

Food additives

Learning objectives

This chapter will help you to:

- Describe FDA's role in regulation of food additives
- Define the terms natural and synthetic additives
- Describe uses for food additives
- Define the term hydrocolloid and describe uses in creating novel foods
- Explain the difference between toxins and toxicants



Introduction

Food additives are employed for a variety of purposes. They are used to improve nutrition, enhance safety, add color and flavor, modify texture, and preserve food. Some food additives contribute more than one function. Acids, for example, give food a tangy flavor, but also inhibit the growth of microorganisms that cause spoilage. Nitrite also has multiple functions. It is responsible for the distinctive flavor and color of cured meats and inhibits the growth of the microbial pathogen responsible for botulism. While food additives are generally chemical substances, biologicals (enzymes) can also be additives. For example, the enzyme chymosin is added to milk in cheese making. This chapter contains an overview of substances added to food directly and some of those that find their way into food indirectly. However, the number of substances used as food additives is quite large (3000+), thus this chapter focuses on the most commonly used ones. Specifically, it covers additives used as acidulants, antioxidants, antimicrobials, hydrocolloids, emulsifiers, and toxins. Additives used to provide flavor and color are covered separately in Chapters 6 and 8, respectively.

This chapter includes questions that will help you explore and better understand the role of additives in food.

- What is alkaline water and does it have health benefits?
- Why is bacon considered an unhealthy food?

- Does the sulfite in wine cause headache?
- What is antioxidant and how does it work?
- What is the difference between food poisoning and foodborne illness?



Regulation of food additives in the United States

In the United States, food additives are regulated by the United States Food and Drug Administration (FDA). Food additives are defined by FDA as “any substance the intended use of which results, or may reasonably be expected to result, directly or indirectly, in its becoming a component or otherwise affecting the characteristics of any food”. The history of governmental regulation of food began in the late nineteenth century with Dr. Harvey Wiley, chief chemist for the Bureau of Chemistry. Dr. Wiley and others led the fight against the practice of adulteration and use of hazardous substances in food and drugs. These efforts established the first nationwide regulation known as the “Pure Foods and Drug Act of 1906”. Under this act, interstate transport of adulterated or misbranded food and drugs was prohibited, adulteration was defined, and misleading or false statements were prohibited by law. For the first time, if a food or drug was in adulterated or mislabeled, it could be seized and the seller could be fined and/or jailed. The United States Congress passed additional legislation called the The Federal Food, Drug, and Cosmetic Act of 1938. This act gave the Federal government authority to closely oversee food, drugs, and cosmetics. Manufacturers were required to provide proof of a drug’s safety and efficacy before putting it on the market. The act required that safe tolerances be met for unavoidable poisonous substances in food. The act established standards of identity for foods and authorized factory inspections. A standard of identity means that specific foods (e.g., milk) must meet the definition set by FDA if the word “Milk” is used on its label. If a product labeled as milk contained added water or other substances, it is considered to be an act of adulteration, a punishable offense.

Additional major legislation

The Food Additives Amendment of 1958, was passed in response to public concern about the growing use of chemicals added to food, especially those used in processed foods. There was particular concern over pesticide substances occurring indirectly in foods. Two major outcomes of this legislation were establishment of substances classified as “Generally Recognized As

Safe,” or GRAS, and adoption of the Delaney Clause. GRAS status was given to those substances with a history of use without harm as determined by review from experts in the field. Initially, 200 substances were listed as GRAS and grandfathered for use without further testing. The number of GRAS substances has increased to more than 800 as a result of FDA’s petition and review process. Additives introduced after the 1958 act are required to be scientifically tested before being allowed in foods. The Delaney Clause was initially intended to address the issue of pesticides in foods. It broadly prohibited the use of any food additive shown to cause cancer in animals. At the time of the regulation, no provision was made for risk factors such as carcinogenic potency of the substance or its level in food. It is now known that substances vary greatly in their ability to cause cancer. Additionally, advances in analytical technology have made detection of these substances possible at extremely low levels. FDA has subsequently adopted a *de minimis* (Latin phrase meaning “about minimal things”) exception to the Delaney Clause. This rule allows FDA to grant an exception to Delaney Clause if the substance occurs at very low levels. Currently, if a potentially carcinogenic substance is present in a food at 1 ppm (part per million) or lower, FDA can invoke the exception ([Overview of Food Ingredients, FDA 2018](#)).

Regulation of additives in other countries

The European Food Safety Authority defines food additives as “any substance added intentionally to foodstuffs to perform certain technological functions, for example to color, to sweeten or to help preserve foods.” In the European Union, food additives are given an E-number (e.g., E-951 aspartame, sweetener). All additives in food sold in the EU must be listed on the food product label. E-number labeling has been adopted by other countries, e.g., Australia, and New Zealand. A summary of food additives grouped by their function and corresponding E-number range is given in [Table 7.1 \(European Food Additive Identifier Numbers 2018\)](#).



Types of food additives

A food additive is defined as a substance not normally found in food. Additives can occur in food as the result of indirect or direct addition. Indirect additives are substances that migrate into food from the environment and include production, processing, and packaging. They do not result from an intentional act. Examples of indirect additives include compounds

Table 7.1 E number classification of food additives.

| E number range | Description of function |
|----------------|--------------------------------------|
| E100–E199 | Colors |
| E200–E299 | Preservatives |
| E300–E399 | Antioxidants, Acidity Regulators |
| E400–E499 | Thickeners, Stabilizers, Emulsifiers |
| E500–E599 | pH Regulators, Anticaking Agents |
| E600–E699 | Flavor Enhancers |
| E700–E799 | Antibiotics |
| E900–E999 | Glazing Agents, Gasses, Sweeteners |

from packaging materials, toxicants such as heavy metals, aflatoxin from mold, and pesticide residues. Direct additives are substances added to a food to provide a desired effect as a colorant, preservative, antioxidant, or sweetener. It is important to note that use of an additive to conceal damage or spoilage is illegal and considered to be an act of adulteration. Food additives are also classified as natural or synthetic. Natural additives are defined as substances occurring in foods or extracted from a natural source. For example, ascorbic acid (vitamin C) is considered to be a natural additive even when obtained as an extract. Conversely, synthetic additives are person-made substances. The distinction between a natural substance and its synthetic counterpart can be blurred when they are demonstrated to be equivalent. Organic foods produced in the United States and Europe must contain at least 95% organic ingredients. They are, however, permitted to contain additives of natural origin. Organic foods produced under the European Food Safety Authority (EFSA) also require that both the additive's name and its function must be stated on the food label. Most additives do not contribute to the food's nutritive value because they are used at very low levels. Vitamin additives are an exception to this statement because they are used for fortification or restoration of a food ([Food Additives EFSA, 2018](#), [Food Additives WHO, 2018](#)).



Food acids and acidity regulators

Several weak acids (e.g., acetic, propionic, malic, lactic, citric, and tartaric) are common food additives used to create flavor, preserve food, provide functionality (e.g., leavening systems) and improve safety. Acetic acid, a short chain fatty acid, is the predominant component of vinegar and is responsible for its characteristically pungent taste. Vinegar is used as a tasant

and preservative in pickled foods, salad dressings, marinades, and as a condiment. Other short chain fatty acids such as butyric and propionic, are volatile compounds with distinctive tastes that contribute to the overall flavor of cheese and other dairy products. Lactic acid produced by bacterial fermentation of lactose in milk is responsible for the sour taste of yogurt. Lactic acid is also the taste of spoiled milk and the principle tastant in sausage and sourdough bread. Fruits such as apples, oranges, and grapes derive much of their tart taste from malic, tartaric, and citric acids. Phosphoric acid is an inorganic acid commonly used as an acidulant in carbonated soft drinks. Phosphoric acid in combination with carbonic acid (produced when CO_2 is dissolved in water) is responsible for the tangy taste of these beverages.

Weak acids preserve food by inhibiting the growth of spoilage microorganisms. The mechanism of microbial inhibition involves diffusion of the acid through pores in the bacteria's outer membrane, causing disruption of essential biochemical pathways. Weak acids contribute to food safety by preventing botulism poisoning. *Clostridium botulinum* is a pathogenic and ubiquitous microorganism that grows well in food environments containing little oxygen. Spores of this organism survive normal heat treatments, such as boiling. This enables them to germinate and release botulinum neurotoxin that causes muscle paralysis and death. Foods, such as sausages, represent an optimum environment for botulism poisoning. Sausages were a major cause of illness and death during the 18th and 19th centuries. Fortunately, it was discovered that spore germination and toxin production could be prevented by keeping the pH at 4.5 or lower. Sausage is made safe from botulism poisoning by directly adding lactic acid or indirectly as a fermentation by-product. However, acidification is not desirable for foods such as green beans and other vegetables. Low pH causes chlorophyll-containing foods to turn brown. The risk of botulism in low acid canned foods (e.g., vegetables) is avoided by using a rigorous canning process that inactivates or kills *C. botulinum* spores.

Chemical leavening

Acids are used in chemical leavening systems for bread dough applications when yeast fermentation producing carbon dioxide (CO_2) is not practical. Chemical leavening systems produce CO_2 through a reaction between a carbonate salt and an acid. An example of this chemical reaction using sodium bicarbonate (NaHCO_3 - baking soda) as the source of carbon dioxide and an acid ($\text{R}-\text{COOH}$) is shown below. In this reaction, a

hydrogen ion from the acid adds to bicarbonate producing the ionized acid (ROO^-), sodium ion, water, and carbon dioxide.



While this chemistry works well in producing CO_2 gas, it has a major limitation in food. Specifically, the production of gas begins as soon as the reactants are mixed. Foods such as refrigerated bread doughs, self-rising flour, and cake mixes must rise during cooking. Gas production is delayed in these products by using different acid sources. Compounds called leavening acids provide hydrogen ions slowly or when heated. Examples of leavening acids include monocalcium phosphate hydrate $[\text{Ca}(\text{H}_2\text{PO}_4)_2] \cdot \text{H}_2\text{O}$, and sodium aluminum phosphate hydrate $[\text{NaH}_{14}\text{Al}_3(\text{PO}_4)_8 \cdot 4\text{H}_2\text{O}]$. Monocalcium phosphate is a more water-soluble acid than is sodium aluminum phosphate and generates acid more quickly. Its rate of CO_2 production is slow compared to acetic acid, but it begins to produce gas as soon as water is added. Sodium aluminum phosphate primarily releases its hydrogen ions in response to elevated temperatures, such as in baking. Monocalcium phosphate and sodium aluminum phosphate are called slow-acting and fast-acting leavening acids, respectively. These leavening acids are commonly used in the household baking ingredient known as double acting baking powder.

Acidity regulators

Excess acid in food can make it unacceptably sour. Acidity regulators are used to reduce the sour taste of a food. For example, sourness in cherries can be reduced by adding the sodium salt of malic acid called sodium malate. This is based on the chemistry of weak acids. Weak acids (HA) are by definition incompletely dissociated into hydrogen ion (H^+) and its corresponding anion (A^-). The amount of H^+ present depends on its dissociation from HA in an equilibrium process. When the sodium salt of A^- is added, an equilibrium is re-established by driving the reaction (shown below) in reverse (to the left) and this decreases level of hydrogen ion in the food.



Other examples of weak acids used as food acidity regulators include the sodium salt of citric acid in fruit juice, lactic acid in cheese, and phosphoric acid in soft drinks.

Buffering capacity

Food acids also provide buffering capacity in food systems. Buffering capacity is defined as the ability to resist change in pH when acid or base is added to a system. Milk, for example, contains a substantial amount of phosphate complexed to its proteins and free in solution. Milk phosphate acts a buffer to absorb hydrogen ions and maintain the pH at a normal level. However, as bacteria in milk metabolize its lactose into lactic acid, hydrogen ions are produced. At some point in time the amount of hydrogen ion produced exceeds the buffering capacity of milk phosphates and causes a drop in pH. The casein fraction of milk is destabilized and precipitates when a pH of about 4.9 is reached.



Bases

A base is chemically defined as a substance that donates hydroxide ions (OH^-). Bases (alkaline substances) have a number of food uses. Sodium bicarbonate is a weak base used for its ability to generate carbon dioxide in the presence of an acid. Sodium bicarbonate also accelerates Maillard browning. Potatoes coated with sodium bicarbonate brown quicker and have a crisp texture. A secret to making French baguettes with a crisp, brown crust is a quick dip in sodium bicarbonate (baking soda) solution before baking. Similarly, sodium bicarbonate accelerates browning of sugar in caramelized products like peanut brittle and other confections. Stronger bases, such as potassium carbonate and sodium hydroxide, are used in olive processing to destroy the bitter compound oleuropein and to give olives a darker color. Potassium carbonate base is used in Dutching of cocoa beans. It neutralizes the acidity of the bean and gives the resulting cocoa powder a darker color and a more intense chocolate flavor. Dutched cocoa is also more soluble in aqueous solution after treatment with base. Strong bases are used in the production of soy protein isolates that are the main ingredient in many soy-based food products. Soy proteins are tightly packed in the soybean and biologically function as a store of energy and amino acids for the plant's growth. Extraction of protein from soybeans is made possible by adjusting the pH to 9 or 10. High pH disrupts protein complexes in the seed and increases the amount of protein extracted. Alkaline pH treatment with sodium pyrophosphate salt is used to make instant pudding. Elevated pH promotes starch gelatinization and has the desirable effect of thickening pudding mix as soon as milk is added. As a result, no cooking is needed.

What is alkaline water? Does it have health benefits?

Alkaline water is a type of bottled water to which bicarbonate salts (sodium, calcium, magnesium, or potassium) are added to raise its pH from 7 to about 9.0–10. Sodium bicarbonate (also known as baking soda) is a safe additive for the purpose of increasing the pH of water. Alkaline water can also be homemade by adding one teaspoon of sodium bicarbonate to a gallon of deionized water. A potential concern for alkaline water, however, is its sodium content. For example, the sodium intake (approximately 1.34g) from drinking a gallon of alkaline water over the course of a day represents about two-thirds of FDA recommended daily sodium intake (2.3 g). Alkaline water has been proposed as a means to mediate the negative effects of diets with a high Potential Renal Acid Load (PRAL). Metabolism of foods such as cheese, meat, and fish elevate the level of acid processed in the kidney and excreted in urine. High PRAL diets are proposed to be linked to higher risk of kidney stone formation and bone mineral loss. Conversely, diets high in vegetables and fruits have a lower PRAL value and reduced risk of stone formation (Remer and Manz, 1995). It should be noted that blood pH is closely regulated (buffered) in the kidney and consuming excess alkaline substances (carbonates) raises potential concern for causing alkalosis. This condition affects the heart's contractile force and may cause neurological symptoms (Al-Abri and Olson, 2013). No health benefit from drinking alkaline water has been demonstrated.



Salts

Sodium chloride (NaCl) is perhaps the most used food additive. Salt enhances flavor, preserves food, and is essential to many processed foods. Saltiness is one the basic five taste modalities with a specific receptor mechanism. Sodium chloride enhances the perception of sweetness (see Chapter 6, Flavors). This effect on sweetness is demonstrated by the popularity of adding salt to chocolate and other sugary foods. Sodium chloride is a preservative used to extend the shelf life of perishable foods like meat. The practice of salting meat and fish has been used for thousands of years to keep it from spoiling. The preservation effect of salt results from its effect on the availability of water to spoilage microorganisms. Water availability in food is measured as water activity (a_w), as described in Chapter 1 (water and pH). The minimum a_w for spoilage bacteria to grow is 0.9 and fresh meat's a_w is typically 0.98. Salt added to pork, beef,

and fish reduces the a_w level to 0.88 or less. This extends the period of time these foods can be kept without spoiling. Sodium chloride is also essential in making processed meat. Large amounts of salt are added during the grinding operation to improve protein extraction and binding between meat pieces. Salt extracted proteins (e.g., myosin) enhance the emulsification of fat and increase water holding capacity in processed meat products.



