatty acids from nonlauric acid oils have no adverse effect on the odor or flavor of fried foods. If the free fatty acid content of oils that are high in lauric acid (coconut oil) reach a level of 0.5%, a soapy flavor will develop in the oil (*22*). The smoke point of the oil is most affected by free fatty acids in the oil (*64*).

Studies on the selectivity of hydrolysis in frying oil and model systems of triglycerides have indicated that shorter chain and unsaturated fatty acids are hydrolyzed at a faster rate than the other fatty acids (*8,47*). This was attributed to the greater water solubility of these acids. No apparent positional specificity for the hydrolysis was detected in these studies.

Lipid oxidation

When fats and oils are in contact with oxygen, they undergo oxidation, which causes degradation of the fatty acids to produce off-flavors and odors as well as other chemical changes in the fat or oil (*39*). Lipid oxidation is usually associated exclusively with unsaturated fatty acids. The oxidation products catalyze the reaction, and increase the reaction rate as oxidation proceeds. A free radical reaction mechanism is now universally accepted as the reation mechanism for autoxidation of lipid materials:

Initiation

$$RH \rightarrow R\bullet + H\bullet$$

Propagation

$$R\bullet + O_2 \rightarrow ROO\bullet$$

$$ROO + RH \rightarrow ROOH + R\bullet$$

Termination

$$ROO\bullet + R\bullet \rightarrow ROOR$$

$$R\bullet + R\bullet \rightarrow R\bullet R$$

$$ROO\bullet + ROO\bullet \rightarrow ROOR + O_2$$

where RH = unsaturated fatty acid
R• = lipid radical
ROO• = lipid peroxy radical

Although the free radical mechanism of lipid oxidation has been well established, the initial reaction or the formation of the first hydroperoxide has not been satisfactory elucidated. Rawls et al. (*53*) proposed that if singlet oxygen were the reactive species instead of ground state triplet oxygen, the intitial reaction in oxidation would take place very easily. He proposed the following mechanism by which singlet oxygen could be formed by photo-chemical reactions in the presence of a sensitizer and presented evidence that singlet oxygen reacts with unsaturated lipids at a rate of 1450 times faster than triplet oxygen:

$$s + h\nu \rightarrow {}^1s^* \rightarrow {}^3s^*$$

$${}^3s^* + {}^3O_2 \rightarrow {}^1O_2^* + {}^1s$$

$${}^1O_2^* + RH \rightarrow ROOH$$

$$ROOH \rightarrow \text{free radicals}$$

where:

${}^1s$ = singlet state sensitizer
${}^1s^*$ = excited singlet state sensitizer
${}^3s^*$ = excited triplet state sensitizer
${}^3O_2$ = ground triplet oxygen
${}^1O_2^*$ = excited singlet state oxygen

The sensitizers required to convert triplet oxygen to singlet oxygen are normally found in oils and foods and consist of photosensitive compounds such as chlorophyls and porphyrin containing compounds. Recent work on model systems

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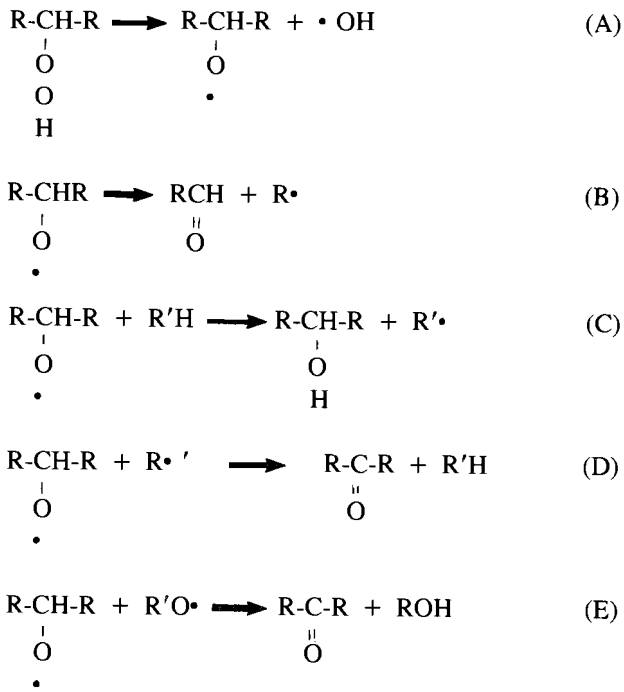
of fatty acids and sensitizers has shown that the hydroperoxide pattern of singlet oxygen is different from that found for autoxidizing lipids (*42,63*), which indicates that the oxidation mechanism is different in the two systems.

