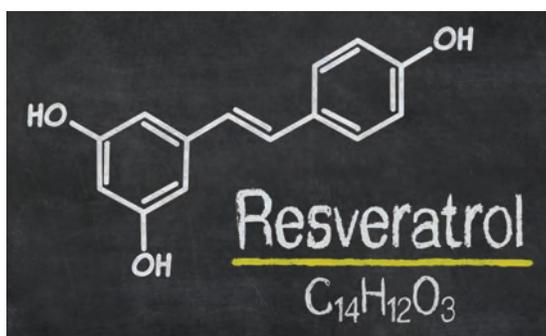


The Chemistry of Food & Health: Molecules and Metabolism



An ACS-e! Discovery Report examining how food interacts with biochemistry to impact health, how food scientists develop healthier food formulas, how chemical companies support the expanding supplements market, and how analytical chemistry advances food safety and quality



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The Chemistry of Food & Health: Molecules and Metabolism

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I. INTRODUCTION:

It's clear that diet influences our health. Protein, sugar, fat, and nutrients in food provide components for biochemical cycles crucial to cellular function. Aberrant interactions among those cellular cycles can lead to disease, and poor nutrition is often cited as one reason for an increase in chronic diseases that strain individuals, families, and societies.

As of 2012, about half of American adults had at least one chronic health condition, like cancer, diabetes, or heart disease. According to the American Heart Association, 34 percent of American adults have metabolic syndrome, a collection of physical symptoms of biochemical imbalances (such as a large waistline or high blood pressure) that increase a person's risk for heart disease, diabetes, and stroke.

Government agencies and medical associations provide dietary recommendations to help patients manage some chronic conditions. A diet low in saturated fat is recommended to control heart disease, and one low in salt is recommended to reduce blood pressure. Diabetics must watch the amount of sugar they consume, making dietary choices to control the amount of glucose in their blood and compensate for metabolic imbalances in insulin production.

When looking for advice about eating to maximize health, there's no shortage of diet recommendations in the nutrition section of libraries and bookstores. The guidance varies from favoring meat to favoring vegetables to only eating raw food. Despite dietary differences, each approach carries a similar promise of vitality.

The challenges of gathering comprehensive data from people about their diet and health make it tricky to run scientific studies that connect specific diets -- or foods -- to health. Many studies can only identify correlations between diet and disease. Academic, government, and corporate food scientists trained in chemistry can provide information about another piece of the diet and health puzzle: the molecular relationships between food ingredients, nutrient composition, cellular function, and organism metabolism.

Along with identifying components like fat, salt, and sugar that are detrimental to health, there's a growing research focus on the beneficial components of food, as seen in publication trends from the *Journal of Agricultural and Food Chemistry*. In 2008, about 18% of papers about antioxidants came from manuscripts relating to healthy food, up from 5% in 1997.⁽¹⁾ Increases were also seen for papers about olive oil and red wine.

Consumers are increasingly aware of a relationship between food and health, and are reading nutrition labels, avoiding particular additives, and consuming nutritional supplements. Food scientists are responding to consumers' demands by creating healthier food formulas. The demand also creates a market for fine chemical companies. Some are designing natural

alternatives to synthetic flavors, colors, preservatives, and texture components. Others are producing pure ingredients for supplements.

A final chemical connection between food and health is often most apparent when something goes wrong: a shipment of produce contaminated with microbes or an adulterated food product. Analytical chemists are working to develop methods to ensure food safety and quality from the field to your shopping cart.

II. FRUITS, VEGETABLES, AND WHOLE GRAINS

Dietary guidelines in the United States recommend eating a variety of nutrient-dense fruits, vegetables, whole grains, beans, nuts, and lean meat. These foods have been linked to a reduced incidence of chronic health conditions like obesity, heart disease, and diabetes.

Scientific investigations of the connections between diet and health are challenging to design and interpret, and they often generate conflicting recommendations. One challenge comes from precisely identifying someone's diet. Participants often under-report the types and amount of food consumed during a study period. Also, health effects, measured by tracking particular diseases in a study population, can be difficult to detect or quantify. With heart disease, for example, risk factors like high blood pressure or cholesterol levels can be measured. However, risk factors for other diseases like cancer are more difficult to identify⁽²⁾

Accurately interpreting the results of nutrition studies requires understanding a study's design to know if the results imply that a particular diet is correlated with a particular health outcome, or if they suggest that diet causes the health outcome. Studies that identify correlations between diet and health effects are called observational studies. The gold standard for determining causal connections between diet and health involves randomized controlled trials where some participants change their diet in a particular way that others do not. Many nutrition studies are observational, though observation can fuel randomized trials.

Once nutritionists identify beneficial foods through clinical trials, chemists then identify the molecular components of the food that provide the beneficial effects. Many of these molecules belong to a class of compounds called polyphenols.⁽³⁾ These compounds are responsible for the anti-inflammatory, antioxidant, or anti-cancer properties of foods like coffee, chocolate, red wine, and olive oil. Polyphenols, in the form of anthocyanins, also give berries their red, blue, or purple color. And foods may contain more polyphenols than researchers recognize. In 2012, researchers in Spain noticed the portion of the dry weight of carob pods considered to be dietary fiber actually contained polyphenols that were insoluble in typical organic solvents.⁽⁴⁾ Like their extractable relatives, these non-extractable polyphenols could influence gut health.

THE “MEDITERRANEAN” DIET

In 1958, the Seven Countries study started following 16 groups of participants from seven countries, examining the effect of diet on risk factors for heart disease. The researchers found that people living in Crete, Greece, and southern Italy tended to live longer and have less heart disease than populations from other countries.

Further observational studies have confirmed the health benefits of a “Mediterranean diet” consisting of fruit, vegetables, olive oil, nuts, beans, and whole grains. This diet also contains small amounts of meat and dairy, along with red wine in moderation. An analysis of clinical trials of the Mediterranean diet shows that it reduces some risk factors for heart disease, but concludes more evidence is needed to study the effects of the diet in different populations.⁽⁵⁾ Chemists are analyzing components of the Mediterranean diet, measuring the carbohydrates that contribute to the dietary fiber content of whole grains and beans, tracking the fat content of nuts, and classifying polyphenols in olive oil and red wine.

Whole grains and legumes are important components of many diets around the world. They serve as complementary sources of protein, energy-providing carbohydrates, and satiety-inducing fiber. There is significant evidence for a correlation between whole grain consumption and lowered blood pressure. But there is limited evidence for a connection between whole grains and reduced cardiovascular disease, type 2 diabetes, or weight loss.⁽⁶⁾ Whole grains are cereals that come from the Gramineae family of grasses. This family includes wheat, rice, barley, corn, rye, oats, millet, sorghum, and wild rice. Amaranth, buckwheat, and quinoa are considered pseudocereals, as they belong to a different family of plants.⁽⁶⁾

A grain contains three components: the starchy endosperm, the fiber-packed outer layer of bran, and an inner reservoir of nutrients called the germ. The bran and germ are removed when a grain is refined. Many commercial whole grain foods are reconstituted by adding components of the bran and germ in the relative proportions found in the natural seed.⁽⁶⁾ The structure of the grain may be important for its overall health benefits; bread made from reconstituted whole grains produces the same spike in blood glucose as bread made from refined flours.⁽⁶⁾