Antimicrobials

Acetic acid

Acids contribute several attributes to food, including flavor (taste), preservation, and safety (Fig. 7.1). Tastes provided by acids are generated by stimulation of pain receptors located in taste buds. The taste of food acids is described as tart, tangy, or crisp. Acetic acid (Fig. 7.1A) is a ubiquitous food flavoring (vinegar) and preservative. Acetic acid and its salts (sodium, potassium, and calcium) are used at low levels in baked goods as dough conditioners. The distinctive tasting condiment known as vinegar is produced by bacterial (oxidative) fermentation of alcohol. In some cases, alcohol derived from wine is used as the starting media for fermentation. *Acetobacter aceti* is commonly used to make acetic acid used as a 3% solution and has excellent bactericidal effects. It may prove to be a suitable antiseptic agent in treatment of burn wounds (Ryssel et al., 2009).

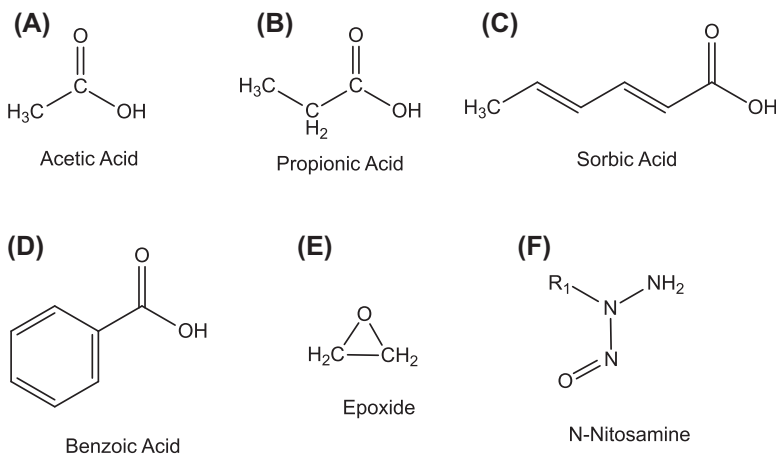


Fig. 7.1 Antimicrobial food additives.

Propionic acid

Propionic acid is a short chain saturated fatty acid containing 3 carbons (no double bonds) and has a characteristic flavor described as cheesy or dairy-like. It is also rather pungent (Fig. 7.1B). It is the predominant acid in Swiss cheese, comprising about 1% (by weight) of the cheese. Propionic acid has antimicrobial activity, primarily against molds in acidic environments. Antimicrobial activity of propionic acid is only effective at low pH because the ionization of its carboxyl group creates a negative charge and limits transport across the microbial cell wall. Sodium and calcium salts of propionic acid (i.e., sodium propionate and calcium propionate) are used as a preservative (mold inhibitor) in baked goods and processed cheese. Calcium propionate occurs naturally in butter and is used in processed cheese and meat for its preservative properties.

Sorbic acid

Sorbic acid is a natural preservative first isolated in 1859 from the berries of an ash tree. Sorbic acid is unsaturated fatty acid containing two carbon-carbon double bonds and both are in the trans configuration (Fig. 7.1C). Investigation of its antimicrobial activity found it to be an effective inhibitor of molds, yeasts, and fungi. Sodium and potassium salts of sorbic acid (i.e., sodium sorbate and potassium sorbate) are not as effective. The free acid form is more effective as an antimicrobial. Antimicrobial activity of sorbic acid increases as the pH of the media decreases. Enhanced activity at low pH results from the acid being fully protonated (unionized) and thus readily taken up by the microorganism. Combination of sorbic acid and lactic acid have also been shown to inhibit the growth of the pathogen *Salmonella*. Sorbic acid is widely used to inhibit yeast and molds in processed cheese, wine, fruit juices, and some baked goods (pastries). It is also used in processed meats as an alternative to preservation using nitrites.

Benzoic acid

Benzoic acid is an organic acid first used in foods almost 100 years ago. It occurs naturally in prunes, cinnamon, and cloves. The free acid form is poorly soluble in water and the sodium salt (sodium benzoate) is often used because of its greater solubility (Fig. 7.1D). Benzoic acid's antimicrobial activity is primarily against yeasts and molds. As mentioned for other organic acids, antimicrobial activity is greatest at low pH. The effect results from greater permeability of the unionized form

into microorganisms. Benzoic acid's most common uses are in carbonated beverages, pickles, sauces, and jelly. Non-food applications for benzoic acid's antibacterial function are found in cosmetics. Benzoic acid itself has low toxicity, but there has been concern because of a potential reaction that converts it to benzene. Although benzene is a toxic and carcinogenic compound, the reaction causing this change has a very low chance of occurring in food. Typically, benzene is rapidly converted to hippuric acid in the body and excreted in the urine. Parabens are antimicrobial compounds chemically derived from benzoic acid. Chemically, parabens are esters made by combining benzoic acid and alcohols such as methanol or propanol. Paraben esters have antimicrobial activity against molds and yeasts and are used in beer, soft drinks, and olives. Cosmetics and pharmaceuticals represent the largest use of parabens.

Antibiotics

The peptide antibiotic nisin is used in cheese making. It is composed of 34 amino acids that includes two unusual products of post-translational modification known as lanthionine and methyl-lanthionine. Nisin is more correctly termed a bacteriocin that involves peptides with the ability to kill or inhibit the growth of other bacteria. Nisin is produced by *Streptococcus lactis*. This organism is found in milk and has little or no activity against yeasts and molds. Nisin's antibacterial activity is very selective. It benefits cheese making by controlling the growth of bacterial strains that cause spoilage. It can also inhibit the growth of pathogens and spore growths, such as *Staphylococcus aureus* and *C. botulinum*. Nisin's antibiotic activity does not present concern for development of antibiotic-resistant strains. Nisin was found to be an effective inhibitor of more than 90% of gram-positive spoilage organisms in beer (Suganthi et al., 2012). In the United States, nisin is approved for use in pasteurized process cheese spreads. In Europe, it is used in processed meats and cheese.

Epoxides

Epoxides, such as ethylene and propylene oxide, are small, highly reactive, and volatile molecules that effectively kill most microorganisms, including bacterial spores (Fig. 7.1E). The effectiveness of epoxides results from the molecule's reaction with the organism's proteins (enzymes) and nucleic acids. As a result, microorganisms are unable to perform essential processes and die off. Epoxides are used in gas form to chemically sterilize processing

and food packaging equipment. Ethylene oxide is also used as a sterilant for medical equipment. The treatment of foods with epoxides is limited to applications where the microbial load is typically high and washing with water-based detergents is not applicable. Spices and nuts are examples of food materials that are treated with epoxides. The increased popularity of spicy foods has logically increased the demand for hot peppers, turmeric, and other ground dry spices. These ingredients are often produced in remote regions, transported great distances, and stored for long periods of time. It is no surprise that they often carry high levels of microorganisms, including pathogens.

Nitrite

Nitrite (NO_2) and nitrate (NO_3) salts (typically sodium) are used in food as a preservative and to create cured meat color and flavor. Nitrite is a potent preservative because it inhibits the growth of some microorganisms that cause spoilage and pathogens, such as *C. botulinum*. Nitrite does not inhibit *Escherichia coli* or *Salmonella* pathogens. While instances of poisoning from botulinum toxin in food are rare, can be fatal. Nitrate is converted to nitrite in meats by microorganisms and/or reducing agents such as ascorbic acid. Nitric oxide (NO) derived from nitrite is the source of the pink color and flavor characteristic of cured meats, such as ham and bacon. Nitric oxide is also an antioxidant that prevents free radicals from causing lipid oxidation and off flavors in meat. However, there are health concerns associated with excessive consumption of nitrite. The LD50 value for nitrite is 71 mg per kg of body weight. This translates to an intake of 4.6 g for a 150 lb person. Lesser amounts of nitrite are known to cause methemoglobinemia when it binds to hemoglobin in red blood cells. The nitrite-hemoglobin complex has low affinity for oxygen and reduces the amount delivered to tissues and organs. High nitrite levels have occurred in ground water supplies due to fertilizer runoff. This causes methemoglobinemia in infants (blue baby syndrome) when the water is used to make their formula. The largest source of nitrite in food is from cured meats and these foods contain 10–30 mg per kg of product. The largest cause for concern regarding nitrites comes from N-nitroso compounds. Specifically, nitrosamines are produced by a reaction between nitrites and proteins under acidic conditions found in the stomach. Nitrosamines (Fig. 7.1F) are also found in foods such as bacon (especially when cooked at high temperature), beer, salted fish, and cheese. There is evidence for a link between nitrosamine intake and risk of gastric and

esophageal cancer (Jakszyn and González, 2006). A combination of ascorbic acid (water soluble) and alpha tocopherol (fat-soluble) antioxidants have been shown to inhibit nitrosamine formation in cooked products such as bacon.

Why is bacon considered an unhealthy food?

Bacon is one of those foods that many people find very desirable because of its flavor. Despite its popularity, there are reasons to use moderation when eating bacon. It is high in fat and salt. A typical two slice serving of bacon (16g) contains about 90 calories (66% from fat and 24% from protein), 160 mg of sodium, and lesser amounts of other minerals. The fatty acid profile of bacon fat is predominately saturated fatty acids. A more serious concern results from cooking bacon at high temperature to make it crispy. Frying temperatures cause nitrites in bacon to react with amino acids, such as proline, and form N-nitrosopyrrolidine, a carcinogen. While most bacon contains added ascorbate and tocopherol to reduce nitrosamine formation, the amount formed is not zero. Reducing the exposure to nitrosamines and their associated health risk can be achieved by alternative cooking methods. Bacon cooked at lower temperature or in the microwave has a significantly lower nitrosamine content (Park et al., 2015).

Sulfur dioxide and sulfite

Sulfur containing compounds, such as sulfur dioxide (SO_2), sulfite (SO_3^{2-}), bisulfite (HSO_3^-), and meta bisulfite ($\text{S}_2\text{O}_3^{2-}$), are effective antimicrobial agents. Sulfur dioxide (SO_2) added to water forms the complex ($\text{SO}_2 \cdot \text{H}_2\text{O}$) that has strong antimicrobial activity at low pH. Hydrogen sulfite is a more effective antimicrobial in the pH range of 3 to 7. Wine makers have a long history of using sulfites to inhibit the growth of bacteria, molds and wild type yeasts in grape musts. Without an initial sulfite treatment of the must, these microorganisms would take over fermentation and ruin the wine. The use of sulfite in wine making was first accomplished by burning elemental sulfur to produce sulfur dioxide gas. Current and common practice today is to add purified sulfur dioxide gas or sulfite salts to control the growth of undesirable microbial species. The addition of sulfur dioxide results in acidification of the media and contributes to its antimicrobial activity. Sulfite salts used in wine making are either sodium sulfite (Na_2SO_3) or potassium sulfite (K_2SO_3). The antimicrobial activity of sulfite

depends on the pH of the environment. In general, the lower the pH, the more effective is the antimicrobial action. Disulfite, also known as metabisulfite, provides antimicrobial activity over a longer period of time. Disulfite also protects wine must from oxidation and turning brown before and during fermentation. Disulfite added at approximately 2% is used as a sanitizing agent for wine bottles. Most wines produced in the United States contain some sulfite. Any wine that contains 10 ppm sulfite must be labeled as, “contains sulfite”. The maximum level permitted by the FDA is 350 ppm. In contrast, the maximum level in the UK is 210 ppm and 160 ppm for white and red wines, respectively. Organic wines made in the United States are not permitted to contain sulfite.

Sulfite reactions affecting color and flavor

In wine, acetaldehyde formed during fermentation provides a pleasant fruity aroma. When hydrogen sulfite (HSO_3^-) is present, a complex is formed that reduces the level of this aldehyde and negatively affects wine flavor. Sulfite is also used as an inhibitor of Maillard reactions responsible for brown pigments in food. Sulfites inhibit Maillard browning by reacting with aldehyde group of reducing sugars. Sulfite addition also affects flavonoid pigments found in a number of fruits. Chemical interaction between sulfite and flavonoid compounds destroys their color and causes a bleaching effect. Added sulfite is an effective agent to control brown color formation in dried fruits and molasses. Sulfites are used to inhibit enzymatic browning in lettuce and freshly cut apples and potatoes. The polyphenol oxidase enzyme responsible for this reaction causes oxidation of phenolic compounds which subsequently become brown pigments. Sulfite interaction with oxidized phenolic compounds prevents pigment formation. Fresh shrimp and lobster can also become brownish in color due the action of the same enzyme. Sulfite treatment is used to stop color development in these shellfish. Sulfites are effective reducing agents that can be used to improve the dough properties of wheat flour. Sulfite addition to wheat flour causes chemical reduction of disulfide bonds in wheat proteins. Overall, new disulfide bonds are formed and these crosslink wheat proteins and improve dough strength.

Physiological effects of sulfite

The body produces about 1000 mg of sulfite per day. Sulfite and other sulfur containing compounds, such as the amino acids cysteine and methionine, are

converted to sulfate by the enzyme sulfite oxidase. They are eliminated in the urine without ill effect. However, there is a caution for asthmatics. About 1% of the U.S. population have sulfite reactions that cause symptoms such as shortness of breath, wheezing, and hives. Dried fruits such as apricots, figs, and prunes are of particular concern for those with sulfite sensitivity because they can contain excessive amounts of sulfite. For this reason, sulfite is prohibited from use on fruits and vegetables presented in salad bars. A final negative aspect of sulfite is its destructive reaction with thiamin (vitamin B₁). Sulfites are therefore prohibited from use in processed meat as they are a good source of thiamin.

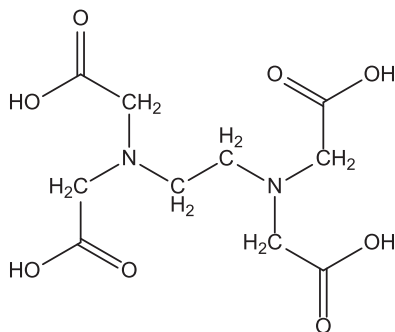
Does the sulfite in wine cause headache?

Adverse reaction to sulfite is a condition known as sulfite sensitivity. Sulfites are components of all wine as a result of direct addition or an indirect addition from yeasts used in fermentation. It is commonly assumed that sulfite is the cause of adverse reactions experienced from drinking a glass of wine. However, there is another possible culprit. A substance called histamine found in fermented foods like beer, soy sauce, and wine is known to cause headache, flushing of the face, and allergy-like symptoms, including rash and difficulty breathing. These are symptoms of histamine intolerance. Are adverse reactions from drinking wine due to sulfite, histamine, or something else? First and foremost, anyone who has an adverse reaction to any food should seek a medical professional's advice for help. But a clue to the cause of the adverse reaction might be found in its histamine content.



