

# Fennema's Food Chemistry

## *Fourth Edition*



CRC Press  
Taylor & Francis Group

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edited by  
Srinivasan Damodaran  
Kirk L. Parkin  
Owen R. Fennema

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# Preface

Another decade has past since the publication of the third edition of *Food Chemistry*, and given the rapid progress in biological research, an update is warranted. However, this fourth edition marks several transitions. Perhaps, most important is the recognition of Owen Fennema's contributions to this text and to the field of food chemistry in general. His timely introduction of the first edition of *Food Chemistry* over 30 years ago, in 1976, filled a long-standing void of a comprehensive text that could serve as both an instructional tool and a desk reference for professionals. To us, it seems only fitting to now recognize this text as *Fennema's Food Chemistry*, as a tribute to his long-lasting contributions to the field through the three previous editions of this text.

Since professor Fennema's "retirement" in 1996, he has remained professionally active, while engaging in more earthly pursuits of global travel, craftsmanship with wood, and stained glass artisanship. While he has been active with the planning of this edition as a coeditor, he entrusted us to assume most of the day-to-day editorial responsibilities. We are humbled, and needless to say that given the high standards set by professor Fennema in the previous editions, we are cognizant of the lofty expectations that likely exist for the fourth edition. Professor Fennema is a hard act to follow, and we hope our effort will not disappoint.

This edition not only marks a transition in editorial responsibilities, but also in contributing authors, as several former authors have retired or are approaching retirement. New (co)contributors appear for chapters on "Water and Ice," "Carbohydrates," "Lipids," "Enzymes," and "Colorants." Some chapters have also evolved in terms of focus and include "Postmortem Physiology of Edible Muscle Tissues," "Postharvest Physiology of Edible Plant Tissues," "Bioactive Substances: Nutraceuticals and Toxicants" (formerly "Toxic Substances"), and "Physical and Chemical Interactions of Components in Food Systems" (formerly "Summary: Integrative Concepts"), all with new (co)contributors. An added chapter appears on "Impact of Biotechnology on Food Supply and Quality."

We are indebted to the contributing authors of this volume for their patience and professionalism in dealing with new editors and for paying serious attention to the needs for chapter updates. It is hoped that both new and faithful readers of this text will find it useful, and be constructive by directing any comments regarding the content of this book (as well as identifying inevitable printing errors) to our attention.

**Srinivasan Damodaran and Kirk Parkin**

*Madison, Wisconsin, USA*

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# Editors

**Owen R. Fennema** is a professor of food chemistry in the Department of Food Science at the University of Wisconsin-Madison. He is coauthor of the books *Low Temperature Foods and Living Matter* (with William D. Powrie and Elmer H. Marth) and *Principles of Food Science, Part II: Physical Principles of Food Preservation* (with Marcus Karel and Daryl B. Lund), both titles published by Marcel Dekker, Inc., and the author or coauthor of over 175 professional papers that reflect his research interests in food chemistry, low-temperature preservation of food and biological matter, the characteristics of water and ice, edible films and coatings, and lipid-fiber interactions. A consulting editor for the *Food Science and Technology* series (Marcel Dekker, Inc.), he is a fellow of the Institute of Food Technologists and of the Agriculture and Food Chemistry Division of the American Chemical Society, and a member of the American Institute of Nutrition, among other organizations. Dr. Fennema received the BS degree (1950) in agriculture from Kansas State University, Manhattan, the MS degree (1951) in dairy science, and PhD degree (1960) in food science and biochemistry from the University of Wisconsin-Madison.

**Srinivasan Damodaran** is a professor of food chemistry and chair of the Department of Food Science at the University of Wisconsin-Madison. He is editor of the book *Food Proteins and Lipids* (Plenum Press) and co-editor of the book *Food Proteins and Their Applications* (with Alain Paraf) (Marcel Dekker, Inc.) and the author/coauthor of 6 patents and over 125 professional papers in his research areas, which include protein chemistry, enzymology, surface and colloidal science, process technologies, and industrial biodegradable polymers. He is a fellow of the Agriculture and Food Chemistry Division of the American Chemical Society and a member of the Institute of Food Science and the American Oil Chemists Society. He is on the editorial board of *Food Biophysics* journal. Dr. Srinivasan Damodaran received his BSc degree (1971) in chemistry from University of Madras, Madras, India, the MSc degree (1975) in food technology from Mysore University, Mysore, India, and PhD degree (1981) from Cornell University, Ithaca, New York.