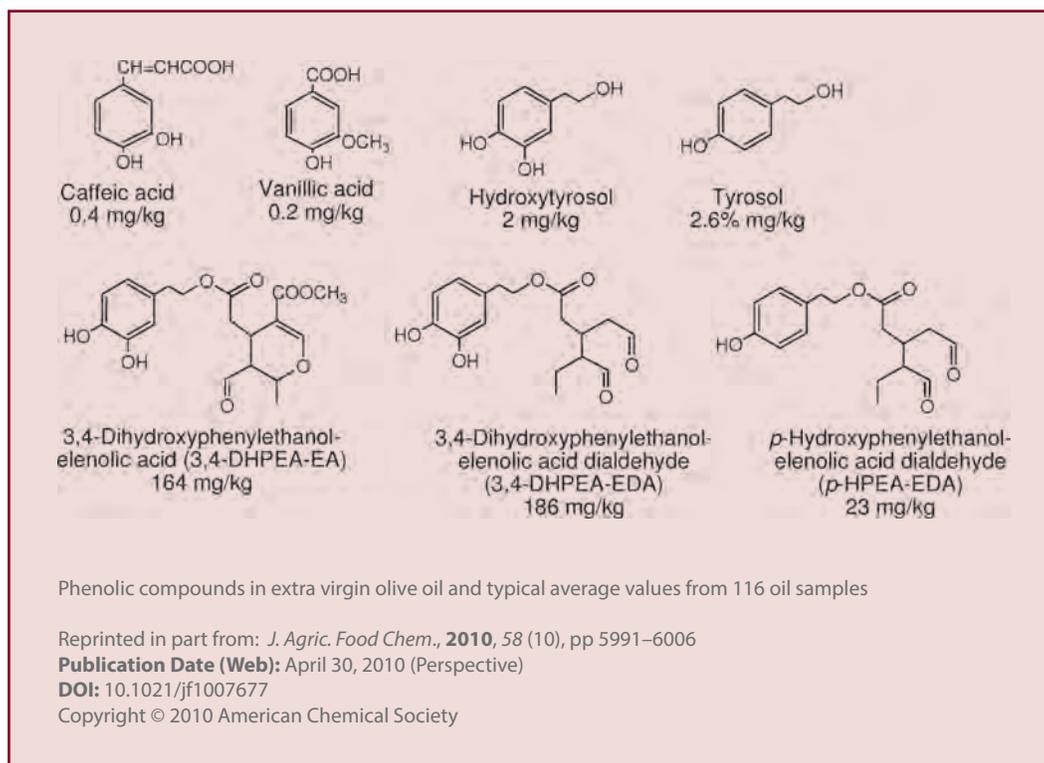
The bran and the germ of whole grains provide dietary fiber in the form of indigestible polysaccharides, oligosaccharides, and lignin. Observational studies suggest that fiber is an important component in the connection between whole grain consumption and reduced risk factors for obesity, diabetes, and heart disease. There is also some evidence that links whole grains to reduced risk for colon cancer; one reason could be the nature of the polyphenols in whole grains.⁽⁶⁾ Polyphenols in whole grains travel to the colon attached to insoluble components of plant cell walls. Soluble phenols from fruits and vegetables, however, seep through the small intestine and escape the digestive tract before reaching the colon. Whole grains are also a good source of protein, though they are low in the amino acid lysine. However, pulses – crops raised solely for dry grain – provide this amino acid, among others. That means beans and whole grains

are dietary complements; together, they provide about 65% of the world's protein.⁽⁶⁾ Some examples of pulses include chickpeas, lentils, and dry beans.

Starchy carbohydrates form the bulk of the weight of pulses. That starch is digested 45% slower than starch from cereal grains. The composition of legume starch, as well as its crystallinity, makes it harder to digest. However, the digestive troubles that some people associate with beans is due to easily digested oligosaccharides like raffinose, stachyose, and verbascose, not the slowly digested starches.⁽⁶⁾ Pulses are also a good source of vitamins and minerals. Beans contain enough folic acid, that two or more servings of some pulses can provide 100% of the daily recommended amount.⁽⁶⁾ Lentils, followed by red kidney beans and black beans, have the highest amount of antioxidant and anti-inflammatory polyphenols.

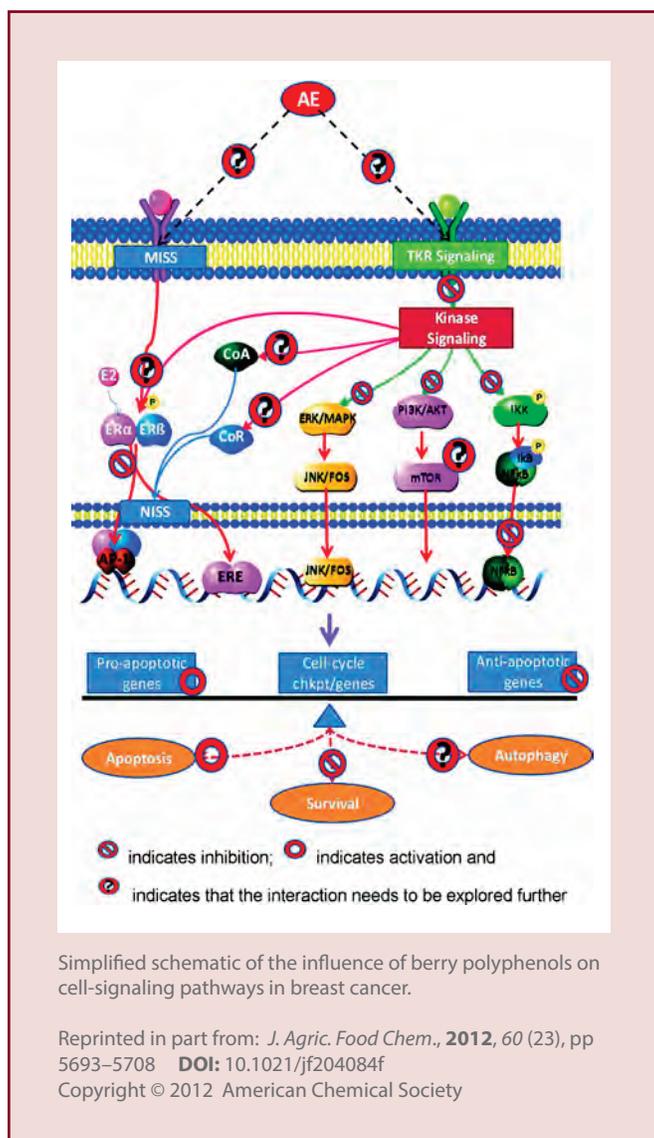
Uncooked beans contain enzymes, enzyme inhibitors, and lectin proteins that can reduce the bioavailability of nutrients. However, these biomolecules usually unfold and break down when the beans are cooked, and they can be beneficial on their own. For example, a lectin from kidney beans is used as antiretroviral therapy for patients infected with the human immunodeficiency virus (HIV).⁽⁶⁾ Randomized controlled trials link pulse consumption to decreased blood pressure and management of type 2 diabetes and metabolic syndrome. Dietary intervention trials show that pulses reduce cholesterol levels as well.⁽⁶⁾

Other well-studied components in the Mediterranean diet are olive oil and red wine. Chemists have analyzed and classified the antioxidants and heart-healthy unsaturated fatty acids in olive oil.⁽⁷⁾



Edwin Frankel, a food chemist at the University of California, Davis, recently reviewed dietary studies involving the molecular components of olive oil.⁽⁸⁾ He concluded that validated analytical methods are needed before the constituents of olive oil are linked to health effects.

Epidemiological studies in the mid-1990s found a connection between decreased incidence of heart disease in a French population, despite high consumption of saturated fats. The effect was attributed to daily consumption of red wine, and since then many studies have sought to learn more about this connection. The results, however, often conflict.⁽⁹⁾ There are debates over whether polyphenols or ethanol in wine confer more health benefits, though the two components likely work together to reduce heart disease, type 2 diabetes, and cancer. Alcohol and polyphenols reduce clotting and inflammation. Alcohol increases the amount of high-density lipoprotein, the “good” cholesterol that shuttles excess cholesterol out of the blood. Polyphenols also act as antioxidants. One polyphenol, resveratrol, has been linked to reducing tumors in animal models of many types of cancer.⁽⁹⁾ It also extends the life spans of fruit flies and worms. The compound has become a popular target for biotech companies, though there is debate over the types of receptors that it activates.⁽¹⁰⁾

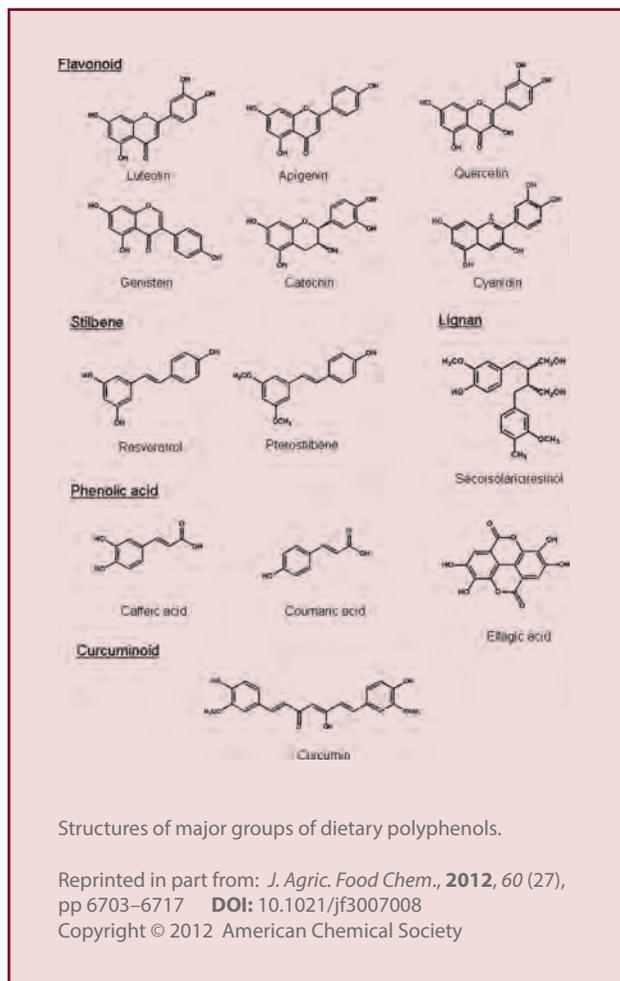


FUNCTIONAL FOODS

Almonds, olive oil, and whole grains are examples of “functional foods” that bring extra health benefits beyond basic nutrition. Functional foods can also be fortified with vitamins, nutrients, or fatty acids, like calcium-enriched orange juice, margarine with added plant sterols, or food fortified with folate (see Section V).