Chelators (sequestering agents)

Chelating agents are compounds that tightly bind and sequester metals like copper, iron, zinc, calcium, and manganese. Chelators, such as EDTA contain an unshared pair of electrons that enable formation of a complex with metal ions. Examples of chelators used in foods are polycarboxylic acid compounds such as; citric, malic, tartaric, and succinic acid. Pyrophosphates and the synthetic compound ethylenediaminetetra acetic acid (EDTA) are also chelating agents used in foods. The chelating effect on metal ions can be illustrated using EDTA as a model. Two nitrogen atoms with an appropriate geometry are able to share unpaired electrons with the metal ion as shown in [Fig. 7.2](#). The pH of the medium affects the metal chelating ability of EDTA and other chelators. Ionization of carboxyl groups



EDTA- Metal Chelator

Fig. 7.2 Metal ion chelator (EDTA).

equates to a more effective metal chelator. Conversely, protonation removes the negative charge and diminishes the strength of the interaction between chelator and metal ion. The relative chelating ability decreases in the following order; EDTA > pyrophosphate > citric acid. A similar chelation of iron occurs in the porphyrin containing proteins, myoglobin and hemoglobin. Iron is essential to the oxygen carrying function of these proteins and is very tightly held. However, iron is released from heme the group during the digestion and is in fact, the most easily absorbable form of iron intake. Chelators can provide antioxidant activity by binding iron (a pro-oxidant) and inhibiting lipid oxidation.

Antioxidants

Oxidation is chemically defined as the loss of electrons from an atom or molecule. More importantly, oxidation is a chemical process causing the breakdown of molecules. The process of oxidation is also accompanied by the release of energy. For example, burning wood is a rapid oxidation process producing energy in the form of heat and light. A much slower oxidation of food materials occurs through the process of digestion and provides the energy required by all forms of life. Oxidation also occurs from chemical species known as free radicals (discussed in Chapter 4, Lipids). Free radicals are reactive atoms or molecules containing unpaired electrons in their outer shell. They can be produced by natural processes, such as metabolism, or can be formed by extrinsic factors, such as ultraviolet light or ionizing radiation. Unchecked free radicals in living systems cause damage by reacting with proteins, lipids, and DNA. DNA modified

by reaction with a free radical, such as hydroxide radical ($\bullet\text{OH}$), represents a mutation in the genetic code and a potential cause of cancer. Fortunately, living systems have compensatory mechanisms that repair and restore the damage caused by free radicals. In food, free radical reactions are the cause of several adverse effects most noticeable as loss of color and production of off flavors. A more immediate effect of free radicals is the destruction of essential fatty acids and amino acids, vitamins, and naturally occurring antioxidant molecules. The net result of these oxidations is loss of food quality and reduction of nutritional value. Additives included in processed foods perform their antioxidant function either as free radical scavengers or chelators of pro-oxidant metal ions.

What are antioxidants? How do they work?

Antioxidants are compounds that inhibit or terminate free radical reactions. Antioxidant molecules are free radical scavengers (FRS). They function by donating a hydrogen atom to the radical, taking away the unpaired electron and converting it to a low energy (non-reactive) species (Shahadi et al., 2002). An effective FRS must be able to react with the radical species before it can damage other molecules (e.g., unsaturated fatty acids, vitamins). The pro-oxidant activity of transition metals, such as iron and copper, can be inhibited by adding a chelating agent. Chelators such as EDTA form tight complexes with iron and copper and limit the ability to participate in the chemistry of oxidation reactions. Additionally, the EDTA-iron complex is more soluble than the mineral alone and exists in the aqueous environment where target molecules are concentrated.

Ascorbic acid

Ascorbic acid exists in two forms: L-ascorbic acid (vitamin C) and the inactive optical isomer, L-isoascorbic called erythorbic acid (Fig. 7.3A). Both forms of ascorbate are equally effective antioxidants and control free radical reactions in several ways. Erythorbic acid is considerably less expensive compared to L-ascorbic acid and therefore is commonly used as an antioxidant additive in food. Ascorbates are potent free radical scavengers (FRS). In this process of controlling free radicals, ascorbate is oxidized (a loss of electrons) to a form that can be readily reduced back to L-ascorbic acid by another antioxidant such as, alpha tocopherol (vitamin E). The combined antioxidant effect of ascorbate and tocopherol is greater than the sum of two, thus they are said to act synergistically. Ascorbate and tocopherol are often used in combination as antioxidant additives in food

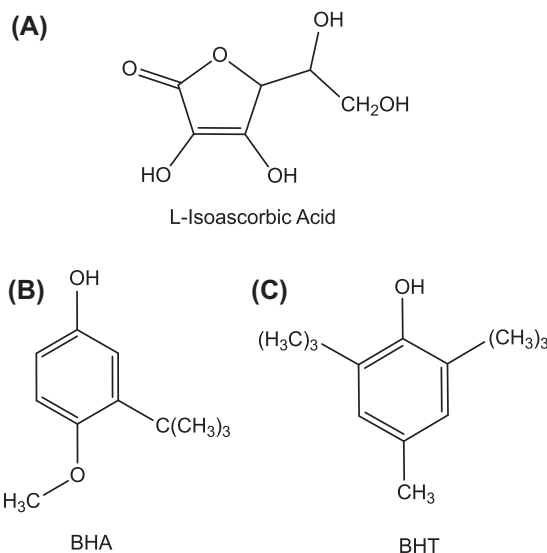


Fig. 7.3 Antioxidants.

because they effectively inhibit free radical reactions in both aqueous and lipid environments. The combination is commonly used to inhibit lipid oxidation in processed meats. Ascorbates are also effective for controlling enzymatic browning in foods such as freshly cut apples or potatoes. Phenolase and other similar enzymes oxidize phenolic compounds in these foods to the corresponding quinone that subsequently changes to a brown color. Ascorbic acid controls enzymatic browning by lowering the pH of the medium and binding pro-oxidant metal ions (Fe and Cu).

BHA and BHT

Butylated Hydroxyanisole (BHA) and Butylated Hydroxytoluene (BHT) are antioxidant compounds that share a similar structure (Fig. 7.3B and C). These function as free radical scavengers and terminate the reaction by donating hydrogen atoms from their hydroxyl (OH) group. Both BHA and BHT are synthetically derived and have long-standing GRAS status. They are effective at very low levels in preventing lipid oxidation in a wide variety of processed foods, such as breakfast cereals, cake mixes, dehydrated meats, and food fats and oils. BHA and BHT are also used in animal feed, pet foods, cosmetics, pharmaceuticals, and plastic packaging. Both BHA and BHT have been in use since the 1950s without major issues. Recent studies have raised concern over their safety. A link between

BHA, but not BHT, and cancer in rats was reported by [Ito et al. \(2008\)](#). BHA's possible carcinogenicity is based on evidence that it caused cancer in the fore-stomachs of tested rats. Humans do not have this organ. Perhaps the health risk of consuming BHA and BHT will be more clearly understood in the future.



Hydrocolloids

The term hydrocolloid is a contraction of the words hydrophilic and colloid. Colloids are technically defined as a homogeneous mixture of one substance dispersed or suspended in another. Polysaccharides (i.e., starch, modified cellulose, pectin, and gums) are the most common form of hydrocolloids used in food. These polymers contain a large proportion of hydroxyl (OH) groups and provide a strong interaction with water via hydrogen bonding. Some proteins, like gelatin (collagen), perform well as hydrocolloids for similar reasons. Hydrocolloids are used in food systems to provide functional properties such as gelation, thickening, and emulsification. Most hydrocolloids are able to provide these properties at low concentration (e.g., < 1%) with little or no impact on flavor. A detailed summary of hydrocolloid agents and their food applications can be found in recent reviews ([Saha and Bhattacharya, 2010](#); [Banerjee and Bhattacharya, 2011](#)).

Molecular gastronomy and hydrocolloids

Molecular gastronomy represents a new field combining technical, artistic, and social components in the creation of novel foods. The phrase molecular gastronomy was coined by two scientists, Nicholas Kurti, a physicist, and Herve' This, a physical chemist. Modernist cuisine and culinary physics are other labels used to describe this field. Unlike traditional Food Science, molecular gastronomy is focused on applying scientific principles to enhance understanding of process (cooking) at a molecular level ([McGee, 1984](#)). Examples of techniques used in molecular gastronomy include low temperature-immersion (sous-vide) cooking, liquid nitrogen fast freezing and shattering, and dehydrator made fruit jerky. Notably, molecular gastronomy makes extensive use of hydrocolloids (e.g., starch, pectin, and gelatin) in the creation of novel foods. Cola caviar, chocolate noodles, salmon mousse, and red wine jelly are just a few examples that rely upon various types of hydrocolloid to provide these innovative foods.

Gelation

Gels represent one of the most important ways to alter food texture. Hydrocolloid gels are made by treatments resulting in formation of a stable 3-dimensional network. The treatment for many polysaccharides involves a heating and cooling process that enables formation of new hydrogen bonds (i.e., cross-links) between polysaccharide chains. Stability of the network is provided by the newly established cross-links between the polymer molecules. Gel networks contain microscopic cavities that entrap water. Gels can contain as much as 90% water by weight. This provides an obvious advantage in texture, appearance, and economy. Examples of additives using gelling agents include agar, gelatin, pectin, carrageenan, alginate, and starch.

Agar

Agar is a galactose-based heterogenous polysaccharide derived from red algae. It is a heterogenous polysaccharide composed of agarose and agaropectin polymers. A typical agar composition is 70% agarose and 30% agaropectin. Agarose is a linear (no branch points) polysaccharide composed of a repeated galactose disaccharide. The composition of agaropectin is more varied and contains D and L isomers of galactose with sulfate and pyruvate substituents that give the polymer a strong negative charge. Agar is best known as the growth media used in identification and enumeration of microbial organisms. Agar gels are reversible (melts at 85°C and solidifies at 32–40°C) and translucent. Refined grades of agar are used in food applications. Agar's properties are similar to gelatin. It is a good substitute for animal-based gelatin in vegetarian foods. Agar is easier to use in food gels than many other substances. Common food applications of agar include puddings, custards, and soft candies. Agar improves the texture of processed cheese and frozen desserts. It is also added to baked goods to inhibit staling. A creative food application uses agar-based gel cubes that are infused with fruit extract or wine to make a vegetable-based aspic. You may have encountered agar in the dentist's office where it is often the polymer used to make dental impressions.

Gelatin

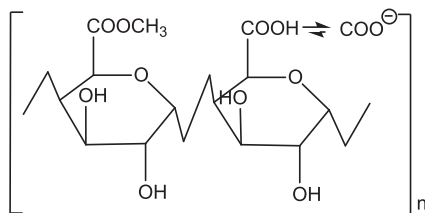
Gelatin is another name for the animal protein collagen that is obtained as a by-product of the meat processing industry. Collagen is extracted from skin, bones, and connective tissue using a variety of conditions (e.g., salt solutions of weak acid, weak alkali, and/or enzymes). The choice of extraction

method is important because it affects gelatin's end use properties. In addition to food, gelatin is used in pharmaceuticals (gelatin capsules) and photography (film emulsions) applications. Gelatin is also made from extracted collagen through enzymatic process. Enzymes break down the protein into smaller fragments called peptides that are better gelling agents. Collagen is an unusual protein because the amino acids proline and hydroxyproline make up about one-third of its total amino acid composition. Proline and hydroxyproline impose structural constraints on the collagen molecule. These amino acids are principally responsible for the ability to make reversible gels. The melting temperature of gelatin ($95^{\circ}\text{F}/35^{\circ}\text{C}$) is just below body temperature ($98^{\circ}\text{F}/37^{\circ}\text{C}$). This provides a desirable mouth feel to the gel. The gelation properties of collagen are used to make aspic, marshmallows, gummy bears, ice cream, yogurt, and more. Gelatin is also used as a clarifying agent in wine and beer. Cloudiness caused by substances such as yeasts, proteins, and tannins bind to gelatin and can be precipitated or filtered out of the solution.

Pectin

Pectin is a polysaccharide found in the cell walls of plant tissues. The native pectin polymer is responsible for the strength of the cell wall and firmness of the fruit as a whole. During ripening, pectin is modified and broken down into shorter segments by enzymes. This natural process makes the fruit softer. Pectin is composed of galacturonic acid monomers, some of which contain an esterified methyl group (Fig. 7.4).

Those galactose monomers without methyl groups have a negative charge when they ionize. The charge inhibits the interaction between pectin molecules and results in a weak gel. Pectin with a high percent of methyl ester groups (high methoxyl pectin) has less negative charge and is better able to form strong gels. The enzyme pectin methyl esterase (PME) is responsible for removing methyl groups during ripening. The extent of



Pectin (Galacturonic Acid Polymer)

Fig. 7.4 Pectin.

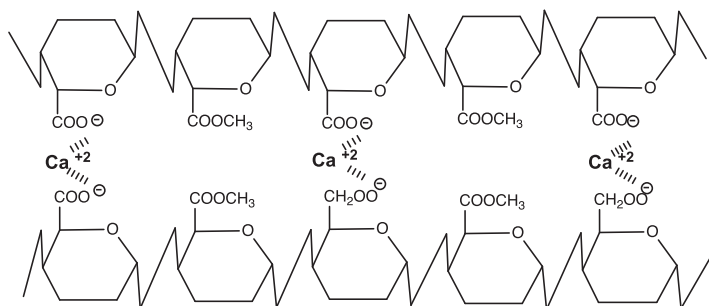


Fig. 7.5 Pectin gel with calcium.

methyl group hydrolysis from pectin results in different commercial grades of pectin, such as low-methoxyl and high methoxyl. High methoxyl pectin is the form of choice for making traditional jams and jellies. A combination of high methoxyl pectin, low pH, and high levels of sugar (50%) is essential to making a firm jelly. It is possible to make firm gels using low methoxyl pectin by the addition of calcium. Calcium (Ca^{+2}) is a positively charged, divalent cation that forms gels with low methoxyl pectin through electrostatic cross-linking between negatively charged pectin molecules. This type of gel has the advantage of requiring lower levels of sugar (10%–15%) and is the choice for making reduced calorie jams and jellies. Added calcium forms a complex between pectin polymers that resembles an egg crate structure (Fig. 7.5). Pectin's ability to form clear gels with calcium has made it a favorite tool for creating novel foods in culinary applications.

Carrageenan

Carrageenan is a polysaccharide gelling and thickening agent obtained from sea weed. The carrageenan polymer is composed of galactose units containing numerous sulfate groups. Carrageenan exists in kappa, iota, and lambda major forms that differ in their content of esterified sulfate groups. The negative charge contributed by sulfate groups creates a mutual repulsion that keeps the polymer chains apart. Carrageenans are thus soluble polysaccharides that substantially increase solution viscosity (thicken) at low concentration. Kappa and iota forms of carrageenan also form gels when the positively charged ions of sodium (Na^+), potassium (K^+), or calcium (Ca^{+2}) are added. These ions enable gels formation through electrostatic links between the polysaccharides that are bridged by the ions. Proteins are electrostatically complexed with carrageenan for the same reason. For example, a weak, pourable gel is formed with milk caseins

through this type of interaction. Carrageenan works well in milk-based desserts such as shakes and ice cream. Carrageenan addition greatly improves the dispersion of chocolate in milk. Processed meats, such as ham containing carrageenan, have a softer texture and retain 20% to 40% more water.

