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Feeding the World Today and Tomorrow: The Importance of Food Science and Technology

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Abstract

This Institute of Food Technologists scientific review describes the scientific and technological achievements that made possible the modern production-to-consumption food system capable of feeding nearly 7 billion people, and it also discusses the promising potential of ongoing technological advancements to enhance the food supply even further and to increase the health and wellness of the growing global population. This review begins with a historical perspective that summarizes the parallel developments of agriculture and food technology, from the beginnings of modern society to the present. A section on food manufacturing explains why food is processed and details various food processing methods that ensure food safety and preserve the quality of products. A section about potential solutions to future challenges briefly discusses ways in which scientists, the food industry, and policy makers are striving to improve the food supply for a healthier population and feed the future. Applications of science and technology within the food system have allowed production of foods in adequate quantities to meet the needs of society, as it has evolved. Today, our production-to-consumption food system is complex, and our food is largely safe, tasty, nutritious, abundant, diverse, convenient, and less costly and more readily accessible than ever before. Scientific and technological advancements must be accelerated and applied in developed and developing nations alike, if we are to feed a growing world population.

Disciplines

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Comments

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Comprehensive
REVIEWS
in Food Science and Food Safety

Feeding the World Today and Tomorrow: The Importance of Food Science and Technology

An IFT Scientific Review

by John D. Floros, Rosetta Newsome, William Fisher

Gustavo V. Barbosa-Cánovas, Hongda Chen, C. Patrick Dunne, J. Bruce German, Richard L. Hall, Dennis R. Heldman, Mukund V. Karwe, Stephen J. Knabel, Theodore P. Labuza, Daryl B. Lund, Martina Newell-McGloughlin, James L. Robinson, Joseph G. Sebranek, Robert L. Shewfelt, William F. Tracy, Connie M. Weaver, and Gregory R. Ziegler

Preamble by Philip E. Nelson, 2007 World Food Prize Laureate; Professor Emeritus, Food Science Dept., Purdue Univ.

Just as society has evolved over time, our food system has also evolved over centuries into a global system of immense size and complexity. The commitment of food science and technology professionals to advancing the science of food, ensuring a safe and abundant food supply, and contributing to healthier people everywhere is integral to that evolution. Food scientists and technologists are versatile, interdisciplinary, and collaborative practitioners in a profession at the crossroads of scientific and technological developments. As the food system has drastically changed, from one centered around family food production on individual farms and home food preservation to the modern system of today, most people are not connected to their food nor are they familiar with agricultural production and food manufacturing designed for better food safety and quality.

The Institute of Food Technologists—a nonprofit scientific society of individual members engaged in food science, food technology, and related professions in industry, academia, and government—has the mission to advance the science of food and the long-range vision to ensure a safe and abundant food supply contributing to healthier people everywhere. IFT convened a task force and called on contributing authors to develop this scientific review to inform the general public about the importance and benefits of food science and technology in IFT's efforts to feed a growing world.

The main objective of this review is to serve as a foundational resource for public outreach and education and to address misperceptions and misinformation about processed foods. The intended audience includes those who desire to know more about the application of science and technology to meet society's food needs and those involved in public education and outreach. It is IFT's hope that the reader will gain a better understanding of the goals or purposes for various applications of science and technology in the food system, and an appreciation for the complexity of the modern food supply.

Abstract: This Institute of Food Technologists scientific review describes the scientific and technological achievements that made possible the modern production-to-consumption food system capable of feeding nearly 7 billion people, and it also discusses the promising potential of ongoing technological advancements to enhance the food supply even further and to increase the health and wellness of the growing global population. This review begins with a historical perspective that summarizes the parallel developments of agriculture and food technology, from the beginnings of modern society to the present. A section on food manufacturing explains why food is processed and details various food processing methods that ensure food safety and preserve the quality of products. A section about potential solutions to future challenges briefly discusses ways in which scientists, the food industry, and policy makers are striving to improve the food supply for a healthier population and feed the future. Applications of science and technology within the food system have allowed production of foods in adequate quantities to meet the needs of society, as it has evolved. Today, our production-to-consumption food system is complex, and our food is largely safe, tasty, nutritious, abundant, diverse, convenient, and less costly and more readily accessible than ever before. Scientific and technological advancements must be accelerated and applied in developed and developing nations alike, if we are to feed a growing world population.