The anticancer, anti-inflammatory, and antioxidant properties of strawberries, blueberries, and cranberries are thought to be due to the variety of polyphenols in these fruits.^(11–16) New studies in animals show that polyphenols from berries could also modulate cell signaling pathways involved in chronic disease.⁽¹¹⁾

Some foods naturally mitigate inflammation, which is a reaction of the immune system that can cause chronic tissue damage.⁽¹⁷⁾ Inflammation is also linked to atherosclerosis, or hardening of the arteries, a condition that can lead to heart attacks and strokes over time. Inflammation has also been linked to cancer and obesity.



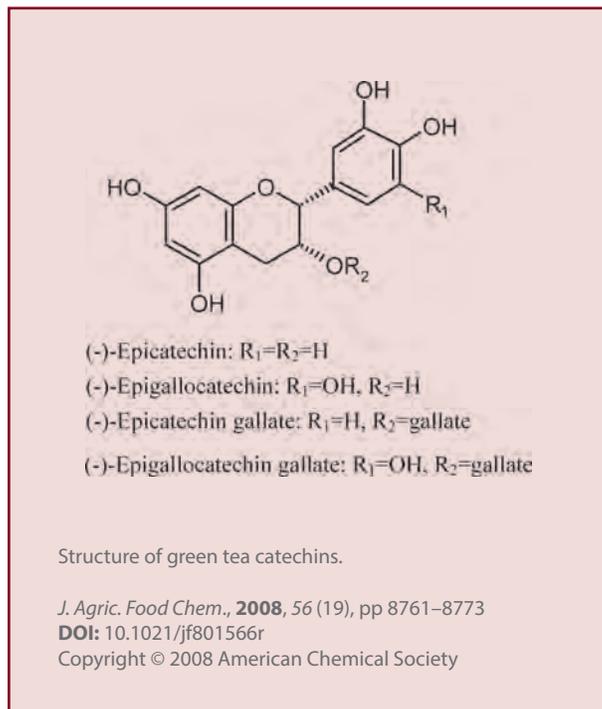
High blood pressure affects about one-third of all American adults, according to the Centers for Disease Control and Prevention (CDC). Left untreated, it can cause stroke, heart disease, and kidney problems. For patients with high blood pressure, dietary changes are a common prescription in place of diuretics or drugs that slow heartbeats, relax blood vessels, or prevent the formation of a metabolite that narrows blood vessels. The low-sodium Dietary Approaches to Stop Hypertension (DASH) diet was shown through randomized controlled trials to reduce blood pressure. Other foods, like coffee beans, apples, and pears, contain natural compounds that lower blood pressure.⁽¹⁸⁾

Cholesterol is another dietary component frequently associated

with disease, though some is needed for several processes in the body. Cholesterol helps to make fluid cell membranes. It's also needed to synthesize bile acids that help absorb fat in the intestines. Finally, cholesterol is a precursor for the synthesis of vitamin D and steroid hormones. However, high levels of cholesterol in the blood are strongly correlated with heart disease.

Foods that lower cholesterol have several actions: inhibit cholesterol synthesis, activate receptors that remove cholesterol from the blood, and block cholesterol absorption.⁽¹⁹⁾ Examples of cholesterol-lowering functional foods include those rich in dietary fiber, which slows cholesterol absorption. Red yeast rice, used in traditional Chinese medicine for circulation issues, has been shown to lower cholesterol levels in humans comparable to levels in patients taking pharmaceutical statins.⁽¹⁹⁾ More research is needed to determine its long-term effects, however.

Compounds in green tea called catechins alter cholesterol metabolism in cells and have been shown to lower cholesterol levels in animal models.



METABOLOMICS

The growing field of metabolomics might be able to provide some detailed insight into the molecular connections between food and health. This technique uses advanced molecular analysis to measure metabolites in a sample of blood, tissue, or urine. Patterns revealed by the type and amount of compounds in a sample provide information about the workings of a patient's entire metabolic system. The most common analytical techniques for metabolomics are nuclear magnetic spectroscopy and mass spectrometry.

For nutritional studies, researchers apply metabolomics to identify markers for types of food that participants have eaten, as well as to track how metabolic biomarkers change after eating certain foods.⁽²⁰⁾ Measurable biomarkers could complement the traditional methods of dietary studies that require participants to self-report their meals or disease state. Metabolomics has also been used to track the molecular changes of semolina flour during processed pasta production⁽²¹⁾ as well as relationships between growing conditions and final nutrient profiles in crops.⁽²²⁾

Combining metabolic profiling of individuals as well as profiles from the food they eat could provide the basis for personalized nutrition, or diet recommendations based on an individual's biochemistry.⁽²³⁾ Another hypothetical version of personalized nutrition involves making recommendations for groups of individuals based on common attributes identified by data mining.⁽²⁴⁾

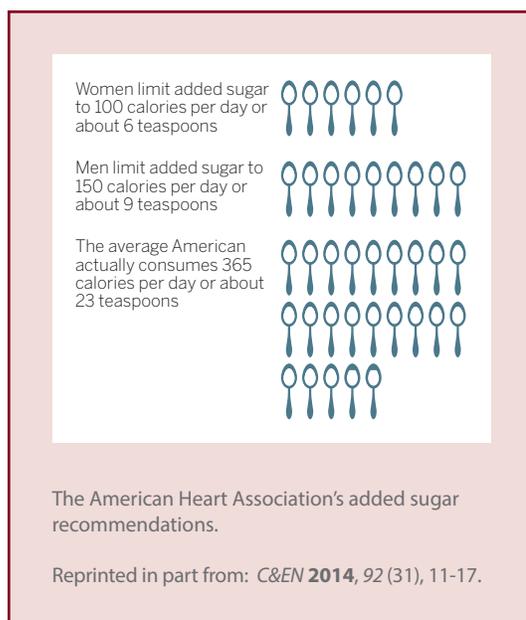
III. PROCESSED FOOD

Processed and pre-packaged foods are convenient ways to get meals. However, ingredients like sugar, salt, and fat could be detrimental to our health. Food manufacturers are working to develop healthier foods without sacrificing flavor, cost, or shelf life. That goal requires creativity to find blends of artificial sweeteners that lack a bitter aftertaste, or to formulate pyramidal salt crystals that deliver a burst of flavor as they dissolve.

SUGAR AND METABOLISM

Obesity grew into an epidemic during the 1980s in the United States. More than one-third of the population in the United States is obese, according to the CDC. Health complications linked to obesity include stroke, heart disease, and type 2 diabetes. These conditions impact a person's quality of life, as well as their pocketbook, in the form of increased health care costs.

Low-fat diets were once popular as a way to control weight, yet the prevalence of obesity has continued to rise even as Americans' fat consumption has decreased.⁽²⁵⁾ Robert H. Lustig, a neuroendocrinologist at the University of California, San Francisco (UCSF), thinks sugar is the main factor contributing to the obesity trend. According to the U.S. Food and Drug Administration (FDA), the average American gets 16% of his/her total calories from added sugar in foods like soda, sports drinks, and grain-based desserts. As consumers struggle to regulate their sugar intake through willpower alone, some cities are looking to provide incentives to help their citizens. The city of Berkeley, California, recently became the first place in the U.S. to add an extra tax on sugary beverages.



In 2009, the American Heart Association recommended a daily limit on sugar consumption: 6 teaspoons (approx. 24 grams) for women and 9 teaspoons (approx. 32 grams) for men.⁽²⁷⁾ When their report was written, the average American consumed about 23 teaspoons of sugar daily, roughly the amount in three 12-ounce sodas.