Alginic acid/alginate

Alginic acid/alginate is a polysaccharide found in brown seaweed. It is the world's most abundant marine polysaccharide. The polymer is linear and composed of glucuronic and mannuronic acid monosaccharides. Because of its carboxylic acid content, it is very acidic and negatively charged at pH 4 and above. The free acid form of this polysaccharide is called alginic acid. When a base such as sodium hydroxide (NaOH) is added, it neutralizes carboxylic acid groups and creates sodium alginate salt. Sodium alginate is soluble in water and forms highly viscous solutions at low concentration. Sodium alginate solutions can form gels when calcium ions are added. Alginate is used to make restructured products such as the pimento in stuffed olives, onion rings, and novel foods. For example, restructured pimento is made by combining its puree with sodium alginate and rolling the mixture into a thin sheet. Spraying a calcium solution on the material causes it to solidify. Gelled pimento is then cut in small pieces and stuffed into olives. Sodium alginate is used to make onion rings. A mixture of minced onion and sodium alginate is extruded through dies of various sizes. Rings formed by the process are solidified by dipping the extruded material in a calcium solution. Rum caviar is a novel application in which alginate-containing liquid is added dropwise to a calcium containing solution (Fig. 7.6). Droplets quickly solidify into small pearl-shaped beads as they hit the



Fig. 7.6 Rum caviar -alginate + calcium.

calcium solution. This technique is used to make faux caviar from a variety of liquids, including juices and wine.



Stabilizers and thickeners

Several types of polysaccharide are used in foods to provide viscosity and/or stabilize suspensions. These large polymers contain numerous hydroxyl (OH) groups that provide good interaction with water and increase the viscosity or resistance to flow of solutions. They are also used to suspend poorly soluble substances, such as colorants. Starch is often used as a viscosity enhancer. In general, starches from root plants (e.g., potato and tapioca) have higher ratios of amylopectin to amylose and provide stable thickening properties to gravies and stews. High amylopectin starch develops high viscosity after heating through gelatinization and cooling (Chapter 3 Carbohydrates). High amylopectin starches retain much of their viscosity after a freeze-thaw cycle and are the form of starch used for frozen food products.

Carboxy methyl cellulose (CMC) is a thickener and emulsifying agent made from modified cellulose. Cellulose is a linear polymer of glucose with a starch-like structure with little or no solubility in water. A chemical process is used to add polar carboxymethyl ($\text{CH}_3\text{-COOH}$) groups to most glucose units in the cellulose backbone to create a negative charge. This greatly improves compatibility with water. The product of this process carboxymethyl cellulose, has many food applications. Notably, CMC is used in ice cream where it stabilizes the fat and liquid emulsion, prevents ice crystal formation, and improves product texture. It is also used to thicken salad dressing, gravies, and ketchup.

Locust bean and guar gum are polysaccharide gums with a similar composition. These polysaccharides are composed of a repeating galactose and mannose structure referred to as a galactomannan. The ratio of galactose to mannose in guar and locust bean gums is 2:1 and 4:1, respectively. Guar gum does not contain ionizable groups, but hydrates readily in cold water and forms a highly viscous solution at low concentration. Guar gum solutions retain viscosity over the range of pH found in most food systems. Combinations of guar gum with other polysaccharides, notably locust bean gum, result in a synergistic effect that substantially increases solution viscosity. Locust bean gum dissolves in water, but heat is required to develop maximum viscosity. This gum can form gels, but its strength is improved when guar gum is also added. Major applications for locust bean and guar

gum include prevention of ice formation in dairy products such as ice cream and frozen novelties. Gums are also used to make spreadable cheese products. Gum arabic is a polysaccharide derived from the sap of the Acacia tree. It is one of the oldest and best-known gums. Gum arabic is composed of several different monosaccharides, including galactose, arabinose, and glucuronic acid. The latter monosaccharide contains an ionizable carboxyl group that contributes a negative charge and water solubility, depending on the pH. Gum arabic readily dissolves in cold water and forms highly viscous solutions. It is used to keep poorly soluble substances, like colorant lakes and flavors, in suspension. Kool AidTM is perhaps the best-known product that uses gum arabic as a stabilizer for its colors and flavors. Xanthan gum is a polysaccharide derived from a bacterial (*xanthomas campestris*) fermentation. It is composed of glucose monosaccharides arranged in a cellulose-like polymer. Xanthan forms highly viscous solutions at low concentration (1% and less). Xanthan gum is commonly used in tooth paste formulations. While xanthan gum is technically not an emulsifier, it works well to keep oil from separating in salad dressings. In gluten free bakery products, xanthan gum provides the texture that would normally be provided by wheat protein (gluten). Xanthan gum also has health benefits. It is a form of natural fiber that binds cholesterol in the gut and thus can lower cholesterol level in the blood.



Emulsifiers

Emulsifiers have long been used to overcome the challenge of combining incompatible substances like oil and water. An emulsion is defined as a stable mixture of two liquids that are normally immiscible. Emulsions exist basically as two types: oil-in-water and water-in-oil. The defining factor is the predominate phase. Oil-in-water represents the most common type of food emulsion. Major examples include homogenized milk, mayonnaise, salad dressing, and vinaigrettes. Water-in-oil emulsions are exemplified by foods such as butter, margarine, and high fat spreads. Emulsifying agents enable formation of a stable dispersion of oil-in-water or water-in-oil. In order for an emulsifying agent to work, it must contain both polar or hydrophilic and non-polar or hydrophobic regions to provide interaction with the corresponding phase. Emulsifying agents used in food systems include natural substances such as lecithin, hydrocolloids, proteins, fatty acids, and other amphiphilic molecules. Several synthetic substances are also available for use as emulsifying agents.

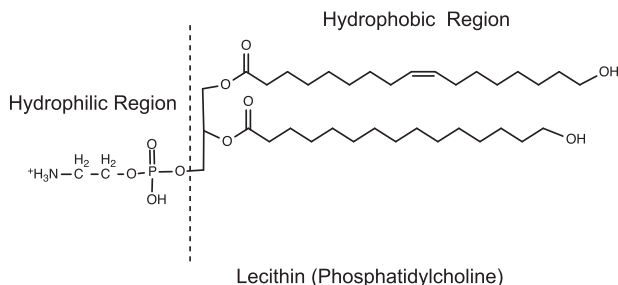
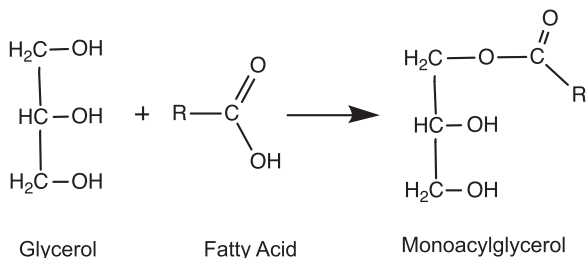
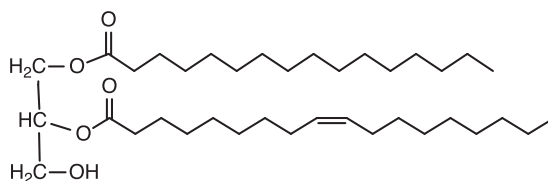


Fig. 7.7 Lecithin.

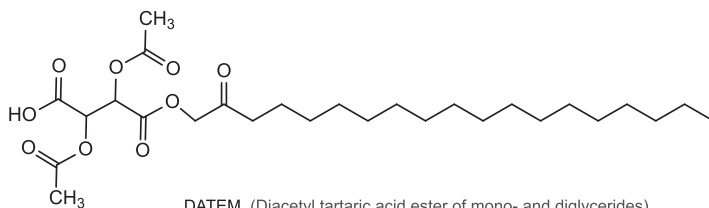
Lecithin is a phospholipid component of all cell membranes. As a food additive, it is a widely used emulsifying agent for water-in-oil applications. Lecithin is commercially derived from soy beans, egg yolk, and sun flower seeds. It is an amphiphilic molecule with the polar character contributed by phosphate and choline groups attached to the glycerol backbone (Fig. 7.7). Lecithin's hydrophobic character is contributed by two non-polar fatty acid molecules that are also attached to the glycerol backbone. Lecithin is actually a mixture of several phospholipids, including phosphatidyl choline (major form), phosphatidyl inositol, phosphatidyl ethanolamine, and phosphatidic acid. It is widely used in food applications, such as controlling sugar crystallization in chocolate, improving wettability of cocoa powder, increasing loaf volume in bread, and as a lubricant in such things as non-stick pan coating. Lecithin is also sold as a dietary supplement. The phosphatidyl choline component of lecithin is a source of the essential nutrient choline.

Mono- and di-glyceride esters of fatty acids are widely used synthetic emulsifiers composed of fatty acid and glycerol molecules. They are made through a chemical process that links unsaturated and/or saturated fatty acids to glycerol hydroxyl groups (Fig. 7.8). The aliphatic tail of fatty acids provides non-polar character needed to interact with lipid and glycerol's hydroxyl groups provide polar character. Glyceride esters are used in bakery, dairy products, peanut butter, and margarine. In bread dough, mono- and di-acylglycerides are used to inhibit staling and preserve a longer soft texture (Fig. 7.9). They also strengthen the gluten network and provide greater loaf volume. A concern has been voiced that some synthetic acylglycerol emulsifiers contain trans fatty acids. However, a recent re-evaluation of their safety by the European Food Safety Authority found no evidence for adverse effects when these were used as food additives (Younes et al., 2017).

Polysorbate 80 is an emulsifier derived from chemical combination of polyethoxylated sorbitan and oleic acid. It is commonly used to make ice

**Fig. 7.8** Monoacylglycerol.

Diacylglycerol (DAG)

Fig. 7.9 Diacylglycerol.

DATEM (Diacetyl tartaric acid ester of mono- and diglycerides)

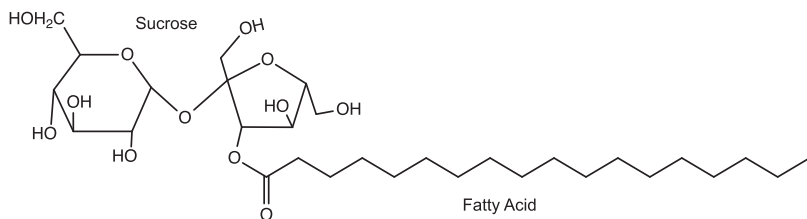
Fig. 7.10 DATEM.

cream smoother and to resist melting. Ice cream is a type of dispersion in which milk protein emulsifies fat molecules and surrounds air cells formed as the product is mixed. Polysorbate 80 prevents milk protein from completely coating fat droplets and allows them to form a network that holds it shape as the ice cream melts.

Diacetyl Tartaric acid Ester of Monoglyceride (DATEM) (Fig. 7.10) is a synthetic emulsifier composed of tartaric acid to two acetate and one fatty acid molecules. It is widely used in bakery products where it improves bread texture and loaf volume. DATEM strengthens bread dough by interaction between gluten proteins and air. A stronger gluten is able to remain stable as loaf volume increases.



Sodium Sterol Lactate

Fig. 7.11 Sodium sterol lactate.

Sucrose Ester

Fig. 7.12 Sucrose ester.

Stearoyl lactate (sodium salt) (Fig. 7.11) is made by combining the saturated fatty acid, stearic acid, with lactic acid through an ester link. The ionized free carboxyl group readily forms a sodium salt after neutralization of the lactic acid with sodium hydroxide (NaOH). Stearoyl lactate is used as an emulsifier and texturizer in foods such as icings, fillings, baked goods, pancakes, creamers. However, its greatest use is in baked goods, breads, buns, and wraps.

Sucrose esters (Fig. 7.12) are emulsifiers made by linking fatty acids with sucrose, via an ester bond. Sucrose ester emulsifiers have a wide range of applications because of the variety of fatty acids that can be combined with sucrose. Sucrose esters therefore have a number of uses in food. For example, they are used in baked goods, ice cream, cereals, and as a coating to prevent sugary substances (confectionaries) from picking up moisture and becoming sticky and prevent blooming in chocolate.

Fat replacers

Fat replacers are substances added to food to mimic the eating qualities of foods that are high in fat. Smooth texture and mouth feel are enhanced. They are used in such products as low-calorie ice cream, dessert novelties, butter-like spreads, and low-fat cheese. Replacement of fat in food potentially benefits health by lowering the calorie content and eliminating undesirable saturated and trans fatty acids from the diet. Several types of fat

Table 7.2 Fat replacers.

| Type | Examples | Source | Applications |
|------------------------|---|--|---|
| Protein-based | Simplese TM , Finesse TM , Dairy-Lo TM | Milk and/or egg protein | Ice cream, butter, margarine, yogurt |
| Carbohydrate- Based | Modified cellulose, | Cellulosic | Frozen desserts, dairy products |
| | Avicel TM , Methocel TM | polysaccharides or oligosaccharides | |
| | Litresse® or Sta-Lite® | Polydextrose | Dietary fiber, Baked goods, chewing gum, gelatins and puddings, gelatins |
| | Oatrim (Beta- Trim TM , TrimChoice) | Hydrolyzed oat flour | Prebiotic fiber, Baked goods, frostings, frozen desserts, processed meat |
| | Inulin (Raftiline TM , Fruitafit TM) | Fructose oligosaccharide | Prebiotic fiber, Baked goods, frostings, frozen desserts, processed meat |
| Lipid-based | Salatrim (Benefat ^T) | Tri-acylglyceride mixtures | Bakery and confectionary products |
| | Olestra (Olean®) | Sucrose fatty acid ester | Snack foods |

replacer additives based on unique or modified proteins, carbohydrates, and lipids are available (Table 7.2).

Protein-based fat replacers are made from proteins created by a micro-particulation process to provide a smooth creamy texture. Most protein-based fat replacers are made from milk and egg sources. The process of making a microparticulated fat replacer involves denaturation of the protein, using a combination of heat and homogenization treatments to create small diameter particles with a charged surface. A small particle size with an average diameter of less than 1 μm is key to achieving a texture similar to that of fat. Examples of protein-based fat replacers include SimpleseTM, FinesseTM, and Dairy-LoTM. SimpleseTM is made from whey milk protein whey. Its applications include ice cream, yogurt, cheese spread, and mayonnaise. Dairy-LoTM is a similar whey protein-based fat replacer used in low-fat cheeses, ice cream, and frosting. Carbohydrate-based fat replacers are made from polysaccharide materials such as starch,

gum, and cellulose that are derived from several plant sources. These substances are extracted from their source by chemical and enzymatic methods, purified, and ground to a fine particle size. Most starch and gum carbohydrate-based fat replacers hydrate well in water and swell to create a smooth, fat-like texture. Cellulose is also used in making fat replacer additives, but it must first be chemically treated to improve its interaction with water. Products such as AvicelTM, MethocelTM, and Solka-Floc® are cellulose-based and have applications in dairy products, sauces, frozen desserts, and salad dressing. Examples of non-cellulosic polysaccharides used as fat replacers in food include polydextrose, OatrimTM, inulin, and several gums. Polydextrose, commercially available as Litresse® or Sta-Lite®, is a synthetic polymer of glucose containing 10% sorbitol, and 1% citric acid. It provides only one-fourth the calories of sucrose, but can create a fat-like mouth feel. Additionally, polydextrose is a source of dietary fiber that contributes to a favorable intestinal microflora population and provides beneficial short-chain fatty acids. Polydextrose applications include dairy products and baked goods in which glucose components participate in Maillard browning. Oatrim is composed of the polysaccharide beta-glucan. This water-soluble glucose polymer is derived from enzymatically modified oat flour. It is commercially available under the trade names Beta-Trim and TrimChoice. Oatrim is a good source of soluble fermentable fiber that is beneficial as a substrate for intestinal microflora that produces short chain fatty acids. Oatrim fiber absorbs cholesterol from the gut and aids in the digestive process. Food applications for Oatrim include baked good, fillings, frostings, desserts, dairy beverages, cheese, salad dressing, and processed meats. Inulin is a fructose-based polysaccharide derived from chicory root. It has a slightly sweet taste that is approximately 10% as sweet as sucrose. Inulin is a soluble fiber that can be used as a fat replacer. Its food applications include yogurt, cheese, frozen desserts, whipped cream, and processed meat. A negative aspect of inulin is its potential activity as a FODMAP. FODMAPS are forms of carbohydrate that can be fermented in the gut and produce bloating, gas, and diarrhea.

