

# Biological Availability of Nutrients in Processed Foods

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Deterioration of foods and raw agricultural products which can be converted into foods is primarily the result of microbial growth, enzymatic deterioration, and chemical changes that occur after harvest or slaughter. Food scientists and technologists have utilized dehydration, high and low temperature processing, chemicals, and radiation to inhibit these deteriorative reactions and protect our food supply.

Thermal processing is one of the most common and effective methods of food preservation and is used alone and in combination with other preservation techniques. The principal effect of thermal processing is protein denaturation, resulting in the destruction of microorganisms and the inactivation of microbial and native deteriorative enzymes in a food.

Most people think of processing as being only detrimental to the nutritional value of foods because of the potential destruction of a food's proteins, lipids, and vitamins. However, thermal processing can be beneficial and is required if we are to maintain a safe, wholesome, and nutritious food supply and obtain the maximum nutritive value of some foods.

The nutritive value of many foods is increased by the thermal destruction of toxic proteins and peptides, enzyme inhibitors, antivitamins, and other natural toxicants in foods which seriously affect their nutritive value. Numerous researchers have shown that, in order to obtain the highest nutritive value of legumes, proper heat treatment is required to destroy naturally occurring trypsin inhibitors, hemagglutinin, and other toxic substances present in legumes. Heat treatment also improves the digestibility and availability of the sulfur amino acids of plant proteins (1–3).

The nutritive value of plant proteins has been the subject of a great deal of research since these foods are an important dietary source of protein for many segments of the world's population, and naturally occurring toxicants are more commonly associated with plant than animal foods.

## Proteins

Heat damage of proteins results from the destruction of amino acids within a protein, reactions of proteins with non-protein components in a food or food system, or by inter- and intra-protein reactions in the presence or absence of oxygen (4). Studies concerning changes in amino acid content of pure protein preparations as a function of temperature and time have shown that tryptophan, methionine, cystine, basic amino acids, and  $\beta$ -hydroxy amino acids are readily destroyed as compared with acidic and neutral amino acids in pure casein or lysozyme preparations (5). Cysteine is heat labile and readily destroyed at temperatures only slightly above 100°C, which is representative of lower commercial processing temperatures. At higher temperatures, 115–145°C, other sulfur compounds, including hydrogen sulfide, methylmercaptan, dimethylsulfide, and dimethyldisulfide have been identified as destruction products of sulfur-containing amino acids (6).

Although various researchers have reported losses in the amino acid pattern of a protein as a result of thermal destruction of amino acids, these losses are not considered to be important because of the large quantity of protein and the variety of foods consumed by Americans. Normally, changes affecting the bioavailability of amino acids override the small

changes in composition that affect the nutritive value of proteins.

As pointed out in an excellent review by Ford (7), one of the most important factors associated with the loss of the nutritional value of proteins is the formation of new linkages within and between protein molecules. These reactions, which cause restructuring of protein molecules, indirectly affect the nutritional value of the protein by changing the rate or extent of enzymatic hydrolysis, which impairs digestibility. These reactions affect the availability of amino acids at the specific site of enzymatic cleavage as well as the availability of adjacent amino acids.

Early studies by Mecham and Olcott (8) reported marked losses of amino nitrogen, decreased solubility, and low digestibility, which were attributed to the formation of internal amide and ester linkages in the heat-treated protein. More recently, Bjarnason and Carpenter (6) and Mauron (7) have reported the involvement of aspartic or glutamic acids and hydroxyl amino acids, thioester linkages between dicarboxylic acids and cystine, and internal bonds between asparagine or glutamine and aspartic or glutamic acids, as well as other intermolecular reactions and their effect on amino acid availability from heat-treated proteins. Strong evidence also exists for inactivation of lysine by interaction of its  $\epsilon$ -amino group with asparagine or glutamine, resulting in intra- or intermolecular linkages between protein molecules (6).

The nutritional value of proteins is also affected by the direct loss of amino acids and decreased digestibility through the interactions of amino acids with non-nitrogen-containing compounds. Nonenzymatic browning (Maillard browning) is of particular importance because of the interaction of free amino groups of proteins with free carbonyl groups associated with reducing sugars or secondary degradation products from lipid oxidation (10). The complexity and involvement of nonenzymatic browning in food systems are as yet not completely understood, and the interested reader is directed to numerous research and review articles (11–13). The interaction of lysine and free carbonyl groups of reducing sugars or lipid oxidation products is one of the most thoroughly studied reactions involving the loss of nutritional value of proteins by nonenzymatic browning. Research (14) has shown that the enzyme trypsin does not hydrolyze peptide linkages of lysine units if the  $\epsilon$ -amino group is blocked through the addition of a free carbonyl group.