The most common sugar added to processed food and drinks is sucrose (granulated sugar or table sugar). Sucrose is a disaccharide composed of a glucose molecule attached to fructose. Another

common sweetener in processed foods is high-fructose corn syrup (HFCS). This low-cost sweetener emerged in the 1970s, when taxes on sugar imports, combined with corn subsidies, made it an affordable sugar alternative. HFCS comes in two concentrations of fructose, 42% and 55%. Since

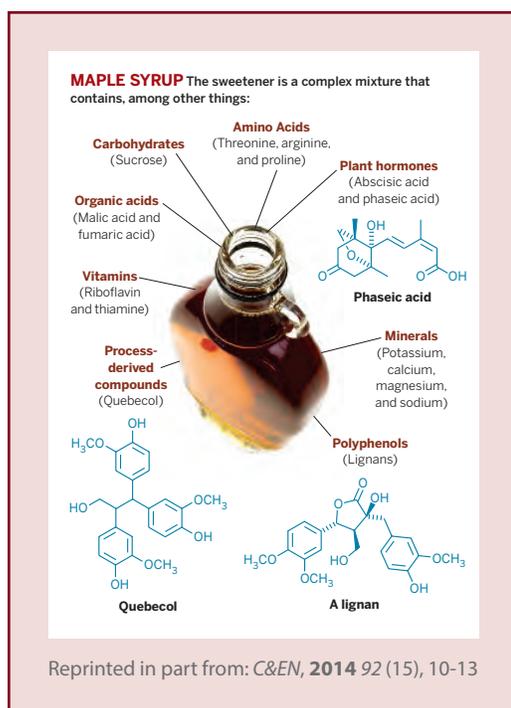
sucrose is half fructose, that means table sugar and HFCS have roughly the same fructose levels. And after much controversy, sugar trade groups, the corn growers association, and consumer groups agree that there is little significant nutritional difference between sucrose and HFCS.⁽²⁶⁾ However, reducing sugar in our diets is more complicated than finding the willpower to avoid sweet foods and drinks. We also have to work with our innate taste preferences, as well as the easy access to sweetened food.

Humans are attracted to sugar from birth, and researcher Julie Menella, of the Monell Chemical Senses Center, believes that our earliest experiences with food shape our preferences for sugar.⁽²⁸⁾ Food companies also create sugary cereals and market them toward children. They engineer the products to have a sweetness level known as the “bliss point.”⁽²⁹⁾ This is the amount of sugar — no more, no less — that we enjoy most in our food and drinks. Foods like candy, kids’ breakfast cereal, cookies, soda, and sports drinks are commonly implicated as foods high in sugar. Sugar can also be found in yogurt, spaghetti sauce, and flavored oatmeal. Whole foods like fruit, milk, and potatoes also contain natural sugars.

The different types of sugars in foods have their own impacts on our biochemistry and metabolism. Glucose, found in starchy foods and table sugar, provides energy to cells. Following a meal, glucose levels rise in the blood, followed by a spike in the hormone insulin. Insulin triggers cells to use the glucose for energy or to store it as glycogen or fat. Fructose, naturally found in fruit, is metabolized in the liver, which triggers production of glycogen, triglycerides, and cholesterol. Galactose, found in milk, is converted into glucose once it reaches the liver.

Lustig’s theory about sugar’s connection to obesity involves a link between fructose and fat production. He says differences in the biochemical pathways used by liver cells to process glucose compared to fructose lead to system-wide metabolic imbalances. Glucose is an efficient fuel for cells, so only about 20% of the consumed glucose reaches the liver, where it’s stored as glycogen or fat.⁽³⁰⁾ Cells cannot process fructose, however, so the liver processes all the consumed fructose. The liver cells pass fructose through pathways that create building blocks for fats, activate inflammation, and deactivate insulin response. The end result, in Lustig’s view, is that spikes of sugar disrupt the endocrine system.⁽³⁰⁾

Researchers at UCSF recently produced a website called “Sugar Science” to share clinical research about sugar with the public. They’ve also generated downloadable fact sheets, infographics, and flyers that can be distributed to community groups. Their goal is to fuel a public-health campaign around awareness of how much sugar is too much.⁽³¹⁾



Scientists are learning that sugar might have a good side too. Natural sweeteners, like maple syrup, agave syrup, and honey contain amino acids, vitamins, minerals, and polyphenols that could have a beneficial effect on health. Researchers are analyzing the components of these sweeteners, and then testing how individual compounds affect cellular or animal metabolism.⁽³²⁾ Experiments with animals fed maple syrup indicate that the sweetener improves insulin sensitivity. Agave syrup contains indigestible branched chains of fructose called agavins, and researchers are investigating if agavins could be useful prebiotics (see Section V). Other researchers are studying the antimicrobial properties of honey.

ARTIFICIAL SWEETENERS

Artificial sweeteners are one way to reduce added sugar in foods. Compounds like saccharin, aspartame, and sucralose are hundreds of times sweeter than sugar, so less is needed to generate the same sweet taste. The tiny amount of added artificial sweetener essentially does not increase the calorie count of food. Artificial sweeteners, however, need some chemical help to be palatable. Companies mix them with additives to mask bitter flavors, and they also blend artificial sweeteners to get the best attributes of each one.⁽³³⁾

Companies searching for new sweeteners include a South Korean company making tagatose, a structural isomer of fructose with roughly the equivalent sweetness of sugar, but with one-third of the calories.⁽²⁶⁾ The structure of tagatose prevents it from being fully metabolized. Tagatose can be prepared through a two-step synthesis. First lactose is hydrolyzed into glucose and galactose. Then an enzyme converts the galactose to tagatose. The sugar derivative appears to function well in ice cream and baked goods, according to a senior scientist at CJ CheilJedang, the company making tagatose.⁽²⁶⁾

Artificial sweeteners also do not increase blood glucose levels, which can help people with diabetes manage their condition. However, some consumers try to avoid products containing artificial sweeteners. These additives have historically faced public scrutiny due to concerns over safety and carcinogenicity.⁽³⁴⁾ To boost consumer comfort without adding calories, companies are looking for naturally occurring non-calorie sweeteners.

An example available on grocery shelves is stevia, a product containing plant-derived glycosides. Supply constraints led companies Cargill and Evolva to team up and start a

pilot plant for producing stevia glycosides by fermentation in engineered microbes.⁽³⁵⁾ This production method means that the companies can synthesize only the sweetest sugars present in stevia, which are in low concentration in the natural extract, and possibly reduce the product's bitter aftertaste. BioVittoria has teamed up with Tate & Lyle to create a different artificial sweetener, derived from a fruit, not a plant. A representative from a market research firm said this product may gain more attention because it's easier for consumers to connect sweeteners to fruit.⁽³⁵⁾

Despite their negligible effect on calories, artificial sweeteners are not necessarily a solution to obesity, as studies indicate that humans and laboratory animals tend to overeat products containing artificial sweeteners.⁽²⁶⁾ Sugary products, on the other hand, trigger a cascade of hormones that signal the brain that the gut is full.

ENGINEERING HEALTHIER PROCESSED FOOD

Coca Cola, Pepsi, and Dr. Pepper Snapple have pledged to reduce 20% of the calories Americans consume in their drinks by 2025.⁽³⁶⁾ Much of that decrease will come from smaller portion sizes, not necessarily by reducing the number of calories in the drinks.

Sodium is another ingredient that food companies, like Boston Market and General Mills, have reduced in some of their products, though they've made the cuts without much fanfare.⁽³⁷⁾ The concern is that consumers will reject food labeled "low sodium," over concerns that it won't taste good. This presents a challenge: providing consumers with healthier food while satisfying preferences for salt, perhaps shaped by experiences eating processed food in childhood.⁽³⁸⁾

Food companies contend that it's hard to reduce the amount of sodium and sugar in their products by more than 10% without affecting them.⁽³³⁾ They say both components are needed for color, taste, browning, and to act as a preservative. Lustig says sugar is also used to mask added salt.⁽³⁰⁾ In turn, salt is used to mask other undesirable flavors in food, as journalist Michael Moss found out when he tasted notes "somewhere between bitter and metallic" in a low-sodium version of vegetable beef soup.⁽³⁹⁾

So food scientists try to make food healthier in ways that the consumer will not notice.⁽⁴⁰⁾ That's a challenge for bread, which is the largest source of sodium in the American diet. Consumers don't like the taste of low-sodium bread, though German researchers found they could improve consumer's taste perception by changing the texture of the bread. They prepared two loaves containing the same amount of sodium, but with different sized pores. A professional taste panel rated the bread with larger pores as saltier than the other loaf.⁽⁴⁰⁾ Switching from sodium chloride to potassium chloride helps lower the sodium content of a food. But this change has to be used carefully, as too much potassium carries a bitter taste.⁽³³⁾

Other chemical tricks to reduce salt involve stimulating the salt taste bud with peptides, yeast extracts, or salt crystals shaped to give a burst of flavor as they dissolve. Tate & Lyle has

produced hollow microspheres of sodium chloride that are 20 μm in diameter, compared to a cubic salt crystal 300 μm long on a side.⁽³³⁾ These microspheres, however, do not dissolve in water, so they are not useful for all applications.

Reducing sugar and salt is not the first challenge that food makers have faced. They've reduced the amount of trans fats in their products over the past decade, and now the FDA is considering regulations that could essentially eliminate trans fat added to processed food.⁽⁴¹⁾

IV. FOOD ADDITIVES

Flavors, colors, and preservatives enhance food's taste, texture, appearance, and shelf life. Every so often, particular additives become the subject of public concern. Food dyes, a buttery flavorant, or a bread elasticizer dubbed the "yoga mat chemical" have been debated in the media and the courtroom. Increasingly, advocacy groups are calling for the FDA to revamp some of its regulations on food additives. Consumer concerns have chemical companies searching for natural alternatives to common flavors, colors, and preservatives. The companies are also producing natural textural additives, to help food manufacturers create new food experiences through different combinations of texture components.