The initial reaction products, hydroperoxides, are very unstable and break down to produce many types of secondary reaction products (*34*). The hydroperoxides are degraded by a free radical mechanism which also accelerates the rate of lipid oxidation.

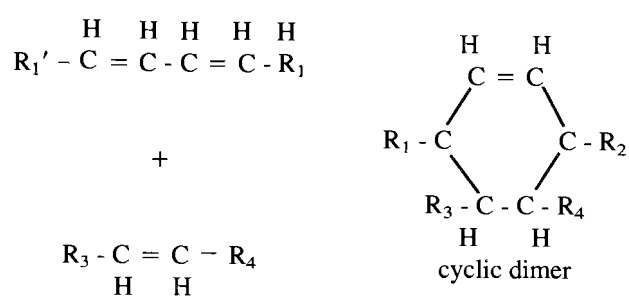


In reaction (A), the hydroperoxide is cleaved to alkoxy and hydroxy free radicals. Reactions (B-E) illustrate the reaction of the alkoxy free radical with other free radicals or compounds to form secondary products which contribute to the flavor or oxidized lipids since hydroperoxides are flavorless (*38*).

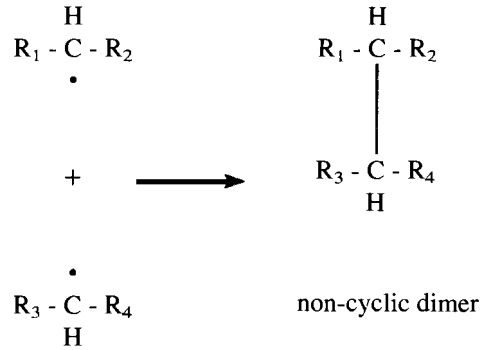
Polymerization

As fats and oil undergo oxidation and heat-stress during the frying operation, polymerization can occur in the oil which leads to changes in molecular weight, viscosity, and heat-transfer efficiency of the oil, and affects the quality of the products fried in it.

Polymers can originate by the Diels-Alder reaction. This reaction involves the olefin group of one fatty acid and a trans-trans-conjugated diene fatty acid. Conjugated diene fatty acid can result from heat or an oxidation reaction (*52*).



Any of the free radicals produced in lipid oxidation can also react to form polymers.



Formation of these cyclic dimers, noncyclic dimers or other polymeric compounds may involve both carbon-carbon and oxygen bonding (*50*). These reactions can occur between free fatty acids, between fatty acids on the same triglyceride or between fatty acids on different triglycerides.

NUTRITIONAL QUALITY OF FRYING FATS

Two approaches have been taken in studies to determine the nutritional quality of frying fats. In some investigations, fats were exposed to oxygen and high temperatures for several hours and then used in animal feeding studies. When fats of this type were fed to rats, their growth rates were reduced and they looked very malnourished (*33,54*). These fats were very unpalatable and in no way were typical of fats used for deep fat frying. Data from studies such as this should in no way be used to determine the effect of use on frying fats and oils.

In feeding studies using fats that were subjected to conditions more typical of frying operations, no obvious difference could be detected in the growth rate of rats fed used or fresh fats. Also no increase in incidence of tumors or other pathological conditions could be detected (*48,49*).

In recent work, Scheutwinkel-Reich et al. (*52*) found that the polar fractions of used frying fats were not mutagenic when subjected to the *Salmonella*/microsome mutagenicity test. The frying fats used in this study were discarded from the catering trade and were no longer used for food preparation. In most instances fats are discarded due to smoking, foaming and strong flavors and odors before public health hazards could develop.