**Kirk L. Parkin** is currently professor in the Department of Food Science of the University of Wisconsin (Madison, Wisconsin, USA), where he has been on the faculty for over 21 years. He has been the College of Agricultural and Life Sciences Fritz Friday Chair of Vegetable Processing Research since 1998, and was elected Fellow of the Agriculture and Food Chemistry Division of the American Chemical Society in 2003. Dr. Parkin's research and teaching interests revolve around food chemistry and biochemistry, with about 80 refereed journal publications in the areas of marine food biochemistry, postharvest physiology and processing of fruit and vegetable products, fundamental and applied enzymology, and most recently in the area of characterizing health-promoting and bioactive phytochemicals from foods of botanical origin. At UW-Madison, Dr. Parkin has been an instructor for undergraduate courses in Food Chemistry, Discovery Food Chemistry Laboratory, as well as for graduate courses in Food Enzymes and Lipids. He has supervised the completion of 10 Ph.D and 17 M.S. graduate degree programs, and serves as associate editor for *Journal of Food Science*, and on the editorial board of *Food Research International*, *Food Biochemistry*, and the *Journal of Food Processing and Preservation*.

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# 1 Introduction to Food Chemistry

*Owen R. Fennema, Srinivasan Damodaran, and  
Kirk L. Parkin*

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## 1.1 WHAT IS FOOD CHEMISTRY?

Food science deals with the physical, chemical, and biological properties of foods as they relate to stability, cost, quality, processing, safety, nutritive value, wholesomeness, and convenience. Food science is a branch of biological science and an interdisciplinary subject involving primarily microbiology, chemistry, biology, and engineering. Food chemistry, a major aspect of food science, deals with the composition and properties of food and the chemical changes it undergoes during handling, processing, and storage. Food chemistry is intimately related to chemistry, biochemistry, physiological chemistry, botany, zoology, and molecular biology. The food chemist relies heavily on knowledge of the aforementioned sciences to effectively study and control biological substances as sources of human food. Knowledge of the innate properties of biological substances and mastery of the means of manipulating them are common interests of both food chemists and biological scientists. The primary interests of biological scientists include reproduction, growth, and changes that biological substances undergo under environmental conditions that are compatible or marginally compatible with life. To the contrary, food chemists are concerned primarily with biological substances that are dead or dying (postharvest physiology of plants and postmortem physiology of muscle) and changes they undergo when exposed to a wide range of environmental conditions. For example, conditions suitable for sustaining residual life processes are of concern to food chemists during the marketing of fresh fruits and vegetables, whereas conditions incompatible with life processes are of major interest when long-term preservation of food is attempted. In addition, food chemists are concerned with the chemical properties of disrupted food tissues (flour, fruit and vegetable juices, isolated and modified constituents, and manufactured foods), single-cell sources of food (eggs and microorganisms), and one major biological fluid, milk. In summary, food chemists have much in common with biological scientists, yet they also have interests that are distinctly different and are of the utmost importance to humankind.

## 1.2 HISTORY OF FOOD CHEMISTRY

The origins of food chemistry are obscure, and details of its history have not yet been rigorously studied and recorded. This is not surprising, since food chemistry did not acquire a clear identity until the twentieth century, and its history is deeply entangled with that of agricultural chemistry for which historical documentation is not considered exhaustive [1,2]. Thus, the following brief excursion into the history of food chemistry is incomplete and selective. Nonetheless, available information is sufficient to indicate when, where, and why certain key events in food chemistry occurred and to relate some of these events to major changes in the wholesomeness of the food supply since the early 1800s.

Although the origin of food chemistry, in a sense, extends to antiquity, the most significant discoveries, as we judge them today, began in the late 1700s. The best accounts of developments during this period are those of Filby [3] and Browne [1], and these sources have been relied upon for much of the information presented here.