Chefs practicing "molecular gastronomy" also use additives to help familiar foods adopt new textures and flavors. They use gelling agents to make fruit foams or beads of beet juice that resemble caviar. Thickening agents absorb the fat in a hazelnut spread, creating a fluffy powder. And now chemists are applying research in sense perception, materials science, and physical chemistry to these creations, so that future molecular gastronomy experiments may include some rational design.^(46,47)

COMMON ADDITIVES

The growing market for flavors has fine chemical companies diversifying their business beyond pharmaceuticals and agrochemicals.⁽⁴⁸⁾ Some flavor chemists look to identify the molecules responsible for undesirable properties of some foods, like the oxidized fatty acids that cause fishy odor and flavors⁽⁴⁹⁾, as well as the sulfuric molecules that make our eyes water when chopping onions.⁽⁵⁰⁾ Others dissect the complex cadre of molecules responsible for the unique flavors of wine, coffee, or chocolate. Flavor molecules are also produced during cooking, through a reaction between certain amino acids and sugars called the Maillard reaction.⁽⁵¹⁾ To create consistent and strong flavors for the pumpkin spice that's so ubiquitous every fall, chemists combine subsets of molecules extracted from a food with Maillard reaction products.⁽⁵²⁾

REVISING NUTRITION LABELS

Another food issue pending U.S. regulation is a revision to the “Nutrition Facts” label on processed foods. Surveys show that more than half of consumers use the label to get a general idea about the healthiness of a food. The goal of the changes is to reflect nutrition science learned in the 20 years since the last revision, as well as current thinking about the connections between diet and health.⁽⁴²⁾ The updated labels would specify the amount of added sugar in a product. (Currently it lists total sugar.) Potassium and vitamin D content would be added to the label, along with calcium and iron. Serving sizes would be updated to reflect the amount of food that people actually consume, rather than the amount they should consume.

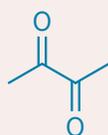
The FDA finished gathering comments on their proposal in August 2014, and the proposed policy update is not without critics. Consumer advocacy groups are asking the agency to set a daily recommended limit for added sugar, but the agency says it does not have enough scientific information to do that. Trade groups for food manufacturers oppose the added sugar declaration, citing “difficult, if not impossible” record keeping needed to separate naturally occurring sugar from added sugar.⁽⁴³⁾ Nutrition experts worry that the addition of vitamin D will lead to over-fortification. Companies have at least two years to make label changes once the FDA finalizes the rule. This debate comes while the agency is also considering requirements over including “natural” on packaging, another area of contentious debate.⁽⁴⁴⁾ The FDA and the U.S. Department of Agriculture (USDA) have different definitions of “natural,” and food manufacturers have asked for clarification. The FDA has never issued a formal rule, and the USDA has released a notice to clarify when a meat, poultry, or egg product can be labeled “natural.”⁽⁴⁵⁾ While the agencies rarely challenge manufacturers who violate the rules, manufacturers frequently challenge each other’s claims through a division of the Better Business Bureau.⁽⁴⁴⁾

Flavor molecules are also part of controversial culinary movements. Flavor-pairing theory connects foods based on common flavor molecules, to help chefs and bartenders identify new food combinations, like white chocolate and caviar or strawberry and coriander.⁽⁵³⁾ A French chef combines key sensory additives to help diners experience foods “note by note.”⁽⁵⁴⁾

Preservatives are common ingredients in processed food. They can be separated into three categories: antimicrobials, which slow the growth of mold, yeast, or bacteria; antioxidants, which prevent oxidation of fats and oils that makes food turn rancid; and agents that prevent ripening following harvest.⁽⁵⁵⁾ Examples of antimicrobials include nitrates and nitrites in processed meat and weak acids like propionates or benzoates. Antioxidants include butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and tert-butylhydroquinone (TBHQ). Common agents that slow ripening are citric acid, ascorbic acid (vitamin C), and ethylenediamine tetraacetic acid (EDTA), which captures metal ions that ripening enzymes need to function.

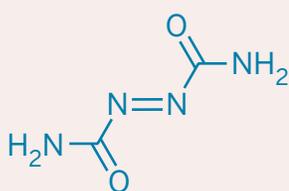
ADDITIVE SAFETY

Every so often, safety concerns about particular food additives emerge in the public consciousness. In 2009, chemical companies faced 300 lawsuits from factory workers alleging that diacetyl, used for butter flavor in microwave popcorn, caused lung disease. The flavor, subject to lawsuits beginning in 2001, has not been used since 2006.⁽⁵⁶⁾



Diacetyl (2,3-butanedione)

In 2011, the FDA convened an expert panel to review studies linking artificial dyes to behavioral problems.⁽⁵⁷⁾ The panel recommended not placing a warning label on foods containing synthetic colors, citing knowledge gaps in the existing studies. Azodicarbonamide made news in 2014 as the “yoga mat chemical” found in hundreds of food products, including bread used by the Subway restaurant chain. In response to an online petition, Subway responded that they would phase out the ingredient, which had been used to make bread elastic.⁽⁵⁸⁾



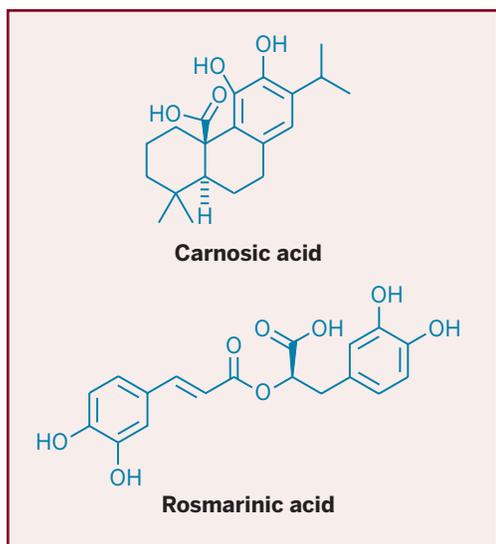
Azodicarbonamide

The FDA reviews and approves the safety of certain additives, like colors. Others, like azodicarbonamide, are classified as Generally Recognized As Safe (GRAS). GRAS ingredients either were used in food prior to 1958 or had been deemed by experts to be safe to include in food.^(59, 60) The experts, who may work for additive producers, make their determination about safety using scientific data about the compounds and information about their intended use.⁽⁶¹⁾

GRAS compounds do not need premarket approval or registration from the FDA, and there is little publicly available information about these ingredients. Increasingly, the Government Accountability Office and advocacy groups say the food industry applies this classification too broadly, endangering public health by including unsafe additives. Now, the Grocery Manufacturers Association, a trade group for the food and beverage industry, has created a plan to standardize its methods of GRAS determination, and build a database of its studies on GRAS ingredients.⁽⁶²⁾

NATURAL ALTERNATIVES

Consumer concern over the safety of additives has companies looking for natural colors, flavors, and preservatives. Vanillin is the component in vanilla beans that is responsible for most of their flavor. There is 400-500 times more synthetic vanillin produced than natural vanilla extract.⁽⁶³⁾ That means that the majority of vanilla flavored or scented products contain vanillin. However, demand for natural sources of vanilla have led chemical companies to search for ways to make vanillin through fermentation. The Belgian company Solvay, which produces most of the synthetic vanillin available today, is developing a process starting from a byproduct of rice bran oil refining. Swiss biotech firm Evolva begins their process with sugar. Both companies are working to scale up production for each of their respective products.⁽⁶³⁾



Naturex, a company specializing in natural additives, has been making a natural antioxidant from rosemary since 1992. Originally, the extract was used to flavor meat, and then some companies realized it also stabilized the meat.⁽⁶⁴⁾ Rosmarinic acid and carnosic acid, the natural antioxidants in rosemary, do not carry the flavor of rosemary. (Naturex is now looking to combine the rosemary compounds with organic acids produced by fermentation to create a product that prevents fat oxidation, as well as microbial growth. Chemistry can help identify new antimicrobial preservatives as well. Chemists at