The various biological effects of cholesterol oxidation products and their presence in food are covered in recent reviews (*59,61*). It is suggested that some cholesterol oxides may be the primary cause of atherosclerosis and some may be carcinogenic. Further research is needed to determine if food containing high amounts of cholesterol oxides are hazardous for human consumption.

OXIDATION IN FOOD LIPIDS

Oxidative deterioration of food lipids also occurs during processing and storage, and is one of the major reactions

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leading to deterioration of product quality. Although the reactions are typical of the reactions that occur in frying fats and oils, there are many other types of reactions that may occur due to the complex nature of foods. In this section, various factors that influence lipid oxidation in foods will be discussed.

Prooxidants

Food contain metals, heme compounds and plant pigments such as chlorophyll which act as prooxidants. The heme pigments are responsible for most the catalyzed lipid oxidation in meats (*25,36,56*). Although the catalytic effect of heme proteins is known, there is disagreement on the exact state of the heme iron when this occurs. Several investigators (*24,67*) believe that the oxidized form (Fe^{+++} hematin), which acts by one-electron transfers, is the only catalytic form of the hematin group. Other scientists (*6,62*) believe that hematin compounds initiate chain reactions by forming complexes with lipid hydroperoxides, which decompose into free radicals with no valence change in the iron. It is now known that Fe^{+++} is the most active form for hemoproteins and that Fe^{+++} -heme is more active than free metals (Fe^{+++}). It is most likely that Fe^{+++} -heme activity enhancement is due to the way the porphyrin can bind and orient lipid molecules which facilitates electron transfer to decompose peroxides (*56*). Since porphyrins can photosensitize lipid oxidation by singlet oxygen mechanisms and singlet oxygen has been implicated in autoxidation of hemoglobin (*51,56*), perhaps research along this line cold give some insight into the mechanisms involved in heme-catalysis of lipid oxidation in muscle foods.

Heavy metals, primarily those having two valency states with suitable oxidation-reduction potentials increase the rate of lipid oxidation. They act as electron donors to hydroperoxides to produce free radicals (RO•) (*30*).

$$ROOH + M^{+2} \longrightarrow RO\bullet + M^{+3} + OH^-$$

$$ROOH + M^{+3} \longrightarrow ROO\bullet + M^{+2} + H^+$$

The oxidized metal (M^{+3}) can be converted back to the reduced state ($M+^2$) by reacting with hydroperoxides to form ROO• free radicals. Evidence also exists that metals may be involved in formation of singlet oxygen which can initiate lipid oxidation (*5,27*).

Antioxidants

Natural antioxidants and their synergists in foods include tocopherols, citric acid, ascorbic acid, lecithin, phenolic compounds and vitamin A. Antioxidants prevent lipid oxidation by reacting with free radicals to break the chain reaction by decomposing peroxidesor by complexing with metal catalysts (*15,36*).

Water activity

The effects of water on lipid oxidation have been extensively studied and reviewed (*36,56*). In purified systems, water interferes with decomposition of hydroperoxides by hydrogen bonding with the hydroperoxides at the lipid-water interace (*36,43*). Water (.5-.6 a_w) may accelerate oxidation by solubilizing catalyst or swelling macromolecules to expose catalytic sites. At water activities of .75 - .85 dilution of catalyst may retard oxidation rate(*36*).

Interaction of oxidizing lipids and other food constituents

Aside from producing oxidized flavors in foods, oxidizing lipids are capable of reacting with other food components such as color pigments, vitamins, enzymes, amino acids and proteins. Interactions of oxidizing lipids with proteins have been reviewed recently (*23,41,56*), and these papers provide detailed information on these interactions.

Oxidizing lipids can react with proteins according to either of two reaction schemes (Fig. 2). Protein may react with free radicals or hydroperoxides to form protein free radicals which lead to protein protein crosslinks and protein to lipid crosslinks (*32,55*).

$$ROO\bullet + PH \longrightarrow ROOH + P\bullet$$

$$P\bullet + P\bullet \longrightarrow P - P$$

$$P\bullet + P\bullet + P\bullet \longrightarrow P - P - P\bullet$$

$$R\bullet OO\bullet + P\bullet \longrightarrow ROO - P\bullet$$

L = lipid, P = protein

Roubal and Tappel (*55*) reported that oxidizing lipids can cause destruction, in varying degree, of individual amino acids including arginine, phenylalanine, serine, glutamic acid, methionine, tyrosine and threonine.