During the period of 1780–1850 a number of famous chemists made important discoveries, many of which related directly or indirectly to food, and these works contain the origins of modern food chemistry. Carl Wilhelm Scheele (1742–1786), a Swedish pharmacist, was one of the greatest chemists of all time. In addition to his more famous discoveries of chlorine, glycerol, and oxygen (3 years before Priestly, but unpublished), he isolated and studied the properties of lactose (1780), prepared mucic acid by oxidation of lactic acid (1780), devised a means of preserving vinegar by the application of heat (1782, well in advance of Appert's "discovery"), isolated citric acid from lemon juice (1784) and gooseberries (1785), isolated malic acid from apples (1785), and tested 20 common fruits for the presence of citric, malic, and tartaric acids (1785). His isolation of various new chemical compounds from plant and animal substances is considered the beginning of accurate analytical research in agricultural and food chemistry.

The French chemist Antoine Laurent Lavoisier (1743–1794) was instrumental in the final rejection of the phlogiston theory and in formulating the principles of modern chemistry. With respect to food chemistry, he established the fundamental principles of combustion organic analysis, he was the first to show that the process of fermentation could be expressed as a balanced equation, he made the first attempt to determine the elemental composition of alcohol (1784) and he presented one of the first papers (1786) on organic acids of various fruits.

(Nicolas) Théodore de Saussure (1767–1845), a French chemist, did much to formalize and clarify the principles of agricultural and food chemistry provided by Lavoisier. He also studied  $\text{CO}_2$  and  $\text{O}_2$  changes during plant respiration (1804) and the mineral contents of plants by ashing, and made the first accurate elemental analysis of alcohol (1807).

Joseph Louis Gay-Lussac (1778–1850) and Louis-Jacques Thenard (1777–1857) devised in 1811 the first method to determine percentages of carbon, hydrogen, and nitrogen in dry vegetable substances.

The English chemist Sir Humphrey Davy (1778–1829) in the years 1807 and 1808 isolated the elements K, Na, Ba, Sr, Ca, and Mg. His contributions to agricultural and food chemistry came largely through his books on agricultural chemistry, of which the first (1813) was *Elements of Agriculture Chemistry, in a Course of Lectures for the Board of Agriculture* [4]. His books served to organize and clarify knowledge existing at that time. In the first edition he stated,

All the different parts of plants are capable of being decomposed into a few elements. Their uses as food, or for the purpose of the arts, depend upon compound arrangements of these elements, which are capable of being produced either from their organized parts, or from the juices they contain; and the examination of the nature of these substances is an essential part of agricultural chemistry.

In the fifth edition he stated that plants are usually composed of only seven or eight elements, and that [5] "the most essential vegetable substances consist of hydrogen, carbon, and oxygen in different proportion, generally alone, but in some few cases combined with azote [nitrogen]" (p. 121).



The works of the Swedish chemist Jons Jacob Berzelius (1779–1848) and the Scottish chemist Thomas Thomson (1773–1852) resulted in the beginnings of organic formulas, “without which organic analysis would be a trackless desert and food analysis an endless task” [3]. Berzelius determined the elemental components of about 2000 compounds, thereby verifying the law of definite proportions. He also devised a means of accurately determining the water content of organic substances, a deficiency in the method of Gay-Lussac and Thenard. Moreover, Thomson showed that laws governing the composition of inorganic substances apply equally well to organic substances, a point of immense importance.

In a book entitled *Considérations générales sur l'analyse organique et sur ses applications* [6], Michel Eugene Chevreul (1786–1889), a French chemist, listed the elements known to exist at that time in organic substances (O, Cl, I, N, S, P, C, Si, H, Al, Mg, Ca, Na, K, Mn, and Fe) and cited the processes then available for organic analysis: (1) extraction with a neutral solvent, such as water, alcohol, or aqueous ether; (2) slow distillation or fractional distillation; (3) steam distillation; (4) passing the substance through a tube heated to incandescence; and (5) analysis with oxygen. Chevreul was a pioneer in the analysis of organic substances, and his classic research on the composition of animal fat led to the discovery and naming of stearic and oleic acids.