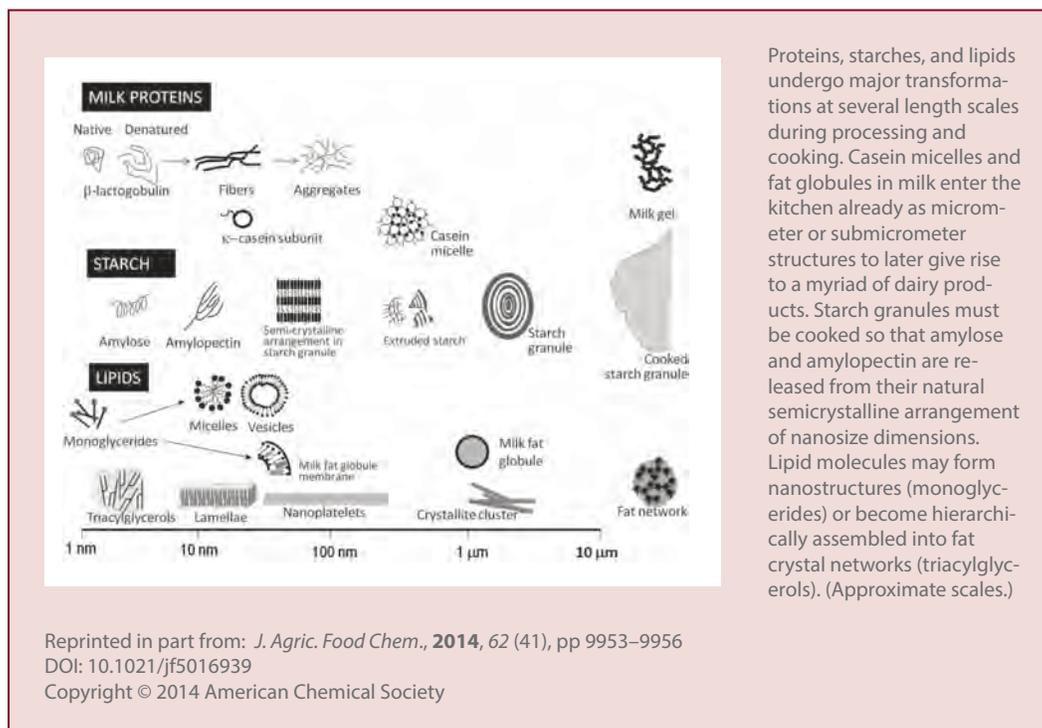
DuPont first identify the specific microbes that grow on a particular food, then use high throughput screening to identify compounds that kill the microbes or slow their growth.⁽⁶⁴⁾

The market for natural colors is growing worldwide, in part due to pressure on food manufacturers from United Kingdom and European Union regulators to remove six colored dyes from their products.⁽⁶⁵⁾ Natural pigments are already used to color red and orange M&M's chocolate candy in the UK. The FDA recently approved an extract from spirulina algae as a blue and green pigment.

Food colors need to be vibrant, non-toxic, and stable to heat, light, air, and pH. While blue is a common color in nature, finding other pigments suitable for food is challenging.⁽⁶⁶⁾ Molecules appear blue because they absorb red light. These molecules are structurally more complex than red or orange pigments that absorb blue light. Carotenoids, used as red pigments, contain conjugated double bonds. Blue pigments also contain conjugated double bonds, as well as aromatic rings, ionic charges, heteroatoms, or transition metals. Berries get their blue and purple colors from a class of molecules called anthocyanins. However, these molecules are not useful food dyes because their color varies with pH, changing from blue at neutral or basic pH to red at acidic pH. Fungi and microbes produce blue pigments as a defense mechanism, and many of these molecules end up being too toxic for use in food. Many natural blue pigments are not as vibrant as the synthetic colors, which means they would have to be used in larger amounts to achieve the same appearance. And interestingly, some of the brightest blues in nature — those found on butterfly wings — are not due to pigment. They come from nanostructures formed by the scales on the wings. Andrew G. Newsome, a graduate student at the University of Illinois, Chicago, is screening aquatic algae and berries from a Japanese shrub for other sources of natural blue pigments. Only seven molecular scaffolds account for more than 95% of blue pigments in nature, Newsome said in a presentation at the Fall 2012 ACS National Meeting in Philadelphia.⁽⁶⁷⁾

TAILORING NANOSCALE FOOD TEXTURE

Other interesting aspects of food additives or components can be found on the nanoscale. There are many examples of naturally occurring nanostructures in food.⁽⁶⁸⁾ Starch granules change shape as flour is hydrated, baked, or extruded from machines. The foam on top of a glass of beer results from molecular interactions at the air/liquid interface. The gel-like texture of yogurt comes from networks of denatured proteins, intact proteins, and fat globules.



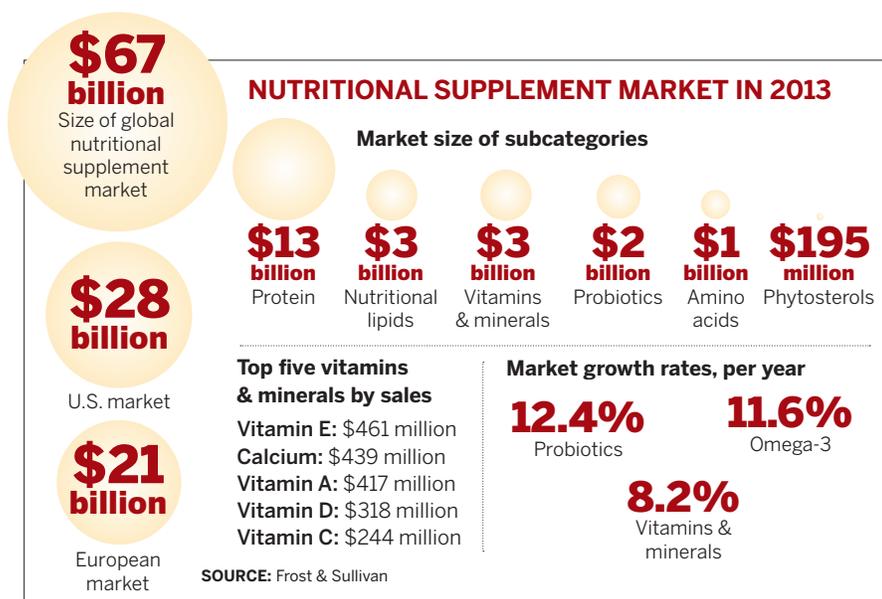
Proteins, starches, and lipids undergo major transformations at several length scales during processing and cooking. Casein micelles and fat globules in milk enter the kitchen already as micrometer or submicrometer structures to later give rise to a myriad of dairy products. Starch granules must be cooked so that amylose and amylopectin are released from their natural semicrystalline arrangement of nanosize dimensions. Lipid molecules may form nanostructures (monoglycerides) or become hierarchically assembled into fat crystal networks (triacylglycerols). (Approximate scales.)

Under a microscope, it's possible to see how different components interact to form nanoscale structures that influence macroscale texture. A yogurt-like gel made from milk fat and proteins looks like a string of beads. Carrageenan, a polysaccharide gelling agent derived from red seaweed and used in flans, creates a network of long, thin fibers.⁽⁶⁸⁾ Carrageenan is part of a common class of food additives called hydrocolloids. These compounds thicken and stabilize sauces, salad dressings, and ice cream.⁽⁶⁹⁾ Food scientists choose from a variety of textural additives when engineering new products, because different gelling agents provide different textures. They can also manipulate the fat content in some processed food to give food a velvety mouthfeel.⁽³³⁾

Starch, gelatin, pectin, alginates, guar gum, xanthan gum, and cellulose derivatives are common hydrocolloids used for texture. Pectin, in particular, is a target of several chemical companies.⁽⁷⁰⁾ Their quest comes as vegetarian consumers look for an alternative to gelatin, which comes from animal sources of collagen.⁽⁶⁹⁾ Pectin, commonly used to make jam, usually requires a large amount of sugar to form a gel. Chemical companies, however, can modify the structure of pectin to create a material that gels in the presence of calcium.

V. SUPPLEMENTS AND FORTIFIED FUNCTIONAL FOODS

More than half of Americans take at least one dietary supplement, most commonly a multivitamin to “improve” or “maintain” their good health.⁽⁷¹⁾ However, there’s little scientific evidence to support their intentions. Few randomized trials show a health benefit to taking multivitamins.⁽⁷²⁾ Other popular supplements, like omega-3 fatty acids and antioxidants, have similarly tenuous scientific connections to health. Nevertheless, supplements are big business. The global supplement market was \$63 billion in 2013, and the market for some types of supplements was projected to grow 8-12% a year.⁽⁷³⁾



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Chemical companies like BASF, FMC, DSM, and Lonza have purchased smaller specialty companies to become major producers of bulk omega-3 fatty acids. Other nutritional products produced by the industry include vitamins, plant sterols, and probiotics. The industry brings value to supplement formulators and marketers through quality markers like purity, source tracing, and Good Manufacturing Practices.⁽⁷³⁾ Industry scientists say they also want to help strengthen scientific knowledge about the relationships between supplements and health. They cite a commitment to working with researchers on better-designed and better-funded studies of these relationships, either for immediate benefits like improved immunity or longer term benefits like reduced heart disease.⁽⁷³⁾