Numerous researchers have reported losses in nutritional value of proteins heated in the presence of carbohydrates (15–17). In all these studies, protein efficiency ratios (PER) were affected by roasting, baking, toasting, and drying. The involvement of lysine in the loss of PER was confirmed by supplementing the diets of test animals with lysine, which resulted in normal growth response. Using multiple substitution of amino acids into the PER assay, several researchers (4, 18, 19) have clearly demonstrated that the availability of methionine, cystine, tryptophan, and arginine is also affected by the browning reaction, the length and temperature of processing, moisture content, presence of reducing substances, moisture, and pH (4, 9, 13, 20). These studies reported that the biological value of a protein can be decreased by as much as 50% to 80%, depending upon the severity of the process.

The nutritional value of proteins can also be affected through the formation of amino acid complexes such as lysinoalanine (21). Lysinoalanine has been associated with decreased protein availability and is considered a factor in the reduction of the nutritional value of heated proteins (22, 23).

Of the other methods of food processing, dehydration is the only one which can significantly affect the biological availability of proteins. Since dehydration is a combination of heat and concentration, this process can lead to a significant loss in protein availability through inter- and intra-amino acid reactions, browning reactions, and formation of amino acid complexes. The extent of the loss of protein availability is dependent upon the rate of dehydration, final moisture content and water activity, and the final drying temperature of the food product.

## Carbohydrates

The retention or destruction of carbohydrates during food processing is not generally of concern. Monosaccharides, and to some extent oligosaccharides and polysaccharides, may be lost as a result of leaching during processing. The extent of these losses, however, is insignificant with respect to the total carbohydrate present. In fact, the effect of processing on the bioavailability of carbohydrates is more beneficial than detrimental. It is well known that heat processing of polysaccharides in an aqueous or moist environment results in increased digestibility. This increase is the result of swelling and rupture of hydrogen bonds within the polysaccharide molecules, which permit greater enzymatic digestion by amylases in salivary juices and the gut.

Mono- and disaccharides can, under certain processing conditions, undergo significant loss in biological availability as a result of physical or chemical reactions. Significant losses of low molecular weight carbohydrates can result from leaching during processing. Mono- and disaccharides when dissolved in an aqueous medium and subjected to thermal processing also may undergo polymerization reactions as a result of caramelization, nonenzymatic browning, or a reaction with free amino groups (Maillard browning), which will alter their biological availability.

Monosaccharides in food systems can undergo many transformations during thermal processing, particularly in the presence of acid and alkali. Even at neutral pH, simple sugars are subject to degradation and epimerization reactions at temperatures commonly used in processing foods. Hydroxymethyl furfural is considered the most important of the more than 100 compounds identified from severely heated glucose and fructose solutions because of its known toxicity at high levels (24).

Processing by dehydration can also lead to loss of bioavailability of carbohydrates. Pyrolysis of starch can occur when the starch is subjected to dry heat at temperatures of 200°C or greater resulting in the formation of amulose and amulopectins, which can in turn, lead to the formation of dextrins and volatile components such as furfural and hydroxymethyl furfural (25).

## Lipids

Deteriorative changes that occur in lipids in food systems as a result of processing may be lipolytic, oxidative, or polymeric in nature resulting in modification of the physical and chemical properties of the lipids as well as their biological properties. Researchers have reported lower energy values, alteration of enzyme systems, lower weight gains and growth rates, nutrient deficiency symptoms, and, in some instances, toxic effects, following ingestion of deteriorated lipids at various dose rates (26).

The most commonly used term to describe the deterioration

of lipids in food systems is rancidity. Two distinct mechanisms are associated with this term. The first is the hydrolysis of fatty acids esterified to the glycerol molecule. The second is the direct attack of oxygen on unsaturated fatty acids in triglycerides and phospholipids to form hydroperoxides and secondary oxidation products.

Hydrolytic rancidity is catalyzed in food products by processing at high temperatures and pressures in an aqueous medium in the presence of acid, alkali, or lipases. The products of this reaction are monoglycerides, diglycerides, and free fatty acids. Hydrolytic rancidity, per se, does not significantly affect the nutritional value of the food, because the reaction involves only the cleavage of the fatty acids from the glycerol molecule. Its primary effect is the objectional flavor imparted to the food by the free fatty acids, which results in lower consumption of the affected food.

Oxidative destruction of lipids is the second type of rancidity. It is probably the one deteriorative mechanism responsible for more losses in quality and nutritional value than any other. Without reviewing the complicated mechanisms by which oxidation proceeds, it is sufficient for our purposes to know that oxidation of unsaturated lipids is a chain reaction and once initiated cannot be stopped until one of the reactant species, namely oxygen or unsaturated fatty acids, has been exhausted. Even the presence of antioxidants will not inhibit oxidation once it has been initiated. Antioxidants, however, will slow down the rate and lengthen the induction period of the reaction, which are a function of temperature, irradiation, light, transition metals, increased surface-volume ratio, the number of double bonds in the unsaturated fatty acid, and the presence of preformed hydroperoxides.