Dr. William Beaumont (1785–1853), an American Army surgeon stationed at Fort Mackinac, MI, performed classic experiments on gastric digestion that destroyed the concept existing from the time of Hippocrates that food contained a single nutritive component. His experiments were performed during the period 1825–1833 on a Canadian, Alexis St. Martin, whose musket wound afforded direct access to the stomach interior, thereby enabling food to be introduced and subsequently examined for digestive changes [7].

Among his many notable accomplishments, Justus von Liebig (1803–1873) showed in 1837 that acetaldehyde occurs as an intermediate between alcohol and acetic acid during fermentation of vinegar. In 1842, he classified foods as either nitrogenous (vegetable fibrin, albumin, casein, and animal flesh and blood) or nonnitrogenous (fats, carbohydrates, and alcoholic beverages). Although this classification is not correct in several respects, it served to distinguish important differences among various foods. He also perfected methods for the quantitative analysis of organic substances, especially by combustion, and he published in 1847 what is apparently the first book on food chemistry, *Researches on the Chemistry of Food* [8]. Included in this book are accounts of his research on the water-soluble constituents of muscle (creatine, creatinine, sarcosine, inosinic acid, lactic acid, etc.).

It is interesting that the developments just reviewed paralleled the beginning of serious and widespread adulteration of food, and it is no exaggeration to state that the need to detect impurities in food was a major stimulus for the development of analytical chemistry in general and analytical food chemistry in particular. Unfortunately, it is also true that advances in chemistry contributed somewhat to the adulteration of food, since unscrupulous purveyors of food were able to profit from the availability of chemical literature, including formulas for adulterated food, and could replace older, less-effective empirical approaches to food adulteration with more efficient approaches based on scientific principles. Thus, the history of food chemistry and food adulteration are closely interwoven by the threads of several causative relationships, and it is therefore appropriate to consider the matter of food adulteration from a historical perspective [3].

The history of food adulteration in the currently more developed countries of the world falls into three distinct phases. From ancient times to about 1820 food adulteration was not a serious problem and there was little need for methods of detection. The most obvious explanation for this situation was that food was procured from small businesses or individuals and transactions involved a large measure of interpersonal accountability. The second phase began in the early 1800s, when intentional food adulteration increased greatly in both frequency and seriousness. This development can be attributed primarily to increased centralization of food processing and distribution, with a corresponding decline in interpersonal accountability, and partly to the rise of modern chemistry, as already mentioned. Intentional adulteration of food remained a serious problem until

about 1920, which marks the end of phase two and the beginning of phase three. At this point, regulatory pressures and effective methods of detection reduced the frequency and seriousness of intentional food adulteration to acceptable levels, and the situation has gradually improved up to the present time.

Some would argue that a fourth phase of food adulteration began about 1950, when foods containing legal chemical additives became increasingly prevalent, when the use of highly processed foods increased to a point where they represented a major part of the diet of persons in most of the industrialized countries, and when contamination of some foods with undesirable by-products of industrialization, such as mercury, lead, and pesticides, became of public and regulatory concern. The validity of this contention is hotly debated and disagreement persists to this day. Nevertheless, the course of action in the next few years seems clear. Public concern over the safety and nutritional adequacy of the food supply continues to evoke changes, both voluntary and involuntary, in the manner in which foods are produced, handled, and processed, and more such actions are inevitable as we learn more about proper handling practices for food and as estimates of maximum tolerable intake of undesirable constituents become more accurate.

The early 1800s was a period of especially intense public concern over the quality and safety of the food supply. This concern, or more properly indignation, was aroused in England by Frederick Accum's publication *A Treatise on Adulterations of Food* [9] and by an anonymous publication entitled *Death in the Pot* [10]. Accum claimed that "Indeed, it would be difficult to mention a single article of food which is not to be met with in an adulterated state; and there are some substances which are scarcely ever to be procured genuine" (p. 14). He further remarked, "It is not less lamentable that the extensive application of chemistry to the useful purposes of life, should have been perverted into an auxiliary to this nefarious traffic [adulteration]" (p. 20).

Although Filby [3] asserted that Accum's accusations were somewhat overstated, it was true that the intentional adulteration of several foods and ingredients prevailed in the 1800s, as cited by Accum and Filby, including annatto, black pepper, cayenne pepper, essential oils, vinegar, lemon juice, coffee, tea, milk, beer, wine, sugar, butter, chocolate, bread, and confectionary products.