OMEGA-3 FATTY ACIDS

One way to reduce the risk of heart disease is by eating a diet low in saturated fat and high in polyunsaturated fatty acids, like omega-3 fatty acids. Omega-3 fatty acids also concentrate in the brain, and they may protect against Alzheimer’s disease. Official dietary guidelines encourage Americans to eat more seafood, particularly fish like tuna, salmon, and sardines that are enriched

in the most beneficial omega-3 fatty acids, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA).⁽⁷⁴⁾ Supplements, taken either as fish oil pills or in foods enriched with EPA and DHA, are increasingly common ways to incorporate these nutrients into our diets, despite conflicting evidence about their effect on heart disease.⁽⁷²⁾

Chemical companies have several techniques that impart beneficial qualities to the fish oil they produce. BASF masks the fishy taste of the oil, so their pills do not leave an aftertaste. FMC can tailor the amount of EPA or DHA in their omega-3 products, so their customers can make supplements targeted for heart health or brain development, respectively.⁽⁷³⁾ DSM prepares a powder containing droplets of EPA and DHA encapsulated in a polymer, so that the fatty acids can easily be added to food.⁽⁷⁵⁾ However, the growing popularity of fish oil supplements impacts the environment in particular areas. In the Chesapeake Bay, small fish called menhaden are harvested to make fishmeal for aquaculture and purified oil for supplements. These fish filter algae from the water, and environmental scientists argue that their harvest influences the entire ecosystem by creating conditions that suffocate life in the ocean.⁽⁷⁶⁾

Synthetic biology could help produce omega-3 fatty acids in microbes rather than purifying it from harvested fish. Archer Daniels Midland recently signed an agreement with Synthetic Genomics to produce DHA for animal feed through fermentation in algae. The company plans to also market it as a nutritional supplement.⁽⁷⁷⁾

ANTIOXIDANTS

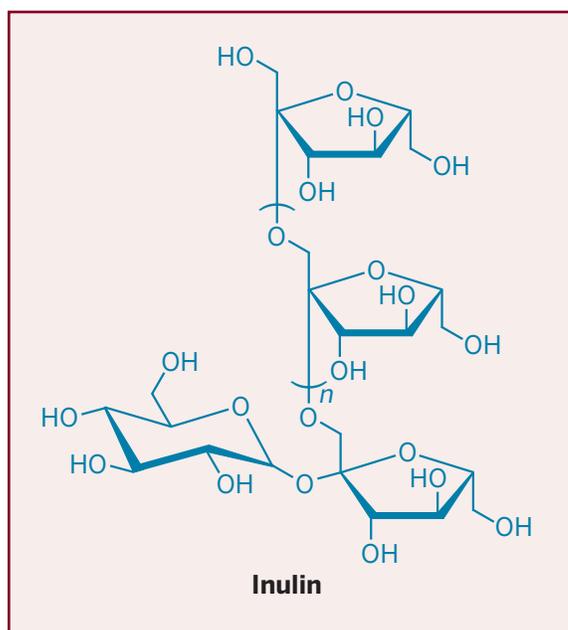
Dietary antioxidants include vitamins A, E, and C; classes of compounds like carotenoids and polyphenols; and metals like zinc and selenium. These molecules scavenge free radicals called reactive oxygen species (ROS) that can damage DNA, fats, and proteins. Traditionally, it has been thought that increased consumption of antioxidants led to better health, because the nutrients kept the levels of ROS low. Following this thinking, antioxidants have been added to cereal, sports bars, and energy drinks. These fortified functional foods have been marketed as preventing heart disease, cancer, and eye problems associated with aging. Randomized controlled trials of individual antioxidant supplements, however, have shown no health benefit.

A new view of the role of ROS in metabolism could influence the amount of these compounds added to food. The theory of hormesis suggests that small amounts of ROS are needed for cell signaling and function. An extension of this theory is that ROS removal using high concentrations of antioxidants could be detrimental to health.⁽⁷⁸⁾ However, one challenge to advancing antioxidant research has been a need for simple methods to determine the redox state inside cells. Finley et al. have noted that, as knowledge grows, the food industry has an opportunity to gain consumer confidence by clearly stating any health benefits of its products.⁽⁷⁸⁾

PREBIOTICS, PROBIOTICS, AND GUT MICROBES

Huge colonies of symbiotic microbes live in the human gut, digesting leftover food and medicines. Diet has a major influence over the composition of these colonies. Beneficial

bifidobacteria and lactobacilli thrive when fed whole grains and plants.⁽⁷⁹⁾ These colonies adjust to our long-term diets: The types of gut microbes vary between vegetarians and meat eaters, or a combination of the two.⁽⁸⁰⁾ Particular microbial profiles also have connections to diseases like obesity, inflammatory bowel disease (IBD), celiac disease, and diabetes.



There are two ways to influence these microbes through diet: (1) eat foods that stimulate beneficial microbial growth or activity (prebiotics), and (2) consume live microbes to enrich the current colonies (probiotics). Prebiotics, studied for almost 20 years, are carbohydrates designed to be digested only by beneficial bifidobacteria and lactobacilli. These carbohydrates include galactooligosaccharides and a group of fructooligosaccharides called inulin. Since the 2000s, food manufacturers have been producing fiber-enriched foods using these prebiotics, most commonly with inulin extracted from chicory root.⁽⁸¹⁾

Probiotic microbes can be naturally found in yogurt and fermented food like sauerkraut. Chemical companies are also making probiotic supplements to deliver live microbes to the intestine.⁽⁷³⁾ But little is known about the effectiveness of this approach and how it impacts health.⁽⁸²⁾ Researchers are working to classify the types of microbes in our intestines, identify the types of molecular metabolites that they produce, and link those metabolites to health effects. One challenge to altering health with probiotics is that metabolic messages might only be effective at particular developmental stages, like early childhood.⁽⁸²⁾ Supplementing with probiotics after that window of opportunity may not influence physiology. Microbial metabolism might also be detrimental to our health. Some gut microbes release fungal toxins on wheat.⁽⁸³⁾ Others alter the bioavailability of environmental chemicals like heavy metals, transforming the chemicals into more (or less) toxic species. To evaluate the potential impact probiotics might have on consumers, government agencies are currently considering how to incorporate gut microbes into chemical risk assessments.⁽⁸⁴⁾

VI. ANALYTICAL CHEMISTRY FOR FOOD SAFETY AND QUALITY

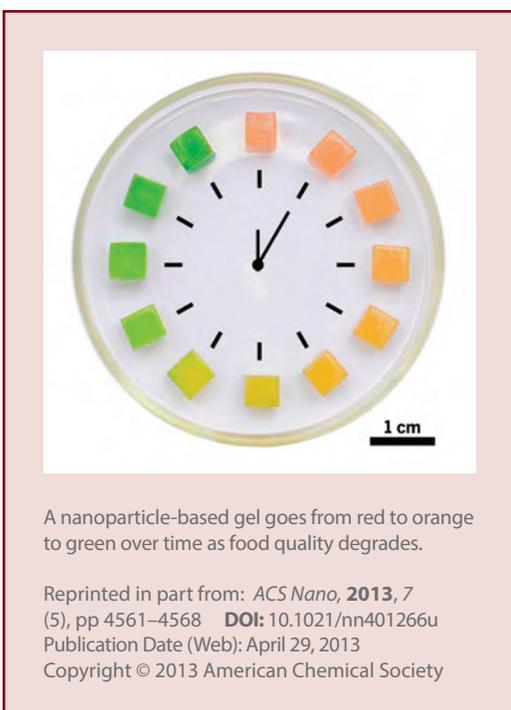
Several reasons make ensuring food safety and quality a challenging task for analytical chemists. First, there are a variety of potential contaminants to detect, including heavy metals, biological pathogens, organic pesticides, or allergenic proteins. Second, contaminants could be found in a broad range of food products, from cereal to canned soup. These matrices can be in a variety of physical states, from solid to liquid to gel, and their chemical complexity can complicate detection of dilute contaminants. Finally, the tests must be able to detect lower levels of contaminants as regulatory requirements for some pesticides and antibiotics tighten.⁽⁸⁵⁾

Allergen testing, for example, requires highly sensitive tests to identify compounds at low parts-per-million levels. People with celiac disease are sensitive to gluten, a mixture of proteins found in grains like wheat and rye. Gluten is treated like an allergen for labeling, and products labeled “gluten free” can contain up to 20 ppm of gluten. Chemists, seeking to help a colleague who is sensitive to even this amount of gluten, have developed a more precise test for the substance. The new test uses two components: (1) magnetic beads covered with a short piece of a protein in gluten called gliadin and (2) engineered DNA strands called aptamers that bind to the gliadin fragment. To test a food sample, the researchers mix the peptide-covered beads, the aptamer, and the sample. The peptide on the beads and the gluten in the food compete to bind to the aptamer. The researchers calculate the amount of gluten in the food by determining the percentage of the aptamer that bound to the food sample. The test detects gluten at levels as low as 0.5 ppm.⁽⁸⁶⁾

Another challenge to food testing involves the variety of conditions under which food can be contaminated. Pesticides may contaminate food in a field, microbes may settle on the food during washing, and food may spoil due to temperature changes after processing. Therefore, a variety of food analysis methods are needed, enabling tests to be run under a range of conditions, from easy-to-use detectors in the field to more complicated instruments in laboratories. These methods must also be fast enough so that the food stays fresh until the end of the test. In response to some of these testing needs, food scientists are developing small, inexpensive, nanomaterial-based devices to detect microbes on produce processed at farms or meat processed in factories.⁽⁸⁷⁾ The nanoparticles are covered with antibodies or viruses that latch onto particular bacteria. Electrical, magnetic, or optical properties of the particles allow researchers to detect the particle-bacteria conglomerates. The goal is to build field tests that are as sensitive and selective as lab tests.