The principal effect of lipid oxidation on the nutritional quality of foods is the destruction of the essential fatty acids, linoleic and linolenic, which is favored because of their unsaturated nature. At the same time, destruction of other unsaturated lipids, such as carotenes, vitamin A, and tocopherols can further reduce the nutrient level of foods.

A second effect of lipid oxidation is the development of off-flavors, which renders foods less palatable. Numerous researchers have (26) shown that animals fed oxidized lipids show reduced growth rates and weight gains. Five mechanisms have been proposed to explain the reduced growth: (1) reduced intake due to decreased palatability; (2) destruction of vitamins, either in the ration or in the gut; (3) irritation of the intestinal mucosa by peroxides causing decreased absorption; (4) decreased absorption resulting from the formation of nonabsorbable polymers, and (5) decreased protein absorption due to cross-linking interactions of proteins with secondary lipid oxidation products.

Thermally processed or oxidized lipids can further affect the bioavailability of lipids and lipid-soluble vitamins by the formation of nonabsorbable polymers. The presence of oxidized and thermally abused lipids has been shown to be antagonistic to thiamin, ascorbic acid, calcium pantothenate, riboflavin, tocopherol, vitamin A, vitamin B<sub>12</sub>, proteins, lysine, and the sulfur-containing amino acids (27). Investigations by Crawford et al. have shown that lipid oxidation products bind to proteins through hydrogen bonding and interactions with malonaldehyde (28). This cross-linking of protein molecules is important because it alters digestibility and thus bioavailability of amino acids.

## Vitamins

The extent of vitamin loss during the processing of foods is primarily a function of temperature, time, pH, moisture content, water activity, and oxygen concentration. Thermal processing has the most destructive effect on vitamins in foods. Since the extent of thermal destruction is a time/temperature relationship, processes which subject products to high temperatures for short periods of time or which result in

an evaporative cooling effect usually cause the least vitamin loss. Processes such as blanching, freezing, and pasteurization normally have a minimal effect on vitamin destruction, but can reach levels as high as 90% of a particular nutrient (e.g., ascorbic acid) depending on the processing conditions. Preservation by refrigeration or freezing is generally regarded as the best method of long-term preservation when judged on retention of sensory attributes and nutrients. Loss of vitamins is generally not considered significant as a result of these processes if proper packaging and freezing procedures are used, such as 10°C in a gas-impermeable package (29, 30).

Variable losses (0–40%) of water-soluble vitamins in frozen foods can occur during thawing as a result of drip loss or thaw exudate. These losses are a function of the initial rate of freezing and subsequent storage conditions of the frozen product. Fat-soluble vitamins are not generally affected by refrigeration or freezing per se, but may be destroyed in significant amounts during frozen storage if product is exposed to oxygen through improper packaging. Freeze concentration can play a very important role because of the increased concentration of reactant species. Vitamin losses are associated primarily with nutrients that are subject to oxidative deterioration.

Preservation by dehydration can also cause destruction and loss of bioavailability of vitamins in foods. During all of the predehydration processes (washing, trimming, blanching, pasteurization, and/or concentration), vitamin losses from 10 to 50% can occur. In all of the many methods of commercial dehydration, heat is used to drive water molecules from the food. The final drying temperature, concentration, and the physicochemical characteristics of the concentrated foods are the important factors in the rate of nutrient destruction.

Destruction of water-soluble vitamins is considered separately from fat-soluble vitamins in dehydrated food, because of the different deteriorative mechanisms. Ascorbic acid is the most labile water-soluble vitamin in dehydrated foods. It is rapidly destroyed by heat and oxidative mechanisms at the pH range characteristic of most foods (31). Thiamin stability can also be a special problem in dehydrated foods because of the use of sulfites to prevent browning in fruits and vegetables. Sulfite is known to cause the cleavage of thiamin, and subsequent dehydration of sulfite-treated foods can result in further loss of the remaining thiamin (32). However, the sensitivity of thiamin to sulfite is pH dependent and, if the pH is low enough to prevent ionization of sulfuric acid to the bisulfite ion, thiamin is stable. The loss of thiamin in non-sulfite-treated foods show losses of from 5 to 20% (33–35).

Data for other B-complex vitamins are not as readily available. Hein and Hutchings reported losses of less than 10% for riboflavin, niacin, and pantothenic acid in various air-dried vegetables after blanching (34). In commercially spray-dried milk, which is representative of nonfat dry milk commonly used as a beverage, losses were shown for thiamin, riboflavin, niacin, pantothenic acid, and vitamin B<sub>6</sub> of less than 10%. Biotin and vitamin B<sub>12</sub> losses in dried milk were reported at 15 and 35%, respectively (34).