Once the seriousness of food adulteration in the early 1800s was made evident to the public, remedial forces gradually increased. These took the form of new legislation to make adulteration unlawful, and greatly expanded efforts by chemists to learn about the native properties of foods, the chemicals commonly used as adulterants, and the means of detecting them. Thus, during the period 1820–1850, chemistry and food chemistry began to assume importance in Europe. This was possible because of the work of the scientists already cited, and was stimulated largely by the establishment of chemical research laboratories for young students in various universities and by the founding of new journals for chemical research [1]. Since then, advances in food chemistry have continued at an accelerated pace, and some of these advances, along with causative factors, are mentioned below.

In 1860, the first publicly supported agriculture experiment station was established in Weede, Germany, and W. Hanneberg and F. Stohmann were appointed director and chemist, respectively. Based largely on the work of earlier chemists, they developed an important procedure for the routine determination of major constituents in food. By dividing a given sample into several portions they were able to determine moisture content, "crude fat," ash, and nitrogen. Then, by multiplying the nitrogen value by 6.25, they arrived at its protein content. Sequential digestion with dilute acid and dilute alkali yielded a residue termed "crude fiber." The portion remaining after removal of protein, fat, ash, and crude fiber was termed "nitrogen-free extract," and this was believed to represent utilizable carbohydrate. Unfortunately, for many years chemists and physiologists wrongfully assumed that like values obtained by this procedure represented like nutritive value, regardless of the kind of food [11].

In 1871, Jean Baptiste Duman (1800–1884) suggested that a diet consisting of only protein, carbohydrate, and fat was inadequate to support life.

In 1862, the Congress of the United States passed the Land-Grant College Act, authored by Justin Smith Morrill. This act helped establish colleges of agriculture in the United States and provided

considerable impetus for the training of agricultural and food chemists. Also in 1862, the U.S. Department of Agriculture was established and Isaac Newton was appointed the first commissioner.

In 1863, Harvey Washington Wiley became chief chemist of the U.S. Department of Agriculture, from which office he led the campaign against misbranded and adulterated food, culminating in passage of the first Pure Food and Drug Act in the United States (1906).

In 1887, agriculture experiment stations were established in the United States following enactment of the Hatch Act. Representative William H. Hatch of Missouri, Chairman of the House Committee on Agriculture, was author of the act. As a result, the world's largest national system of agriculture experiment stations came into existence and this had a great impact on food research in the United States.

During the first half of the twentieth century, most of the essential dietary substances were discovered and characterized, namely, vitamins, minerals, fatty acids, and some amino acids.

The development and extensive use of chemicals to aid in the growth, manufacture, and marketing of foods was an especially noteworthy and contentious event in the mid-1900s.

This historical review, although brief, makes the current food supply seem almost perfect in comparison to that which existed in the 1800s. However, at this writing, several current issues have replaced the historical ones in terms of what the food science community must address in further promoting the wholesomeness and nutritive value of foods, while mitigating the real or perceived threats to the safety of the food supply. These issues include the nature, efficacy, and impact of nonnutrient components in foods, dietary supplements, and botanicals that can promote human health beyond simple nutrition (Chapter 12); molecular engineering of crops (genetically modified organisms or GMOs) and the benefits juxtaposed against the perceived risks to safety and human health (Chapter 18); and the comparative nutritive value of crops raised by organic vs. conventional agricultural methods.

### 1.3 APPROACH TO THE STUDY OF FOOD CHEMISTRY

Food chemists are typically concerned with identifying the molecular determinants of material properties and chemical reactivity of food matrices, and how this understanding is effectively applied to improve formulation, processing, and storage stability of foods. An ultimate objective is to determine cause-and-effect and structure–function relationships among different classes of chemical components. The facts derived from the study of one food or model system can be applied to our understanding of other food products. An analytical approach to food chemistry includes four components, namely: (1) determining those properties that are important characteristics of safe, high-quality foods; (2) determining those chemical and biochemical reactions that have important influences on loss of quality and/or wholesomeness of foods; (3) integrating the first two points so that one understands how the key chemical and biochemical reactions influence quality and safety; and (4) applying this understanding to various situations encountered during formulation, processing, and storage of food.