Careful, yet rapid, sample preparation helps concentrate contaminants to enable detection with increased sensitivity. This preparation depends on the class of contaminant to be tested — pesticides, or antimicrobial agents, for example. It must also consider the composition of the matrix, as well as the detection limit needed to meet regulations.⁽⁸⁵⁾

Laboratory analytical methods vary from gas chromatography for volatile contaminants to mass spectrometry for ones regulated at parts-per-billion levels. Biological contaminants, like bacteria, mold, viruses, or parasites, are typically identified using immunoaffinity assays or polymerase chain reaction (PCR).⁽⁸⁵⁾ PCR allows producers to identify particular genetic sequences in a target microbe. Detecting heavy metal contaminants, like arsenic absorbed from soil, requires methods to differentiate various inorganic and organic forms of the metals, which could have varying toxicity.⁽⁸⁸⁾ Analytical instrument makers are developing products to provide faster results, either through speedy methods or instruments that can be installed on a production line.⁽⁸⁹⁾ They are also partnering with government agencies, academic researchers, and food producers to bring their expertise to address global food safety through method development and contaminant identification.⁽⁹⁰⁾ The current system of food import and export means that contamination in one part of the world can quickly spread around the globe.



Transport and storage is another aspect of food safety where chemical innovation can provide useful tools. Sell-by dates on perishable foods can be misleading estimates of a food's quality, if the product experienced temperature fluctuations during transport or storage. Chinese researchers have developed gels that change color over time ⁽⁹¹⁾.

They then tracked the rate of color change, from red to orange to green, in response to the addition of acid produced in sour milk or by bacterial contaminants. The researchers say the gels could be attached to food and beverage cartons to help consumers identify products that have reached temperatures that promote bacterial growth.

ADULTERATION AND AUTHENTICATION

In 2008, infant formula produced in China was deliberately contaminated with melamine to increase the apparent protein concentration. Approximately 300,000 infants and young children were sickened with kidney stones and renal failure; six deaths were reported.⁽⁹²⁾ Soon after the contaminated formula was identified, melamine was found in liquid milk and yogurts, frozen desserts, powdered milk and cereal products, confectionaries, cakes and biscuits, protein powders, and other products originating in China, like animal feed and nondairy creamer. Forty-seven countries received melamine-contaminated products, and many countries began testing imported products from China.⁽⁹²⁾

Identifying adulterated food is challenging because scientists often do not know what contaminant to look for until a scandal breaks. Then companies rapidly develop test kits for the new contaminant. Demand for those products, however, typically wanes as a scandal fades.⁽⁹³⁾ Milk, olive oil, and honey are commonly adulterated by dilution with cheaper liquids, oils, or sugars. Plentiful seafood, like tilapia, can be substituted for rarer and more expensive species, like grouper or tuna.

Chromatography connected to mass spectrometry is one way to detect known adulterants. Chemical profiling with optical spectroscopy or NMR can identify unknown contaminants based on differences from known constituents in a particular food.⁽⁹³⁾ Protein profiles, or “fingerprints,” can also be used to identify contamination or authenticate a food’s origin.^(94, 95) Under European Union regulations, Parmigiano-Reggiano cheese may only carry that name if it was produced in a particular region of Italy by a particular process. Because of the large market for this cheese, manufacturers or retailers may try to sell less expensive, or younger cheeses, as Parmigiano-Reggiano. Italian scientists have used NMR to differentiate Parmigiano-Reggiano cheese from similar hard cheeses based in part on differences in amino acid composition. The scientists also identified fingerprints for cheese aged for 14, 24, or 30 months.⁽⁹⁴⁾

BOTANICAL SUPPLEMENTS

Botanical supplement safety begins with knowing the identity of the plant in a supplement. However, ambiguity can be introduced if the plant is identified with a common name. Echinacea powder, for example, could come from three species of Echinacea: *E. purpurea*, *E. angustifolia*, or *E. pallida*.

The same common name can also be used for different species of plants, as revealed in recent studies of black cohosh supplements following increased reports of liver disease.⁽⁹⁶⁾ Black cohosh is the North American plant *Actaea racemosa*. Analyses of commercially available black cohosh supplements found that some contained Asian *Actaea* species, one with the synonymous scientific name *Cimicifuga racemosa*. These plants are used in traditional Chinese medicine, at lower amounts than the North American plant. Experts say using the Chinese plant instead of the North American plant could account for the observed toxicity.⁽⁹⁶⁾ Another factor that complicates identifying the contents of botanical supplements is that some may contain multiple plants. Other supplements may originate at botanical brokers who converted different deliveries of one plant into the same lot of powder.

Information about a plant’s production and processing is also relevant to determining the supplement safety and efficacy. The chemical composition of a supplement can vary based on how the plant ingredients were grown, what plant parts were used in the supplements, and how the plants were processed.⁽⁹⁶⁾ In 2007, the FDA required supplement manufacturers to implement Good Manufacturing Practices, including verifications about the identity, purity, strength, and composition of supplements. But that regulation does not provide recommendations about analytical methods to achieve those specifications.⁽⁹⁷⁾ Academic

researchers and government agencies are working to develop and validate analytical methods for botanical supplements. They are also working to make the methods, as well as reference material, publicly available.

Microscopy can be used to identify the contents of ground plant matter by cellular structure or physical characteristics. It can also reveal foreign matter, like crystals of Viagra mixed into an “herbal Viagra.”⁽⁹⁷⁾ Genetic fingerprinting is useful to identify the components in a mixture of several plants. Ikhlas Khan and his colleagues at the University of Mississippi’s National Center for Natural Product Research are gathering reliable molecular fingerprints for a variety of plants, using chromatography coupled with an appropriate detection method.⁽⁹⁷⁾

NMR, infrared, and ultraviolet spectroscopy, as well as mass spectrometry, can provide information about the molecules in a crude extract, which can be useful in identifying adulterants. Getting useful information from the data, however, depends on the parameters in the statistical models used to find patterns. Parameters that are too restrictive might cause good lots to fail a contamination test, and parameters that are too loose may mean that manufacturers miss a new adulterant.⁽⁹⁶⁾

VII. CONCLUSION

Scientific research is increasingly providing information about how ingredients in processed food, as well as the constituents of whole food, influence our health. This information can guide individual dietary choices to reach personal health goals. Despite this growing research, advice on the general aspects of a healthy diet remains relatively consistent: Eat fruits, vegetables, and whole grains. Limit consumption of sugar and saturated fat.

Some food experts argue that large societal shifts in chronic disease may not be possible without governmental policies to provide equal access to healthy food.⁽⁹⁸⁾ Processed food, laden with salt, sugar, and fat, is often cheaper and more available than nutrient-dense produce and grains. This can present a challenge to people looking to maintain a healthy diet. However, there are signs that consumers can influence what’s in their food. Food companies are working to find subtle ways of reducing salt and sugar in their products, so that the changes go unnoticed by consumers. Demand is also driving food manufacturers and chemical companies to seek natural alternatives to common additives. And large chemical companies are creating components for the growing global nutritional supplement market.

Connections between consumers, companies, policy makers, and research can also be found in an upcoming wave of food innovation: nanotechnology. Nanoparticles are seen as ways to

encapsulate ingredients or create antimicrobial packaging, for example. Food manufacturers are already anticipating how consumers might respond to these additives. The FDA has published draft guidelines about using nanotechnology in food.⁽⁹⁹⁾ But lacking concrete regulations, combined with worries about consumer acceptance, manufacturers seem wary about using nanotechnology in their products.⁽¹⁰⁰⁾ Should nanotechnology appear in foods, it will also present a challenge for food safety chemists working to understand if nanomaterials are altered as they pass through the digestive system.⁽¹⁰¹⁾

Chemists have the expertise to identify and quantify the molecular components of food. They also know how to apply techniques that connect those components to metabolic markers for health. These skills make them valuable participants in current quests to identify connections between food and chronic disease. These same skills can be useful for future food concerns. And they can also be applied to topics that are ripe for scientific discovery, like the health benefits of milk or organic produce⁽¹⁾. Though the research questions and applications may change as knowledge grows, there are a variety of ways chemists can be involved with investigating the molecular connections between food and health.

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