The major lipid-based fat replacers include SalatrimTM and OlestraTM. These fat replacers are chemically modified and/or synthesized lipids. Salatrim (BenefatTM) is a reduced calorie fat replacer composed of triacyl glycerides that contains mixtures of hydrogenated short and long chain fatty acids. The name Salatrim is an abbreviation for **short and long chain acyl**

triglyceride molecule. Salatrim is a synthetic fat made by the process of interesterification. Olestra (OleanTM) is a synthetic fat replacer made by esterifying fatty acids to hydroxyl groups of sucrose. Olestra is a polyester fat so it is called a sucrose fatty acid ester. Olestra is a very stable fat-like compound that can be used in high heat cooking such as frying chips and fries. It is not metabolizable, has zero calories, and little or no flavor. Olestra has been commercially used in frying snack foods as a means to offset its high calorie content. Major negatives for the use of Olestra involve interference with fat soluble vitamin and carotenoid uptake in the gut. Anal leakage may be caused when olestra fried foods are over consumed.



Food enzymes

Enzymes are biological catalysts. As such, these protein molecules speed up chemical reactions without being transformed in the process. Enzymes are essential to digestion and energy production, vision, the immune system, and every other function needed to sustain life. Enzymes within food materials (endogenous) are responsible for numerous reactions that affect food quality. For example, ripening of fruits and vegetables is a result of endogenous enzymes that bring about changes in color, texture, and flavor. Exogenous enzymes, in contrast, are those added to food systems to bring about change. Exogenous enzymes provided by yeast convert starch to glucose and subsequently turn glucose into ethanol. Fermentation of milk performed by exogenous bacterial enzymes is used to make yogurt and cheese. Microbial enzymes produce many of the compounds that create distinctive cheese flavors and preserve a perishable commodity. Chymosin, also known as rennin, is a proteolytic enzyme widely used in cheese making. It hydrolyzes a specific casein protein and causes precipitation of this fraction from milk. The remaining fraction of protein is left in the whey along with lactose and other soluble constituents. Rennin is a mixture of enzymes containing chymosin. It has traditionally been extracted from the stomach of calves to make cheese. This practice requires sacrifice of the animal, its loss from the milk producing population of cows, and inconsistent cheese quality because of its heterogenous nature. Chymosin is now made using recombinant technology. In a process approved by FDA in 1999, the genes for chymosin were inserted into yeast that produces the enzyme through fermentation. The product of this process is called recombinant chymosin. It provides a consistent enzyme supply without the need for calf stomach.



Toxins and toxicants

There is a subtle distinction between the terms toxin and toxicant. Toxins are the natural products of organisms, such as substances found in snake venom and poisonous mushrooms. Toxins can occur in food as a result of biological processes or food processing. This section of the chapter describes some of the more often encountered toxic substances in food, but should not be considered as comprehensive. Toxicants are person-made substances, such as pesticides and herbicides, with the potential to cause harm if ingested. Toxicant substances can also enter foods through contact with packaging materials. A comprehensive review of naturally occurring toxins in food can be found in the work of [Dolan et al. \(2010\)](#) and also in Toxic Substances (Center for Disease Control 2018).



Food toxins

Plants are essential to life. They use sunlight to convert carbon dioxide and water into sugars in the process known as photosynthesis. In turn, sugars are converted into energy-rich polysaccharides molecules that animals use to sustain life. In the delicate balance between these different forms of life, plants have developed mechanisms that provide a competitive advantage and protect against predation. Some plants produce toxins as a strategy to enhance their survival. The discussion below describes examples of plant toxins and their occurrence in food ([Table 7.3 Food Toxins](#)).

Alkaloids

Alkaloids are a large and diverse class of plant-based molecules whose structure is characterized by a nitrogen containing ring. The word alkaloid is a contraction of the term alkali-like. This term refers to nitrogen compounds that form salts when neutralized by acids. Alkaloids are noted for pharmacological effects in animals, ranging from analgesic to poison. Morphine, opium, strychnine, quinine, ephedrine, and nicotine are members of the alkaloid family. Alkaloids are most often bitter tasting, a trait that reinforces the association between bitterness and poison. Pyrrolizidine alkaloids function in plants as a biological defense against insect predation. Variants of pyrrolizidine alkaloids (PA) are common to several plant families such as *Asteraceae*, *Leguminosae*, and *Orchidaceae*. PA is found in borage, comfrey, and herbs used in traditional Chinese medicine. It is not unexpected that pyrrolizidine alkaloids occur in herbal teas, infusions, and even some

Table 7.3 Food toxins.

| Substance | Food origin | Biological effects |
|---------------------------|---|---|
| <i>Alkaloids</i> | | |
| Solanine | Potatoes, Eggplant | Gastrointestinal |
| Caffeine/Theobromine | Coffee and cocoa beans | Increased heart rate and blood pressure |
| Furanocoumarin (Psoralen) | Grapefruit, parsnip, celery | Photodermatitis, inhibition of DNA synthesis |
| <i>Glycosides</i> | | |
| Amygdalin | Cassava, almonds, apricot pit, lima beans | Cyanide poisoning |
| Glucosinolate | Cabbage, broccoli, horseradish, mustard, rape seed | Impaired thyroid function |
| Saponins | Potatoes, beans, tomato seeds, and quinoa | Intestinal mucosal damage |
| <i>Proteins</i> | | |
| Lectins | Soybeans and other legumes | Anti-nutritional, hemagglutination, diarrhea |
| Trypsin Inhibitor | Soybean, lentils, and peas | Anti-nutritional (limits protein digestion) |
| Allergens | Milk, eggs, peanut, tree nuts, wheat, fish, and shellfish | Wide ranging, (skin rash to life-threatening anaphylaxis) |
| Histamine | Decomposition product of amino acid, histidine | Rash, edema, and gastrointestinal |
| <i>Other</i> | | |
| Phytoestrogens | Soybeans, nuts | Weakly mimics human estrogen hormone |

food supplements. Pyrrolizidine alkaloids also known to contaminate honey and milk as a result of transmission from bees to cows when they feed on silage and hay containing this alkaloid can also contaminate honey. PA represents a significant health concern because they are known to cause liver damage and cancer. There is a risk in processed food because PAs are stable to most cooking procedures, such as boiling. Solanine is a poisonous

glycoalkaloid found in potatoes, and eggplants. Tomatoes also contain a solanine-type glycoalkaloid, but it is not as toxic as the compound found in potatoes. The structure of solanine is composed of an alkaloid to which mono- and disaccharides are attached. Solanine can also be found in the flowering night shade plant that is sometimes used as a food. Potatoes produce solanine as a defense against insect and herbivore animal predation. Solanine is present in all parts of the potato plant but tubers contain the highest level. Freshly dug, potatoes will turn green when exposed to sunlight. The green color is due to chlorophyll, but light exposure also increases solanine content. Thus, green colored potatoes are a warning of elevated solanine content and should not be eaten. Bitter tasting potatoes are also a warning of high solanine content. While boiling potatoes does little to destroy solanine, higher temperatures such as in frying can reduce the content by half. Solanine is not a very potent toxin and few fatalities have been attributed to solanine poisoning. Symptoms of solanine poisoning are typically limited to gastrointestinal upset, such as vomiting and diarrhea. Caffeine and theobromine are structurally very similar methylxanthine alkaloids found in the seeds or beans of coffee and cocoa plants. Coffee beans predominantly contain caffeine at about 1%–2%, while cocoa beans contain 2% or more theobromine and 0.2% caffeine. Caffeine is a stimulant that generally improves cognition, reaction time, and coordination, but it also increases blood pressure. Caffeine is the most widely used psychoactive compound in the world. It contributes a pleasant bitter taste to coffee, tea, chocolate, and cola drinks. Caffeine is a weak toxin requiring doses of 10g per day to cause toxic effects in the average adult. A cup of coffee typically contains about 150 mg of caffeine. It would require consumption of over 50 cups of coffee to reach the level of toxic effects.

Furanocoumarins are phytochemicals produced in a variety of plants as part of their defense mechanisms against predation and microbial pathogens. Grapefruit, parsnips, and celery are common food sources of furanocoumarin. Furanocoumarins in grapefruit can have adverse effects on prescription medications. This is known as the grapefruit juice effect. Furanocoumarins inhibits an enzyme in the small intestine that degrades medications such as those used to treat hypertension, infection, and cancer. The inhibiting enzymatic breakdown of the drug causes individual to receive a much larger a dose than intended and this may have adverse side effects. Furanocoumarins also enter the system through skin contact and can cause very unpleasant photodermatitis skin reactions. Cleaning celery or coming into contact with weeds, such as giant hogweed, can cause

photodermatitis that presents as redness, rash, and large welts on the skin. In contrast, furanocoumarins in grapefruit are also beneficial as antioxidants with the ability to neutralize free radicals (Hung et al., 2017). Psoralens are compounds belonging to the furanocoumarin group. Plants use psoralens to ward off predation by a variety of animals. Psoralens are found in figs and the leaves of celery. They are mutagenic compounds that modify DNA by intercalating between thymidine residues of DNA molecules. When exposed to UV light, a chemical reaction forms a bond between psoralen and thymidine base. The result of this reaction is inhibition of DNA synthesis, cell replication, and darkening of skin. An interesting application of psoralens involves its use for treatment of serous skin diseases such as psoriasis, vitiligo, and skin cancer. Oral doses of psoralen make psoriatic cells susceptible to UV light and causes them to die off preferentially. The treatment is known as Psoralen UltraViolet A (PUVA) therapy.

Glycosides

Glycosides are compounds consisting of a sugar molecule (typically a monosaccharide) attached to a functional group through a glycosidic bond. A variety of functional group molecules, such as flavonoids, phenolics, steroids, thiols, and nitriles, are present as glycosides in food. The most toxic glycosides contain a nitrile functional group that potentially can be converted to hydrogen cyanide. These substances are thus termed cyanogenic glycosides. Cyanogenic glycosides become poisonous after enzymes act on the molecule and release hydrogen cyanide. The most significant source of toxicity occurs in plant materials that have been ground or crushed. Some gut microorganisms also contain the enzymes acting on cyanogenic glycosides and produce hydrogen cyanide that is absorbed into the blood stream. Cyanide's poisonous properties result from inhibiting energy producing pathways, especially in the heart and respiratory system. A lethal dose for most people is approximately 0.5–3.5 mg per Kg of body weight, which translates to about 50 mg for an adult male. Long term exposure to low levels of cyanide have serious consequences. Conditions such as goiterism, blindness, ataxia (loss of motor control), and paraparesis (progressive weakness of the legs) can result. Amygdalin is a cyanogenic glycoside present in several foods, including cassava, almonds, apricot pits, lima beans, clover, and flax. The molecule is composed of a glucose disaccharide linked through a glycosidic bond to a nitrile group. Cassava and the pits of stone fruits such as apricots contain levels of amygdalin that make them a potential health hazard. Cassava contains sufficient amygdalin

to generate approximately 50 mg of hydrogen cyanide per 100g of fresh root. An equally hazardous dose of hydrogen cyanide can also be obtained from the seeds taken from 10 apricot pits. Amygdalin is the source of synthetically derived substance called laetrile. Laetrile is purified from amygdalin after hydrolyzing one of its glucose units. It is important to note that laetrile is not a vitamin and is ineffective as a cancer treatment (Wade, 1977). Several individuals have been incarcerated in the United States for promoting it as such.

Glucosinolate is a glycoside found in cabbage, broccoli, horseradish, mustard, rape seed. The oil extracted from rape seed is known as canola oil. Glucosinolate is converted by the enzyme myrosinase to the active components, thiocyanate and a nitrile, when the plant material is sliced or crushed. They are a plant defense mechanism and a natural pesticide against predation by insects. However, excessive consumption of glucosinolate is known to impair thyroid production (hypothyroidism) and may result in enlargement of the gland in a condition called goiterism. Saponins are glycosidic compounds with surface-active properties. They are found in a variety of legumes such as soybeans, peanuts, garbanzo beans. They are also present in potatoes, tomato seeds, and quinoa. The surface-active property of saponin is due to the presence of both non-polar and polar groups that provide the ability to mix with both lipid and aqueous fractions. Saponin molecules are composed of a polycyclic ring structure and a carbohydrate group. The polycyclic ring is lipophilic and responsible for the molecule's structural diversity. Saponin ring structures occur in two chemical types: terpenoids and steroids. Conversely, monosaccharide carbohydrates such as glucose or galactose, provide aqueous solubility to saponins. Saponins are bitter tasting substances that have long been considered anti-nutritional factors in animal feed. They damage the membranes of intestinal mucosal cells and cause a condition known as leaky gut. Saponins bind cholesterol and reduces the amount of this essential molecule. This contributes to poor growth in animals fed materials high in saponins. The damaging effects of saponins on cell membranes can also cause hemolysis of red blood cells and result in anemia. More recently, triterpenoid saponins are suggested to have human health benefits including lowering serum cholesterol level and providing antioxidant and anticancer activity (Bishayee et al., 2011). Saponins are not destroyed by typical cooking methods. A frothy foam formed during boiling of beans is due to solubilized saponins and should be

discarded. Fermentation used in making products such as soy sauce is the only method known to eliminate saponins. A review of saponins in foods can be found in the work by [Price et al. \(2009\)](#). Fava beans contain the toxic vicine and convicine pyrimidine glycosides that are normally broken down in the gut. The absorption of vicine and convicine at sufficient levels triggers destruction of red blood cells and can cause a condition known as hemolytic anemia. The adverse effects most often occur in individuals with an inherited deficiency in the enzyme glucose 6 phosphate dehydrogenase.

Proteins

Most food proteins provide a source of energy and essential amino acids. There are few examples of proteins encountered in food which have toxic side effects. Some food proteins, especially those from plants, are well known sources of allergens that cause a variety of symptoms ranging from discomfort to anaphylaxis and death. Proteins, such as trypsin inhibitor and lectins (hemagglutinins), are examples of proteins with toxic and/or anti-nutritional properties. Ricin is a lectin and very toxic protein found in castor bean. Two mg (a dose about the size of several grains of salt) inhaled, ingested, or absorbed through the eyes is sufficient to kill an adult. Consequently, ricin has been used as a biological weapon.