Safety is the first requisite of any food. In a broad sense, this means a food must be free of any harmful chemical or microbial contaminant at the time of its consumption. For operational purposes this definition takes on a more applied form. In the canning industry, “commercial” sterility as applied to low-acid foods means the absence of viable spores of *Clostridium botulinum*. This in turn can be translated into a specific set of heating conditions for a specific product in a specific package. Given these heating requirements, one can then select specific time–temperature conditions that will optimize retention of quality attributes. Similarly, in a product such as peanut butter, operational safety can be regarded primarily as the absence of aflatoxins—carcinogenic substances produced by certain species of molds. Steps taken to prevent growth of the mold in question may or may not interfere with retention of some other quality attribute; nevertheless, conditions producing a safe product must be employed.

A list of quality attributes of food and some alterations they can undergo during processing and storage is given in Table 1.1. The changes that can occur, with the exception of those involving nutritive value and safety, are readily evident to the consumer.

Many chemical and biochemical reactions can alter food quality or safety. Some of the more important classes of these reactions are listed in Table 1.2. Each reaction class can involve different reactants or substrates depending on the specific food and the particular conditions for handling,

**TABLE 1.1**  
**Classification of Alterations That Can Occur During Handling, Processing, or Storage**

Attribute	Alteration
Texture	Loss of solubility
	Loss of water-holding capacity
	Toughening
	Softening
Flavor	Development of
	rancidity (hydrolytic or oxidative)
	cooked or caramel flavors
	other off-flavors
Color	Development of desirable colors (e.g., browning of baked goods)
	Darkening
	Bleaching
	Development of desirable colors (e.g., browning of baked goods)
Nutritive value	Loss, degradation, or altered bioavailability of proteins, lipids, vitamins, minerals, and other health-promoting components
Safety	Generation of toxic substances
	Development of substances that are protective to health
	Inactivation of toxic substances

**TABLE 1.2**  
**Some Chemical and Biochemical Reactions That Can Lead to Alteration of Food Quality or Safety**

Types of Reaction	Examples
Nonenzymic browning	Baked goods, dry, and intermediate moisture foods
Enzymic browning	Cut fruits and some vegetables
Oxidation	Lipids (off-flavors), vitamin degradation, pigment decoloration, proteins (loss of nutritive value)
Hydrolysis	Lipids, proteins, vitamins, carbohydrates, pigments
Metal interactions	Complexation (anthocyanins), loss of Mg from chlorophyll, catalysis of oxidation
Lipid isomerization	<i>cis</i> → <i>trans</i> isomerization, nonconjugated → conjugated
Lipid cyclization	Monocyclic fatty acids
Lipid oxidation–polymerization	Foaming during deep-fat frying
Protein denaturation	Egg white coagulation, enzyme inactivation
Protein crosslinking	Loss of nutritive value during alkali processing
Polysaccharide synthesis and degradation	In plants postharvest
Glycolytic changes	Animal postmortem, plant tissue postharvest

**TABLE 1.3**  
**Examples of Cause-and-Effects Relationships Pertaining to Food Alteration During Handling, Storage, and Processing**

Primary Causative Event	Secondary Event	Attribute Influenced (see Table 1.1)
Hydrolysis of lipids	Free fatty acids react with protein	Texture, flavor, nutritive value
Hydrolysis of polysaccharides	Sugars react with protein	Texture, flavor, color, nutritive value
Oxidation of lipids	Oxidation products react with many other constituents	Texture, flavor, color, nutritive value; toxic substances can be generated
Bruising of fruit	Cells break, enzymes are released, oxygen accessible	Texture, flavor, color, nutritive value
Heating of horticultural products	Cell walls and membranes lose integrity, acids are released, enzymes become inactive	Texture, flavor, color, nutritive value
Heating of muscle tissue	Proteins denature and aggregate, enzyme become inactive	Texture, flavor, color, nutritive value
<i>cis</i> → <i>trans</i> conversion in lipids	Enhanced rate of polymerization during deep-fat frying	Excessive foaming during deep-fat frying, diminished nutritive value and bioavailability of lipids, solidification of frying oil