Deterioration of fat-soluble vitamins follow reaction mechanisms associated with lipid oxidation, and the rate and amount of destruction is dependent upon factors associated with lipid oxidation, which have been discussed previously. Of the fat-soluble vitamins, A, E, and the carotenes (pro-vitamin A) are affected by food processing to varying degrees and the quantitative effect is product and process specific. Both vitamin A and carotenes exhibit maximum biological activity in the trans configuration. Thus, any physical or chemical factor such as heat or oxidation that can cause a shift from the trans isomer to the cis isomer seriously affects the biological activity of these compounds. Limited data are available on losses of vitamin E. Because of its natural antioxidant properties, the stability of vitamin E is dependent upon the oxidative conditions of the process.

## Bioavailability of Vitamins

Current evidence would indicate that the bioavailability of vitamins in food following processing will vary considerably as a function of processing, package atmosphere, moisture content, water activity, oxygen concentration, and storage temperature. Previous studies in model systems and selected foods indicate that the bioavailability of ascorbic acid, thiamin, riboflavin, and niacin would be equivalent to the level of each of these nutrients determined by chemical or microbiological assay methods. However, the bioavailability of selected water soluble vitamins may be affected by the presence or absence of other nutrients, as is the case with iron and ascorbic acid.

The bioavailability of folacin and vitamin B<sub>6</sub> have been more extensively studied than many of the other B complex vitamins and conflicting data have been reported. The availability of folacin has been shown to be a function of the form of folacin in the food, and several factors have been suggested as possibly influencing the bioavailability of folacin in foods. Dietary fiber, which may retard absorption by ionic bonding, adsorption, or entrapment, and dietary factors that affect conjugase activity have been suggested as factors responsible for the reduced availability of folacin in foods (36).

Studies concerning the bioavailability of vitamin B<sub>6</sub> have been more extensive, although the results have not always been less confusing than for folacin. The bioavailability of B<sub>6</sub> is dependent upon the form of the vitamin present in a food: pyridoxal, pyridoxamine or pyridoxine, and their phosphorylated forms (37).

In meats, the effect of cooking on the bioavailability of B<sub>6</sub> were examined using *S. uvarum* and the rat growth bioassay. The data suggest little or no effect of cooking on bioavailability, while data from long-term storage studies are inconsistent and of little value. Similar data are available concerning the bioavailability of B<sub>6</sub> in cooked vegetables and legumes.

In low-moisture foods, including ready-to-eat cereals, data indicate that the bioavailability of the B<sub>6</sub> in the dehydrated product may decrease 18 to 44%, as indicated by rat growth, feed efficiency, liver pyridoxal phosphate, and erythrocyte aspartate transaminase activity. On the other hand, the bioavailability of B<sub>6</sub> in nonfat dry milk was found to be fully available by the rat assay. These data indicate that the bioavailability of B<sub>6</sub> varies widely. Food processing and storage exert variable effects on B<sub>6</sub> bioavailability, probably as a function of B<sub>6</sub>-vitamer distribution, food composition, and conditions of storage (38).

Long term storage can affect the bioavailability of B<sub>6</sub> in foods. Factors affecting bioavailability include: sequestering or entrapment of B<sub>6</sub> vitamers by dietary fiber components, formation of B<sub>6</sub> antagonists, and structural analogues or compounds such as hydrozines, hydroxylamines, and semicarbazides, which complex with pyridoxal and pyridoxal phosphate to form inhibitory products. Numerous researchers have also postulated the interaction of B<sub>6</sub> vitamers with proteins, amino acids, or reducing sugars to form complexes of limited activity or availability. Further research, however, is required to fully assess the bioavailability of B<sub>6</sub> in human diets (39).

Biological availability of fat-soluble vitamins have not been extensively studied. Data available indicate that if the vitamin does not undergo oxidative deterioration or isomerization during storage it would be biologically available. One factor which could affect absorption of fat-soluble vitamins would be the amount of lipid polymerization that may have occurred in the food system and would affect lipid uptake, including fat-soluble vitamins.

## Minerals

It can be generally stated that the stability and availability of minerals in foods is affected less by processing than other

macro- and micronutrients within a food. In many instances processing increases the availability of minerals by increasing the digestibility of a food. Chemical processes, such as acidification, can increase the solubility of mineral complexes making selected metal ions more available.

Losses associated with the processing of foods are normally associated with leaching or with forming insoluble metal complexes, which decreases absorption. The availability of minerals associated with proteins is not significantly altered by thermal processing, unless serious thermal destruction of protein occurs.

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