Lectins are proteins that recognize and bind to specific carbohydrate-containing molecules. They have important roles in biological processes, including the immune system and metabolism. Lectins are not enzymes or antibodies, but have bioactive properties upon binding to receptor carbohydrates located on the surface of cells. For example, influenza virus contains a hemagglutinin that recognizes a glycoprotein on the surface of host cells. This allows it to attach and gain entry. Plants are the predominant source of the lectins often referred to as phytohemagglutinins. Lectins protect plants from microorganism, insect predation, and can pose a problem when eaten. Lectins are found in many plant foods including wheat and legumes (soybeans, peanuts, and beans) (see the review by [von Buul and Brouns, 2014](#)). Red kidney bean has the highest lectin level of all legumes. Food lectins are considered to be anti-nutritional factors because they interfere with the uptake of nutrients from the gut. This mechanism protects plants from being eaten by insect predators. Most animals, including human, are unable to breakdown lectins. The toxic effects of lectin in food include nausea, vomiting, and diarrhea. Some lectins, such

as soybean agglutinin, can cause damage to the cells forming the wall of the small intestine. Lectin's antinutritional properties can be reduced or eliminated by some processing techniques. Soaking for several hours followed by boiling is a time-honored method for preparing beans. This practice is effective because soaking allows a substantial portion of lectin to diffuse out and boiling destroys most of the remaining content. Fermentation is another effective method to reduce lectin content. Fermented products such as beer, tempeh, and soy sauce retain only small amount of the original lectin content. Wine is the exception because its fermentation process does not destroy lectins. Ricin is found in castor beans and the oil extracted from it (castor bean oil). The biological toxicity of ricin results from a complete shut-down of protein synthesis and eventually causes multiple organ failure. Ricin poisoning in foods is rare because the castor beans and extracted oil are always heated to destroy the lectin's biological activity. Trypsin inhibitors are common to many legumes such as soybean lentils and peas. Trypsin inhibitor acts in the small intestine to reduce the activity of the major digestive enzyme, trypsin. The net result is lower protein uptake which can negatively affect animal growth. Trypsin inhibitors are fairly heat stable proteins and remain active in processed soy protein, which is widely used in food products.

Food allergens are proteins that cause adverse immunological reactions soon after the ingestion or contact with food containing the offending protein. Reactions to food allergens involve the immune system and are mediated by IgE type antibodies. The allergic reaction can be initiated by very small amounts of protein. For example, a few mgs of peanut in 100g of chocolate can produce a serious reaction. Symptoms of food allergy range from mild skin rash, to welts, wheezing, and difficulty in breathing. Unfortunately, reaction to a food allergen can be lethal when it causes anaphylactic shock. It is estimated that 150 to 200 deaths occur each year due to food allergy-related anaphylaxis. Eight foods represent the most common source of food allergy, milk, eggs, peanut, tree nuts (walnuts, almonds, pine nuts, brazil nuts and pecans), soybean, wheat, fish, and shellfish. Food allergy affects 5% to 8% of children and 2% of adults in the United States. Fortunately, most of these reactions are not life-threatening. Proteins known to cause food allergy are diverse in nature, but share some common properties. Most allergens are stable to thermal processes and resistant to enzymatic digestion. However, it remains unclear regarding how protein structure and their resistance to digestion is involved in development of a food allergy (Breiteneder and Mills, 2005).

Histamine is a decomposition product of the amino acid histidine. Free histidine is converted to histamine by loss of its CO_2 group through the action decarboxylase enzymes. Histamine is found in all cells and present in most foods. Biologically, histamine has several roles. It functions as a neurotransmitter in inflammation processes, and in the immune response to allergens. Its role in allergy is to cause additional release of histidine from its stores in mast cells. This release triggers the symptoms associated with allergies, including runny nose, itchy eyes, and sneezing. However, the reaction to histamine is not a food allergy, rather it is another type of intolerance resulting from lack of enzymes (histamine-methyltransferase and diamine oxidase) necessary to break down the compound. Histamine naturally occurs in many foods such as, smoked meats, aged cheese, fish, shellfish, nuts, chocolate, and other cocoa-based foods. Additionally, foods produced by fermentation processes, such as beer, red wine, and cheese, can contain high levels of histamine. Ingestion of histamine-containing foods can trigger a reaction that resembles food allergy. Scombroid food poisoning is an example of a foodborne illness caused by eating fish high in histamine. Decomposition of fish muscle occurs quickly after fish are caught and results in high levels of histamine. High levels are also caused by storage at elevated temperatures or for extended time. Initial symptoms of scombroid poisoning initially include facial flushing, dizziness, and headache. This can progress to edema, rash, and gastrointestinal illnesses.

Phytoestrogens are substances bearing structural similarity to the female estrogen hormone responsible for fertility. Phytoestrogens, such as isoflavone, genistein, and coumestrol, are found in nuts, beans and other legumes. The structural similarity between phytoestrogens and estradiol is sufficient to cause a weak hormone-like effect in some animal studies. For example, isoflavone has a ring structure containing hydroxyl groups that is overall very similar to estradiol. Structural similarity enables phytoestrogen to weakly mimic the effect of human estrogen and may be beneficial to women approaching menopause. Phytoestrogens show some health benefits, including increased bone density and maintenance of hormone levels (Bacchiotti et al., 2007).



Microbial toxins

Toxins produced by bacteria, molds, and viruses are responsible for many foodborne illnesses and food poisonings world-wide. It is estimated that there are 48 million cases of foodborne illness and 3000 deaths each

year in the United States alone. In most cases the adverse consequences of encountering microbial toxins in food are short lived. However, some toxins have serious consequences. Aflatoxin from aspergils molds and botulinal toxin from *C. botulinum* cause life-threatening illness. This section describes notable examples of microbial toxins and their properties (Table 7.4). A more comprehensive summary of this important subject can be found in the publication Bad, Bug, Book and Foodborne Illnesses: What You Need to Know (FDA 2018).

Table 7.4 Microbial sources of food poisoning and foodborne illness^a.

| Organism | Sources | Symptoms |
|---------------------------------|---|--|
| <i>Algae (Dinoflagellates)</i> | Mussels, clams, oysters, scallops | Nausea, vomiting, and diarrhea Neurologic symptoms include tingling, numbness, and weakness |
| <i>Campylobacter jejuni</i> | Water, unpasteurized milk, undercooked meat, poultry, shellfish | Diarrhea, abdominal pain, fever |
| <i>Clostridium botulinum</i> | Improperly canned or vacuum-packed foods | Slurred speech, muscle weakness, paralysis and death |
| <i>Clostridium perfringens</i> | Cooked meat and poultry held for long periods of time at room temperature | Nausea, cramps, and diarrhea |
| <i>Escherichia coli</i> O157:H7 | Uncooked meat, unpasteurized milk or apple cider, fruits and vegetables | Severe diarrhea, abdominal cramps, and vomiting. Hemolytic uremic syndrome and kidney failure in children under 5 |
| <i>Listeria monocytogenes</i> | Ready to eat foods, soft cheeses from unpasteurized milk, smoked seafood, deli salads, especially made with ham, chicken or seafood | Fever, muscle ache, nausea, diarrhea, can cause miscarriage or death to newborns. |

Table 7.4 Microbial sources of food poisoning and foodborne illness^a.—cont'd

| Organism | Sources | Symptoms |
|------------------------------|--|---|
| Mycotoxins | Fungal infections of crops, such as corn, sorghum, and wheat | Acute and chronic effects gastroenteritis to life-threatening illness |
| Norovirus | Food, water, and infected individuals | Vomiting, diarrhea, headache Symptoms usually short-lived, 1–3 days |
| Salmonella | Contaminated eggs, poultry, unpasteurized milk or juice, cheese, seafood, fruits and vegetables | Diarrhea, fever, abdominal cramps, and death for immuno-compromised individuals |
| Shigella | Food and water contaminated by workers with poor hygiene e.g., especially salads and other foods | Diarrhea, (bacterial dysentery), abdominal cramps |
| <i>Staphylococcus aureus</i> | Food contaminated by skin contact from people who carry the organism, typically without symptoms | Severe nausea, abdominal cramps, and diarrhea occurring within 1 h after eating |
| <i>Vibrio vulnificus</i> | Uncooked or raw seafood; fish shellfish or oysters | Diarrhea, abdominal cramps, can become life-threatening |

^aAdapted from [USDA Food Safety and Inspection Service, 2017](#).

What is the difference between food poisoning and foodborne illness?

The terms food poisoning and foodborne illness are often used interchangeably, but they are different. Food poisoning refers to adverse reactions such as nausea, vomiting, and diarrhea resulting from eating a toxin-containing food. Symptoms of food poisoning usually occur within a few hours after eating. Botulism is an example of food poisoning caused by *Clostridium botulinum* toxin produced during its growth in a food, such as sausage. Foodborne illness is caused by eating food contaminated with pathogenic microorganisms. Illness results from toxin produced by the pathogen

growing in the gut. Toxin-producing strains of *E. coli* are examples of microorganisms causing foodborne illness. [Table 7.3](#) contains a summary of microorganisms most often associated with food poisoning and foodborne illness.

Algae

Dinoflagellates are unicellular organisms (members of the *Gambierdiscus* species) that attach to algae and produce neurotoxins such as ciguatoxin. Filter-feeding organisms such as mussels, clams, and oysters concentrate toxins into their flesh. The level of toxin is progressively increased as larger fish concentrate toxin via the food chain. Symptoms of eating contaminated fish or shellfish include both gastrointestinal and neurological disorders. Nausea, vomiting and diarrhea are typical gastrointestinal symptoms. Neurological symptoms are more significant and include numbness, tingling, muscle weakness that often progress to vertigo, irregular heartbeat, and low blood pressure. Neurological symptoms may persist for years. The risk of eating ciguatoxin-contaminated fish or shellfish is much greater in warm water areas. Ciguatoxin is very stable and its toxicity is not affected by cooking, freezing, or other food processing methods.

Campylobacter

Campylobacter jejuni is a pathogenic microorganism common to animal feces, especially poultry. *Campylobacter* is often found in unpasteurized milk and the cheese made from it. It is estimated to be third leading cause of foodborne illness in the United States and Europe. The illness called campylobacteriosis is an inflammation of the intestinal tract. Symptoms include diarrhea, vomiting, and abdominal pain. While the illness can be severe and debilitating, it is typically not life-threatening. However, those who experience *Campylobacter* illness are at increased risk of developing Guillain-Barre syndrome. This condition is characterized by rapid onset of muscle weakness in the extremities that progresses to the upper body. Difficulty in breathing can become life-threatening.

Clostridium botulinum

Botulinal toxins are neurotoxic proteins secreted by *C. botulinum* bacteria. These toxins are extremely lethal and require less than 1 µg to kill a 200 lb (90 kg) person. The toxin is produced during the germination of spores. Growth of *C. botulinum* bacteria requires an environment with little or

no oxygen, a pH above 4.6, and temperature above 20 °C. Biologically, the toxin works by blocking release of the acetylcholine neurotransmitter and causes muscle paralysis. Eight types of botulinal toxin are known and denoted by the letters A through H. Specifically, types A, B, E, F, and H are associated with human illness. Symptoms of *Clostridium botulinum* poisoning are called botulism and vary with the type of toxin ingested. Effects of the toxin include muscle weakness, blurred vision, vomiting and diarrhea. The lethal effects of *C. botulinum* toxin result from muscle paralysis, causing cardiac and respiratory failure. The toxin can be destroyed by heating to 100 °C for 15 min. However, *C. botulinum* spores can survive for years in soils and other environments. Perhaps the oldest known example of botulism is associated with sausage. Fermented sausage has been employed as a means to preserve meat for centuries, but conditions within the product (i.e., absence of oxygen, favorable pH and temperature) can enable the outgrowth of *C. botulinum* spores and toxin production. Home canning of low acid foods (pH greater than 4.6) like green beans, potatoes, and other vegetables also represent a potential source of botulism poisoning. Canning of low acid foods requires a stronger thermal process (i.e., at 121 °C for 3 min) to insure safety of the food. Processing these foods in a pressure cooker or boiling the food just before serving also increases their safety. Spores of *C. botulinum* can be found in honey and corn syrup, but are unable to grow because of the low water activity in these foods.

Clostridium perfringens

Clostridium perfringens is a common cause of food poisoning in the United States and Europe. It is an intestinal inhabitant of most animals. Like *C. botulinum*, the *perfringens* species are spore-forming organisms. Spores are ubiquitous in soils and decaying vegetation. They are heat-resistant and remain viable for years. Spore germination in food occurs quickly and produces an enterotoxin responsible for gastrointestinal symptoms such as diarrhea and cramps. Fortunately, the enterotoxin of *Clostridium perfringens* is heat labile and destroyed by temperatures at or above 74 °C (165 °F). A common scenario for *Clostridium perfringens*-caused food poisoning is the big turkey dinner. Typically, a large bird is roasted and served. If the remaining portion is left for a few hours at room temperature, *perfringens* spores will germinate and produce numerous infective bacteria and their enterotoxin. Eating that leftover turkey without reheating is very likely to

cause illness. More serious and life-threatening consequences can occur if the food contains large amounts of enterotoxin.

***Escherichia coli* O157:H7**

E. coli bacteria inhabit your gut as part of its normal microbiome and play a beneficial role. Notably, *E. coli* prevent intestinal colonization by pathogenic microorganisms. However, some *E. coli* strains are themselves pathogens that may cause foodborne illness. Several forms of *E. coli* are recognized as pathogenic, based on virulence factors they produce. These include enterotoxigenic *E. coli* (**ETEC**), enteropathogenic *E. coli* (**EPEC**), enterohemorrhagic *E. coli* (**EHEC**), enteroinvasive *E. coli* (**EIEC**), and enteroaggregative *E. coli* (**EAE**C), and diffusely adherent *E. coli* (**DAEC**) (FDA [Bad Bug Book](#), 2012). ETEC, EPEC, EHEC, and EIEC are responsible for milder forms of food borne illness that results in vomiting, diarrhea, and fever. A majority of illnesses (approximately 75%) are caused by *E. coli* belonging to the EHEC group. These produce Shiga toxin that causes infectious diarrhea (gastroenteritis), and inflammation of the digestive tract (enterocolitis). In severe cases, the infection can progress and cause loss of kidney function which is a life-threatening illness. The best known of this strain is *E. coli* O157:H7. It is responsible for thousands of hospitalizations and many deaths annually. A number of outbreaks due to *E. coli* O157:H7 have occurred in foods such as hamburgers from fast food restaurants, unpasteurized juices, and bagged salad greens. *E. coli* O157:H7 is spread by contaminated food, water, and person to person contact.

Listeria monocytogenes

L. monocytogenes is a pathogenic bacteria responsible for the foodborne illness known as listeriosis. The cause of listeriosis is a toxin called listeriolysin O produced by the bacteria. Listeriolysin O toxin is a virulence factor or a molecule that enhances the organism's ability to invade and colonize host tissues. Specifically, it enables the organism to enter the host's circulatory system and infect its cells and organs. *Listeria monocytogenes* is responsible for a variety of illness ranging from flu-like symptoms to more serious conditions. It causes sepsis, meningitis, spontaneous abortion, and encephalitis. Elderly, with a weakened immune system, and women who are pregnant are most at risk for developing listeria toxin diseases. Pregnant women are 20 times more likely than other healthy adults to contract listeriosis. Since the organism is able to cross the placental barrier, listeriosis can be deadly or cause life-long problem for the fetus. *Listeria* occurs in soil, water,

and animals. It is often found in poultry, cattle, and unpasteurized milk. The organism can inhabit processing plant equipment and cause repeated contamination of processed food such as, meat, soft cheeses, smoked seafood, store-prepared salads, fruits, and vegetables. One of the most dangerous properties of the organism is its ability to grow at refrigerator temperature (2–4 °C).