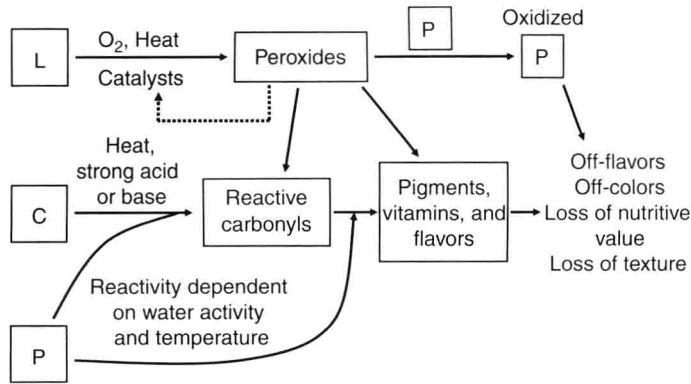
processing, or storage. They are treated as reaction classes because the general nature of the substrates or reactants is similar for all foods. Thus, nonenzymic browning involves reaction of carbonyl compounds, which can arise from existing reducing sugars or from diverse reactions, such as oxidation of ascorbic acid, hydrolysis of starch, or oxidation of lipids. Oxidation may involve lipids, proteins, vitamins, or pigments, and more specifically, oxidation of lipids may involve triacylglycerols in one food or phospholipids in another. Discussion of these reactions in detail will occur in subsequent chapters of this book.

The reactions listed in Table 1.3 cause the alterations listed in Table 1.1. Integration of the information contained in both tables can lead to an understanding of the causes of food deterioration. Deterioration of food usually consists of a series of primary events followed by secondary events, which, in turn, become evident as altered quality attributes (Table 1.1). Examples of sequences of this type are shown in Table 1.3. Note particularly that a given quality attribute can be altered as a result of several different primary events.

The sequences in Table 1.3 can be applied in two directions. Operating from left to right, one can consider a particular primary event, the associated secondary events, and the effect on a quality attribute. Alternatively, one can determine the probable cause(s) of an observed quality change (column 3, Table 1.3) by considering all primary events that could be involved and then isolating, by appropriate chemical tests, the key primary event. The utility of constructing such sequences is that they encourage one to approach problems of food alteration in an analytical manner.

Figure 1.1 is a simplistic summary of reactions and interactions of the major constituents of food. The major cellular pools of carbohydrates, lipids, proteins, and their intermediary metabolites are shown on the left-hand side of the diagram. The exact nature of these pools is dependent on the physiological state of the tissue at the time of processing or storage, and the constituents present in or added to nontissue foods. Each class of compound can undergo its own characteristic type of deterioration. Noteworthy is the role that carbonyl compounds play in many deterioration processes. They arise mainly from lipid oxidation and carbohydrate degradation and can lead to the destruction of nutritional value, to off-colors, and to off-flavors. Of course, these same reactions lead to desirable flavors and colors during the cooking of many foods.





**FIGURE 1.1** Summary of chemical interactions among major food constituents: L, lipid pool (triacylglycerols, fatty acids, and phospholipids); C, carbohydrate pool (polysaccharides, sugars, organic acids, etc.); P, protein pool (proteins, peptides, amino acids, and other N-containing substances).

**TABLE 1.4**  
**Important Factors Governing the Stability of Foods During Handling, Processing, and Storage**

Product Factors	Environmental Factors
Chemical properties of individual constituents (including catalysts), oxygen content, pH water activity, $T_g$ , and $W_g$	Temperature ( $T$ ); time ( $t$ ); composition of the atmosphere; chemical, physical, or biological treatments imposed; exposure to light; contamination; physical abuse