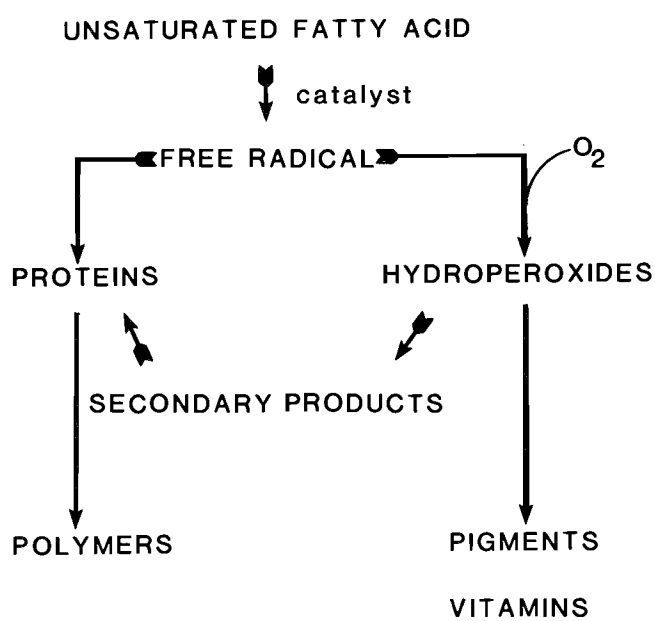

Figure 2. *Reaction initiated by lipid oxidation* (32).

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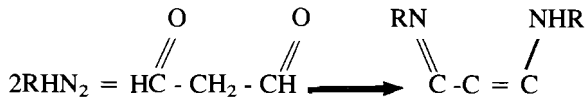
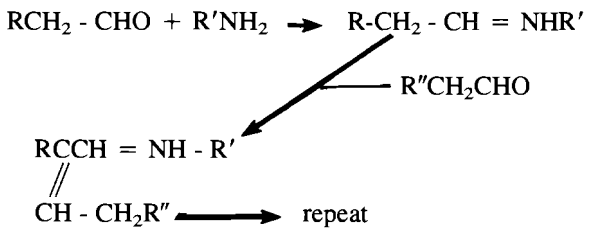
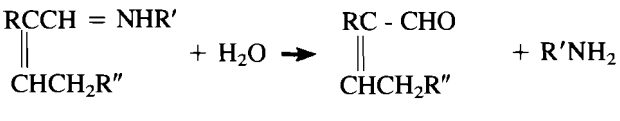
The second type of reaction involving oxidizing lipids and proteins involves the reaction of secondary reaction products with proteins. Malonaldehyde, a secondary product of lipid oxidation, causes cross-linking between two free amino groups by forming a Schiff base conjungate between malonaldehyde and two amino groups (*11*).



Methionine, lysine, tryrosine, arginine and histidine residues were partially damaged when myosin was incubated with malonaldehyde (*7*). Various aldehydes are scission products of lipid hydroperoxides (*40*). Since they react with proteins, their presence in foods is important to flavor and quality. The aldehydes can react with amines to form aldehyde-Schiff bases which can undergo nonenzymatic browning by reacting with other aldehydes by an aldol condensation reaction (*45*).



Montgomery and Day (*45*) found that 2-alkenals were produced from a mixture of heptanal and tyrosine ethyl ester. They suggested that the 2-alkenals were formed from the aldol condensation products.



Even though oxidizing lipids are especially damaging to three limiting amino acids, cystine, methionine and trypthophan, it was concluded in a recent review (*17*) that oxidizing lipids do less nutritive damage to proteins than carbohydrates do in the Maillard reaction.

It is obvious from this review that numerous reactions involving lipids can occur when foods are processed and stored. In most instances, however, the major concern is destruction of flavor or color since these defects are apparent before known nutritional damaging reactions occur.

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