Norovirus

Norovirus is found in food, water, and on the food preparation or serving surfaces. Eating utensils can carry the organism. Norovirus are very contagious and easily transmitted by person to person contact. In many instances norovirus outbreak are associated with restaurants, dormitories, cruise ships, nursing homes, and daycare centers. This supports the person to person contact cause. Norovirus is very hardy and resistant to most household disinfectants. The recommended disinfecting agent is a 5% solution of bleach. Symptoms of norovirus infection are projectile vomiting, diarrhea, and abdominal pain. An electrolyte imbalance can result from excessive fluid loss. Fever and headache may also result from this infection. Fortunately, the illness produced by norovirus is short lived. Most people recover in 1–3 days without long term health consequences. Prevention of norovirus illness requires several measures, including thorough hand washing, rinsing of fruits and vegetables with a dilute solution of dishwashing detergent, and cleaning and sanitizing utensils and food preparation surfaces.

Salmonella

Salmonella is responsible for two types of illness: Typhoid fever and non-typhoid salmonellosis. Typhoid disease is caused by fecal contamination of water used for drinking and food preparation. It is a very serious illness with high fever and spread of the infection to other organs. The mortality rate from typhoid fever can be 10%. Gastrointestinal illness caused by non-typhoid salmonellosis is a prominent cause of foodborne illness in the United States. Outbreaks of salmonellosis have been caused by contaminated eggs, meat, poultry, milk, cheese, or juice, alfalfa sprouts, melon, nuts and spices. Over 1 million people are affected by salmonellosis each year in the United States. Infection and illness are caused by eating food contaminated by animal feces. This is called the fecal-oral route. Contact with pet turtles and reptiles has also been associated with human infection. Cooking kills salmonella, but the degree of heat treatment is important. Salmonella may be viable in eggs with runny whites or yolks. The safe

temperature for whole meat cuts (i.e., beef, lamb, and pork) is 63 °C (145 °F). Poultry, ground beef, egg dishes, and ground beef should be cooked to 74 °C (165 °F).

Shigella

Shigella bacteria are found in human feces. The organism spreads to foods through water or when handled by a person who does not wash their hands after a bowel movement. The illness caused by *Shigella* (shigellosis) causes diarrhea, fever, cramps, and typically subsides without treatment in a week. *Shigella* is the world-wide leader in causing diarrhea. Over 80 million cases of diarrhea and 74,000 deaths are attributed to infections caused by this organism annually. Children aged 2–4 years are most at risk. *Shigella* organisms invade the epithelial lining of the colon resulting in inflammation and dysentery. Once the gut lining has been perforated, *Shigella* enterotoxins can enter the blood and cause a potentially fatal condition known as hemolytic-uremic syndrome. This involves a combination of hemolytic anemia, acute kidney failure, and low platelet count.

Staphylococcus aureus

S. aureus produces a bacterial toxin while it grows on food. The toxin is a protein that causes gastrointestinal illness, vomiting and diarrhea that occur soon after contaminated food is eaten. The illness referred to as Staph poisoning is one of the most common types of food poisoning. Staph toxin is an enterotoxin with more than 20 identified isoforms. It is heat stable and resistant to digestive enzymes. Enterotoxins cause irritation and swelling of the small intestine in a condition known as enteritis. The onset of symptoms occurs within 6 h of eating toxin-containing food and often results in explosive vomiting with subsequent cramping and dehydration. An estimated 25% of the population carry *S. aureus* bacteria on their skin and are without symptoms. Thus, food handlers can be a primary source of Staph poisoning unless appropriate sanitary precautions (e.g., handwashing, gloves) are taken. Keeping food in the safe zone above 60 °C (140 °F) or below 4 °C (40 °F) is critical. Staph poisoning is associated with a variety of foods, including meat, poultry, eggs, dairy products and some vegetables.

Vibrio vulnificus

V. vulnificus is one of several *Vibrio* pathogens genetically related to the cholera causing bacteria, *Vibrio cholerae*, but it does not cause cholera. *V. vulnificus* is found coastal marine environments where freshwater and salty

sea water mix. More than 90% of the *Vibrio vulnificus* illnesses are associated with eating raw oysters from the Gulf coast. Illness can be caused by drinking the water or eating raw shellfish, such as oysters, shrimp, and clams contaminated with *V. vulnificus*. Initial symptoms of *V. vulnificus* illness are classified as acute gastroenteritis and include diarrhea, vomiting, and abdominal pain. Left untreated, the illness can progress to an immune response triggered by the infection as it enters the blood, this is called septicemia. *V. vulnificus* caused illness is fatal to about one-third of individuals in which the infection has spread to the blood. People with weakened immune systems, such as those with HIV/AIDS or those taking medicines to control arthritis, are at higher risk. Proper storage and handling of raw seafood is effective in reducing risk of infection. *V. vulnificus* grows rapidly on cooked food. For this reason, care should be taken to keep raw and cooked food from touching. *V. vulnificus* is destroyed by cooking to 63 °C (145 °F) for 15s. A quick blanching (1–2 min) in boiling water is a good precaution.

Mycotoxins

Mycotoxin is the general term referring to toxic substances produced by several types of fungi that infect commodities such as wheat, corn, sorghum, rice, cocoa beans, figs, spices (e.g., ginger and nutmeg) peanuts and tree nuts. Mycotoxins are ingested as a result of eating foods made from contaminated grains and cereals. Meat and milk products are also a human source of mycotoxin exposure that result from livestock fed contaminated silage and grain. Mycotoxins are produced by proliferating fungi. This condition is accelerated by high humidity. The major groups of mycotoxins include aflatoxin, ochratoxin, citrinin, ergot, patulin, and fumonisins.

Aflatoxins produced by *Aspergillus flavus* and *Aspergillus parasiticus* are potent carcinogens. They cause liver cancer in humans as a result of DNA mutation. *Aspergillus* species produce several subtypes of aflatoxin (B₁, B₂, G₁, G₂, M₁) and B₁ is the most potent carcinogen. Cow's milk is a source of aflatoxin resulting from aflatoxin-contaminated silage feed. In the cow's rumen, aflatoxin B₁ is converted to M₁ which is excreted into the milk. Crops with the greatest aflatoxin occurrence are peanuts, pistachios, and corn. Types A, B, and C ochratoxins are produced by *Penicillium* and *Aspergillus* species and occur as a contaminant of beer and wine. Type A ochratoxin is a carcinogen linked to tumors in the brain and urinary tract. Citrinin is a mycotoxin produced by *Penicillium* and *Aspergillus* species. Its mycotoxins are a contaminant in cheese (camembert) and fermented miso and soy products. Ergot are alkaloid type toxins

produced by fungi of the *claviceps* genus. When ingested from sources such as bread made from contaminated flour, a disease known ergotism can result. Symptoms of the disease in the digestive system include spasms, nausea, vomiting, and diarrhea. Ergot alkaloid can also spread through the blood and result in swelling and death of peripheral tissues. Ergot poisoning can be transmitted from mother to child through breast milk. Patulin is another mycotoxin product of *Penicillium* and *Aspergillus* species. It is typically found in rotting fruit such as apples. It is often a contaminant in apple products such as juice, jam, and cider. The level of patulin in apple juice is used as an indicator of quality. A maximum concentration of 50 $\mu\text{g/L}$ of juice is recommended as the upper limit of safety by the World Health Organization. Fumonisin, such as zearalenone, are toxins produced by *Fusarium* species most often found in corn. It is also found in wheat, sorghum, barley, rice and oats. Zearalenone-contaminated feed is of particular concern to livestock producers causing infertility and abortion in animals, with particular effect in swine (Table 7.4).

Mushrooms are prized for the flavors they contribute to foods, such as salads, soups, sauces, and cooked dishes. However, some poisonous varieties are difficult to distinguish from edible ones (Poisonous Mushrooms 2019). Incidents of mushroom poisoning most often involve unknowing individuals who gather wild mushrooms from the woods or the lawn. Visual identification of poisonous mushrooms is difficult. There have been cases when professionals have mistakenly picked a poisonous variety. The source of toxins is the fungi from which the mushrooms grow. Mushroom toxins are stable to typical processing treatments, such as cooking, freezing, or drying. They are grouped into four basic categories based on their physiological effects: protoplasmic poisons, neurotoxins, gastrointestinal irritants, and disulfiram-like toxins. Protoplasmic toxins represent the greatest risk because these can cause organ failure and death if treatment is not received soon after the mushroom is eaten. Illness from this type of toxin is characterized by a latent period without symptoms, followed by the sudden onset of severe symptoms from which the individual may not recover. Protoplasmic toxins include amanitin, hydrazine, and orellanine. Amatoxins, such as the octapeptide amanitin, are found in several mushroom species, including *Amanita phalloides* (Death Cap), *Amanita vberna* (Fools mushroom), and *Galerina autumnalis* (Autumn Skullcap). Poisoning is characterized by a 6–15 hr latent period after ingestion of the toxin-containing mushroom. The latent period is followed by a

sudden onset of abdominal pain, vomiting, diarrhea, and loss of strength. The disease progression includes liver and kidney damage in its final phase. The mortality rate from amanitin type of toxin can be 90%. Hydrazine type toxins, such as gyromitrin, are found in *Gyromitra esculenta* (False Morel) mushrooms. The disease follows a similar pattern of an asymptomatic latent period followed by sudden onset of headache, vomiting and diarrhea, but is less severe. The mortality rate is 2%–4%. Orellanine type toxins are found in *Cortinarius orellanus* (Sorrel Webcap) mushrooms. The long latent period (3–15 days) is followed by multiple symptoms that include burning thirst, nausea, headache, chills, and loss of consciousness. Progression of this disease causes kidney failure and death in up to 15% of the cases. The remaining categories are lower in their life-endangering risk and most people recover from the toxin-caused illnesses. Those who are elderly or have existing health problems have a higher risk of death. Neurotoxins of note include muscarine, muscimol, and psilocybin. They are responsible for profuse sweating, manic-depressive behaviors, and alcohol-like intoxications or hallucinations. Gastrointestinal irritants or toxins cause nausea, cramps, vomiting, and diarrhea. Disulfiram-like toxins result from production of an unusual amino acid (coprine) that interferes with the metabolism of alcohol. The individual who has eaten mushrooms containing this toxin is typically asymptomatic unless they also drink alcohol within 72 h. The combination of coprine and alcohol results in nausea and vomiting ([Bad Bug Book FDA, 2018](#)) ([Table 7.5](#)).

Tetrodotoxin

Tetrodotoxin is a potent neurotoxin found in pufferfish, porcupinefish, and blue-ringed octopus. The toxin is produced by bacteria species such as *Vibrio alginolyticus* and *Pseudomonas tetraodonis*. Bacteria live symbiotically in these marine and freshwater animals. Pufferfish, also known as blowfish or fugu, are one of the most dangerous foods eaten. The poison is a very potent neurotoxin that blocks sodium ion channels and prevents brain signals from activating muscle contraction. The toxin is concentrated in the liver and sex organs of pufferfish. If the fish is improperly prepared, tetrodotoxin can contaminate the meat of the fish. Eating low doses of the toxin causes tingling sensations in the mouth, fingers and toes. Higher doses produce nausea, vomiting, and respiratory failure. Lethality of this tetrodotoxin is similar to that of cyanide poisoning. Death can be caused by ingesting as little as 1 mg of the toxin. Tetrodotoxin also has an interesting pharmaceutical

Table 7.5 Mushroom toxins.

| Toxin type | Toxins | Species | Effects |
|----------------------------|--|--|---|
| Protoplasmic Toxins | Amanitin | Death Cap (<i>Amanita phalloides</i>) | Latent period followed by |
| | | Fools mushroom (<i>Amanita vberna</i>) | vomiting and diarrhea, |
| | | Autumn Skullcap (<i>Galerina autumnalis</i>) | resulting in organ failure, mortality rate approx. 90% |
| | Hydrazine | False Morel (<i>Gyromitra esculenta</i>) | Latent period followed by vomiting and diarrhea, Mortality rate 2%—4% |
| | Orellanine | Sorrel Webcap (<i>Cortinarius orellanus</i>) | Long latent period (3–15 days), liver and kidney damage. Mortality rate approx. 15% |
| Neurotoxins | Muscarine Muscimol, and Psilocybin | <i>Clitocybe dealbata</i> | Perfuse sweating, manic-depressive behavior, hallucinations |
| Gastrointestinal irritants | Allenic Norleucine | Green Parasol (<i>Chlorophyllum molybdites</i>) | Nausea, cramps, vomiting, and diarrhea. |
| Disulfiram-like toxins | Coprine | Coprinopsis atramentaria | Similar to above |

application as an agent to manage pain in cancer patients. Low doses of tetrodotoxin also block signals in nerve fibers responsible for pain.



Toxic metals in food

Metallic elements are minerals that originate in the earth’s crust. In general, minerals leach into water and enter the food chain when incorporated into organic molecules by microorganisms. Plants take up minerals in various forms and subsequently pass them up the food chain to humans. Metallic elements, such as such as sodium, calcium, iron, potassium, zinc and others, are often referred to as trace elements because they are needed in small amounts for normal biological functions. Iron, for example, is

essential to the oxygen carrying property of hemoglobin in blood. Calcium is required for bone strength and muscle contraction. However, elements such as lead, mercury, arsenic, and cadmium are classified as heavy metals and have no biological function. Aluminum, while technically not a heavy metal, has no biological function and is potentially toxic. The toxic effect is caused by binding to enzymes and other proteins and result in inactivation of biochemical pathways. Heavy metals are poorly eliminated from the body and this increases their toxicity. Lead, for example, has many toxic effects including inhibition of the synthesis of heme needed to make red blood cells. Toxicity of metals varies with the element and the amount ingested. Heavy metals are also suspect in causing cancer. They have genotoxic effects that damage DNA. It is unlikely that a single food represents a serious risk. Rather, the cumulative amount from all sources is more important. The following is a brief summary of the more significant toxic metals occurring in food. Additional information regarding metals in food and water can be found in the review by [Tchounwou et al. \(2012\)](#) and United States Food and Drug Administration summary on metals ([Metals, 2018](#)).

Aluminum (Al)

Aluminum is the most abundant metallic element in the earth's crust where it exists in the form of compounds such as aluminum sulfate or aluminum oxide. The metallic form of aluminum does not occur in nature, but is obtained from processing bauxite ore that is principally composed of aluminum oxide. Exposure to aluminum can occur by inhaling dust particles that contain the metal or from aluminum-contaminated drinking water and food. Small amounts are released from aluminum equipment used in food manufacture and preparation. If the material being cooked in an aluminum pot is acidic, higher levels of aluminum will be released. Fortunately, aluminum is poorly absorbed from the digestive track and most is eliminated in the feces. Investigations of aluminum's toxicity reveal it is a neurotoxin affecting cognitive and motor functions when fed at high levels to animals. This discovery led to a suggested link between aluminum and Alzheimer's disease, but analysis of data from several studies have not been conclusive. Aluminum is found in foods additives such as baking powder (sodium aluminum sulfate and sodium aluminum phosphate), anticaking agents (sodium aluminosilicate), and colorants (FD&C blue). Over the counter medications, such as buffered aspirin contain 10–20 mg/tablet and antacids contain 100–200 mg/dose, in the form of aluminum hydroxide. It is estimated that the average adult consumes about 7–9 mg/kg of body weight

of aluminum per day. Most of this is from food additives and analgesics. This level of daily intake is equivalent to about 650 mg for a 175lb person. Although the neurotoxicity of aluminum has not been established for healthy individuals, a precautionary recommendation is to reduce the level of intake.