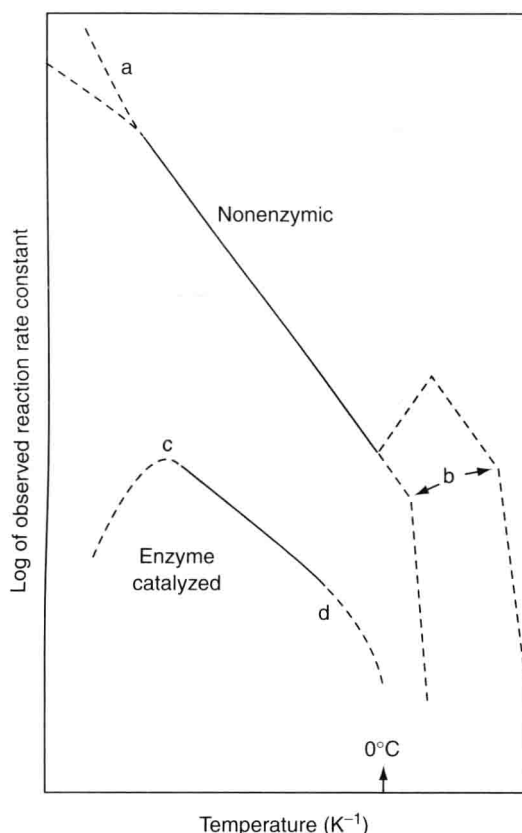
*Note:* Water activity =  $p/p_0$ , where  $p$  is the partial pressure of water vapor above the food and  $p_0$  is the vapor pressure of pure water;  $T_g$  is the glass transition temperature;  $W_g$  is the product water content at  $T_g$ .

**1.3.1 ANALYSIS OF SITUATIONS ENCOUNTERED DURING THE STORAGE AND PROCESSING OF FOOD**

Having before us a description of the attributes of high-quality, safe foods, the significant chemical reactions involved in the deterioration of food, and the relationship between the two, we can now begin to consider how to apply this information to situations encountered during the storage and processing of food.

The variables that are important during the storage and processing of food are listed in Table 1.4. Temperature is perhaps the most important of these variables because of its broad influence on all types of chemical reactions. The effect of temperature on an individual reaction can be estimated from the Arrhenius equation,  $k = Ae^{-\Delta E/RT}$ . Data conforming to the Arrhenius equation yield a straight line when  $\log k$  is plotted vs.  $1/T$ . The parameter  $\Delta E$  is the activation energy that represents the free energy change required to elevate a chemical entity from a ground state to transition state, whereupon reaction can occur. Arrhenius plots in Figure 1.2 represent reactions important in food deterioration. It is evident that food reactions generally conform to the Arrhenius relationship over a limited intermediate temperature range but that deviations from this relationship can occur at high or low temperatures [12]. Thus, it is important to remember that the Arrhenius relationship for food systems is valid only over a range of temperature that has been experimentally verified. Deviations from the Arrhenius relationship can occur because of the following events, most of which are induced





**FIGURE 1.2** Conformity of important deteriorative reactions in food to the Arrhenius relationship. (a) Above a certain value of  $T$  there may be deviations from linearity due to a change in the path of the reaction. (b) As the temperature is lowered below the freezing point of the system, the ice phase (essentially pure) enlarges and the fluid phase, which contains all the solutes, diminishes. This concentration of solutes in the unfrozen phase can decrease reaction rates (supplement the effect of decreasing temperature) or increase reaction rates (oppose the effect of declining temperature), depending on the nature of the system (see Chapter 2). (c) For an enzymic reaction there is a temperature in the vicinity of the freezing point of water where subtle changes, such as the dissociation of an enzyme complex, can lead to a sharp decline in reaction rate.

by either high or low temperatures: (1) enzyme activity may be lost, (2) the reaction pathway or rate-limiting step may change or may be influenced by a competing reaction(s), (3) the physical state of the system may change (e.g., by freezing), or (4) one or more of the reactants may become depleted.

Another important factor in Table 1.4 is time. During storage of a food product, one frequently wants to know how long the food can be expected to retain a specified level of quality. Therefore, one is interested in time with respect to the integral of chemical and/or microbiological changes that occur during a specified storage period, and in the way these changes combine to determine a specified storage life for the product. During processing, one is often interested in the time it takes to inactivate a particular population of microorganisms or in how long it takes for a reaction to proceed to a specified extent. For example, it may be of interest to know how long it takes to produce a desired brown color in potato chips during frying. To accomplish this, attention must be given to temperature change with time, that is,  $dT/dt$ . This relationship is important because it allows the determination of the extent to which the reaction rate changes as temperature of the food matrix changes during the course of processing. If  $\Delta E$  of the reaction and temperature profile of the food