Arsenic (As)

Arsenic is a toxic heavy metal found in soil and water in organic and inorganic (salts) forms. Rice is a food with high potential for becoming contaminated with arsenic because the plants are very efficient in absorbing it from soil as they grow. The organic form of arsenic is methylarsonic acid. There are two inorganic arsenic forms: arsenite (NaAsSO_2) and arsenate (Na_3AsO_4). Inorganic arsenate (Na_3AsO_4) is the most toxic form. Its toxicity stems from its role as an easy substitute for phosphate which is a cofactor for enzymes involved in metabolism and other processes. Long term consumption of arsenate-containing food is associated with increased risk of cancers of the skin, bladder, and lungs. The risk of cancer is believed to be linked to arsenic inhibition of enzymes that repair DNA damage. The risk of cancer, while not dramatically high, increases with the frequency of consumption. Because rice is a food staple for much of the world's population, a limit of 100 ppb (parts per billion) has been set by FDA for arsenic in rice. The limit for arsenic in infant foods is much lower with 1 ppb in infant rice cereals and formula. Infant apple juice has a limit of 10 ppb arsenate.

Cadmium (Cd)

Cadmium is a toxic heavy metallic element widely found in the earth's crust. Mining, metal processing, and battery production are sources of cadmium exposure. Cigarette smoke also contains cadmium. However, food represents the major source of cadmium for most people. Cadmium is present at low levels in a variety of food, including green leafy vegetables, seaweed, potatoes, and grains. Animal sources include liver, kidney, and shellfish. Among these foods, rice, seafood, edible offal, and vegetables represent greatest source of cadmium. Ingestion of cadmium can cause kidney damage. Cadmium can also cause gastrointestinal symptoms ranging from nausea and vomiting to erosion of the gut epithelium. The later and more serious effect is thought to result from generation of reactive oxygen species (ROS) in reaction to cadmium. Adverse biological effects of cadmium, production of ROS, and inhibition of DNA repair mechanisms are sufficient to classify cadmium as a carcinogen. The maximum level of cadmium exposure for adults is $2.5 \mu\text{g/kg}$ of body weight. This amount is equivalent

to approximately 205 μg for a 175lb person. The maximum limit for cadmium in bottled water is 5 ppb.

Lead (Pb)

Lead is a toxic heavy metal that occurs ubiquitously in soil, water, food, and air as lead-containing dust particles derived from paint. Until 1996, lead was commonly added to gasoline as fuel for cars and trucks. Food crockery and crystal glasses commonly contained lead that could leach into food, especially if the food or beverage was acidic. Lead and other heavy metals have been shown to contaminate traditional Ayurvedic medicines used for centuries in India. Lead is responsible for a wide range of health problems including; anemia, kidney, and brain damage. Cardiovascular and reproductive system problems are also linked to lead in the environment. Among the more serious outcomes of lead ingestion results from its action as a neurotoxin. This is especially harmful to young children. Lead affects the developing brain with life-long consequences that include cognitive impairment and learning and behavioral problems, among other things. In view of lead's toxicity, FDA guidelines for the level of lead in food and water are very low, in the ppb (part per billion) range. The levels for lead in food and bottled water and drinking water are 5 ppb and 15 ppb, respectively.

A sad case of lead pipes and chemistry

A series of missteps and mistakes by government officials in Michigan precipitated a public health crisis resulting in the exposure of over 100,000 (40%) Flint Michigan residents to high levels of lead in their drinking water. The crisis began in 2014 when the city changed its source of municipal water to the Flint river. Compared to the original source of water, the Flint river contains high levels of the highly corrosive element chloride. The second mistake was not adding corrosion inhibitors, such as orthophosphate to the new water source. Orthophosphate forms a chemical bond with lead water pipes and prevents its oxidation and subsequent release of the toxic metal into drinking water. Without the protective coating, chloride in the water accelerated the corrosion process and caused even higher levels of lead to be released. The level of lead in Flint Michigan's water reached 100 ppb and persisted for almost two years. During this time, residents had to rely on bottled water for drinking and cooking. Outcomes of these mistakes have been costly. Millions of dollars have been spent to rebuild the water system and criminal charges have been filed against officials. Most costly of all is injury to the health of many Flint residents, especially

children. Their blood lead levels remain high and the effects on their lives is potentially profound.

Mercury (Hg)

Mercury is a toxic metallic element found in soil, water, and air. The presence of mercury in the environment results from multiple sources, including leaching from the soil, industrial waste, volcanic eruptions, and emissions from coal burning energy plants. Mercury exists in inorganic or elemental mercury and organic or methylmercury forms. Elemental mercury is a liquid at room temperature and can volatilize. Exposure results from skin contact or inhalation. Organic mercury occurs as methylmercury which is a product of the action of microorganisms on the inorganic form. Major sources of mercury exposure result from eating fish and shellfish and from dental amalgams. Fish, especially long-lived species like albacore tuna, shark, and swordfish contain the highest level of mercury because they are bioaccumulators of methyl mercury. Shellfish and other aquatic animals feed on mercury-containing algae and plankton. These animals, in turn, are sources of food for larger fish. This effectively concentrates the level of mercury in their tissues. Once absorbed, mercury is poorly eliminated and is highest in fish at the top of the food chain. Mercury is a potent neurotoxin. Adverse effects of methylmercury include effects on cognitive functions of memory, speech, and fine motor skills. Children and fetuses are most susceptible to methylmercury during fetal development. It can pass through the placenta and enter the fetus. Methylmercury is a suspected carcinogen, linked to its ability to cause depletion of cellular antioxidants. The subsequent increase in reactive oxygen species (ROS) results in DNA damage that is a known initiator of cancerous processes. Exposure to inorganic mercury forms, such as elemental mercury or mercury compounds, can also cause adverse health effects. Symptoms of inorganic mercury exposure include headache, cognitive impairment, and muscle weakness. Exposure to high levels of mercury can result in respiratory failure and death. The FDA limit for mercury in bottled water is 2 ppb.



Process induced toxins

Acrylamide

Acrylamide is a neurotoxin and carcinogen formed in food materials as a result of cooking. Specifically, acrylamide is produced by heat-induced chemical reactions collectively known as the Maillard reaction. This reaction

is widely recognized as responsible for the color and flavor of cooked foods. Discovery of acrylamide toxin-producing chemistry is rather recent (Tareke et al., 2002). The major reactants in food are the amino acid asparagine and reducing carbohydrates such as glucose and fructose. The amount of acrylamide produced in a food varies with temperature, highest at 247 °F (120 °C), type of sugar, fructose > glucose > sucrose, and moisture level, low moisture > high moisture. Foods such as French fries, potato chips, cookies, crackers, breakfast cereals and coffee have the highest levels of acrylamide. Acrylamide's neurotoxic effects include cognitive impairments such as memory loss, confusion, numbness in the limbs, and muscle atrophy. It has demonstrated ability to be genotoxic and cause cancerous tumors in mice. FDA and other regulatory agencies consider the present state of science regarding acrylamide's toxicity inadequate to make recommendations on the allowable limits in foods. However, recommendations regarding methods to reduce the amount of acrylamide formed in foods can be found in *Guidance for Industry: Acrylamide in Foods*, a 2018 publication from the Center for Food Safety and Applied Nutrition of the FDA.



Toxicants

Bisphenol A

Bisphenol A (BPA) is a component of materials used to make polycarbonate. These include hard, clear plastic, beverage containers and epoxy resins used to form protective coating inside metal cans. Concern has arisen over the unintended migration of bisphenol A from plastic bottles and can coatings into foods. Heating the food while in the container increases the level of BPA released. Concern over BPA ingestion is linked to reports of neurotoxicity and estrogen-like effects in animal studies. As a result of this concern about BPA in reusable plastic food containers, a number of states in the United States have banned BPA in bottles, mugs, and tableware used in infant feeding. The European Food Safety Authority has set a safe level termed the Tolerable Daily Intake of 0.05 mg per kg of body weight, equivalent to about 4 mg for a 175lb person. This level is about 100 times lower than the No Observable Adverse Effect Level (NOAEL) guideline used in toxicity assessment. It should be noted that BPA is unmodified and rapidly eliminated in urine. While safety and risk assessments are on-going, the regulatory agencies of the United States, Canada, Europe, and Australia have concluded that BPA is not expected to be a health

risk. Precautions that individuals can take to avoid BPA exposure include buying and storing food in glass containers and refraining from use of plastic containers to microwave food.

Dioxin

Dioxins are a group organic compounds that are persistent environmental contaminants. They are man-made products typically resulting from incinerating chlorine compounds and hydrocarbon (petroleum) compounds. They are also formed as by-products of polyvinyl chloride (PVC) plastics. Dioxin is a potent carcinogen and has damaging effects on immune and reproductive systems system. Dioxins find their way into the food chain because of their hydrophobic nature. Dioxin in the soil is taken up by microorganisms and plants that are concentrated (bioaccumulated) in meat, milk, egg, and animal fats. Meat and milk can contain 10 to 20 times the dioxin level of soils. They may also persist in fat depots of the body. Because of dioxin prevalence in the environment, avoiding it is almost impossible. It is possible, however, to reduce dioxin intake by limiting consumption of animal-based foods and switching to a plant-based diet containing fruits and vegetables. A more comprehensive approach to reduction of dioxin exposure for everyone is to seek better waste incinerators with restrictions on the types of materials burned and limits on emitted dioxins. Additionally, animal feed and feedlot soils should be monitored for dioxin levels.



Summary

Food additives are used in processed foods to enhance safety, add color and flavor, modify texture, and preserve food. Food additives, including colorants, are a major source of confusion and controversy. For example, the terms natural and artificial (synthetic) have straight forward meanings to most, but are confusing when it comes to food labeling. Natural flavor, as defined by the US Code of Federal regulations is “a natural flavor is the essential oil, oleoresin, essence or extractive, protein hydrolysate, distillate, or any product of roasting, heating or enzymolysis, which contains the flavoring constituents derived from a spice, fruit or fruit juice, vegetable or vegetable juice, edible yeast, herb, bark, bud, root, leaf or similar plant material, meat, seafood, poultry, eggs, dairy products, or fermentation products thereof, whose significant function in food is flavoring rather than nutritional.” Thus, any substance not included in this definition and added to another food is considered to be an artificial additive and the product must be labeled as such. For example, yogurt containing only

blueberries as flavoring can be labeled as “blueberry yogurt”. However, if a blueberry extract is also added, the product must be labeled “naturally flavored blueberry yogurt with other natural flavors”. It is no wonder that there is confusion. The controversy about the safety of food additives is made worse by claims of adverse effects in the popular press. The evidence for many of these claims is weak, re-evaluations of food additive safety with current science and knowledge, by food regulatory agencies, is warranted (Carocho et al., 2014).

Glossary

Adulteration: A food that does not meet a legal standard of identification or contains a poisonous substance

Amphiphilic: Substance possessing both hydrophilic and hydrophobic and is thus compatible with water and oil.

Artificial (synthetic) additive: Substance added to foods for any of the purposes listed above but is man-made.

Bacteriocin: Short peptides having bactericidal or bacteriostatic effects on other species.

Botulism: Disease resulting from ingestion of toxin secreted by *Clostridium botulinum*. The toxin blocks neurotransmitter release and prevents muscle contraction.

Certified color additive: Any dye, pigment, or other substance used impart color to a food, drug, or cosmetic.

Chelating agent: Substances that tightly bind metal ions such as copper, iron, calcium, and zinc through coordination of electrons.

Colloid: Homogeneous mixture of one substance dispersed in another, without separation.

Deliquescent: Property of a substance to absorb moisture from the atmosphere until it dissolves.

Direct additive: Substance added to a food for use in processing, packaging, or to provide a desired effect such as a; colorant, preservative, nutrient, antioxidant, or sweetener.

Enterohemorrhagic: Medical term meaning bloody diarrhea.

Fat mimetic: Biopolymer derived from protein, carbohydrate, or lipid modified by physical, chemical, or enzymatic means to imitate the eating properties of fat.

Food regulation: An enforceable law regulating the production, trade, and handling of food.

Free Radical Scavengers (FRS): Substances that stop free radical reactions by donating a hydrogen atom. Examples of FRS include ascorbic acid and alpha tocopherol, vitamin C and E respectively.

Free radical: An atom, ion, or molecule that has unpaired valence electrons. The high reactivity of a free radical comes from the need to gain or lose an electron and achieve a stable configuration.

Gastroenteritis: Illness caused by inflammation of the gastrointestinal tract. Vomiting and stomach cramps and diarrhea may also result.

Genotoxic: Property of chemical agents resulting in damage to DNA without causing a mutation. The damage may lead to cancer.

GRAS: Acronym standing for Generally Recognized As Safe and refers to a number of substances used as additives in food, drugs and cosmetics.

Heavy metals: Metallic elements characterized as having high density and poisonous properties.

Hydrophilic: Substance that is compatible with water, mixes in and or dissolves in water.

Hydrophobic: Substance that is not compatible with water and repels it. “water hating”.

Hygroscopic: Property of a substance to absorb moisture for the atmosphere.

Indirect additive: Substance that migrates into food from the environment which can include; growing, processing, and packaging.

LD50 value: Amount of a toxic agent that is sufficient to kill 50 percent of a population of animals.

Lectin: Protein that binds to carbohydrate molecules on the surface of cells, a mechanism for the regulation biological processes such as immunity.

Mutation: Heritable alteration in nucleic acids of an organism.

Natural additive: Substance found naturally in some foods and extracted for use in others.

Nanoparticle: Very small particles ranging in size between 1 and 100 nanometers (10^{-9} meter).

Terpenoid: Class of organic compounds composed of a repeating, five carbon (isoprene) subunit. Their composition is limited to carbon and hydrogen atoms only and thus are not water soluble.

Toxicant: Person-made substances such as pesticides and herbicides which can be harmful to animals.

Toxin: Poisonous substance produced by organisms to provide biological advantage, such as protection against predation.

Vitamin Fortification: Addition of a vitamin to a food for the purpose of making it a superior source of that nutrient.

Vitamin Restoration: Addition of a vitamin to a level normally found in that food.

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Further reading

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Review questions

1. What are the important outcomes of the Pure Food and Drug Act of 1906?
2. Why is adding water to milk considered to be an act of adulteration?
3. Describe the term GRAS and its importance to food additives.
4. Give one example each of an acid and a base used as food additive.
5. What is “Chemical Leavening”? Give an example of how it works in a food system.
6. What are the major reasons for adding salt to food?
7. What is the function of acetic, propionic, and sorbic acids in food?
8. Give two reasons for adding nitrite to processed meats.
9. What is the health concern for nitrite in bacon?
10. Why is sulfite used in food systems? Give two examples.
11. What is a chelator and why are they added to foods?
12. Why is ascorbic acid added to food systems? Give two examples of its use.
13. Define the term hydrocolloid and give two examples of their use as food additives.
14. What is the importance of gels in processed foods? Give two examples of substances used to form gels in food systems.
15. What is rum caviar and how is it made?
16. Give two examples of emulsifiers and describe their use in food systems.
17. What is a fat replacer? Give an example.
18. Give an example of enzymes used as food additives.
19. Define the terms toxin and toxicant. Give an example of each.
20. Give an example of a toxicant that results from the Maillard reaction.
21. What is trypsin inhibitor and where is it found?
22. Name 2 sources of trypsin inhibitor.
23. What is the difference between direct and indirect food additives?
24. What are mycotoxins? Give two examples.
25. Name three toxic elements and foods they might be found in.