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Introduction

The world has progressed through hunter–gatherer, agricultural, and industrial stages to provider of goods and services. This progression has been catalyzed by the cultural and social evolution of mankind and the need to solve specific societal issues, such as the need for preservation to free people from foraging for food, and the need for adequate nutrition via consistent food supply year round. These forces led to the development of the food industry, which has contributed immensely to the basis for a healthy human civilization and helped society prosper and flourish (Lund 1989).

Development of food science and technology

According to Harvard Univ. biological anthropologist Richard Wrangham, food processing was launched about 2 million years ago by a distant ancestor who discovered cooking, the original form of food processing (Wrangham 2009). Later, but still during prehistoric times, cooking was augmented by fermenting, drying, preserving with salt, and other primitive forms of food processing, which allowed groups and communities to form and survive. Humans thus first learned how to cook food, then how to transform, preserve, and store it safely. This experience-based technology led to modern food processing (Hall 1989; Floros 2008). Much later, the domestication of plants and land cultivation became widespread, and at the end of the last Ice Age, humans revolutionized eating meat by domesticating animals for food. Thus, plant and animal agriculture also contributed to improving the human condition.

Study of every ancient civilization clearly shows that throughout history humans overcame hunger and disease, not only by harvesting food from a cultivated land but also by processing it with sophisticated methods. For example, the 3 most important foods in Ancient Greece—bread, olive oil, and wine—were all products of complicated processing that transformed perishable, unpalatable, or hardly edible raw materials into safe, flavorful, nutritious, stable, and enjoyable foods (Floros 2004).

Today, our production-to-consumption food system is complex, and our food is largely safe, tasty, nutritious, abundant, diverse, convenient, and less costly and more readily accessible than ever before. This vast food system includes agricultural production and harvesting, holding and storing of raw materials, food manufacturing (formulation, food processing, and packaging), transportation and distribution, retailing, foodservice, and food preparation in the home. Contemporary food science and technology contributed greatly to the success of this modern food system by integrating biology, chemistry, physics, engineering, materials science, microbiology, nutrition, toxicology, biotechnology, genomics, computer science, and many other disciplines to solve difficult problems, such as resolving nutritional deficiencies and enhancing food safety.

The impact of modern food manufacturing methods is evident in today's food supply. Food quality can be maintained or even improved, and food safety can be enhanced. Sensitive nutrients can be preserved, important vitamins and minerals can be added, toxins and antinutrients (substances such as phytate that limit bioavailability of nutrients) can be removed, and foods can be designed to optimize health and reduce the risk of disease. Waste and product loss can be reduced, and distribution around the world can be facilitated to allow seasonal availability of many foods. Modern food manufacturing also often improves the quality of life for individuals with specific health conditions, offering modified foods to meet their needs (for example, sugar-free foods sweetened with an alternative sweetener for people with diabetes).

Applications of Disciplines Involved in Food Science and Technology

Discipline	Examples of Food Science and Technology Applications
Biology, Cell Biology	Understanding of postharvest plant physiology, food quality, plant disease control, and microbial physiology; food safety
Biotechnology	Rice with increased content of beta-carotene (vitamin A precursor); enzymes for cheesemaking, breadmaking, and fruit juice manufacture
Chemistry	Food analysis, essential for implementing many of the applications listed here; improved food quality; extended shelf life; development of functional foods (foods and food components providing health benefits beyond basic nutrition)
Computer Science	Food manufacturing process control, data analysis
Genomics	Understanding of plant and animal characteristics; improved control of desirable attributes; rapid detection and identification of pathogens
Materials Science	Effective packaging; understanding of how materials properties of foods provide structure for texture, flavor, and nutrient release
Microbiology	Understanding of the nature of bacteria (beneficial, spoilage, and disease-causing microorganisms), parasites, fungi, and viruses, and developments and advances in their detection, identification, quantification, and control (for example, safe thermal processes for commercial sterilization); hygiene; food safety
Nutrition	Foods fortified with vitamins and minerals for health maintenance; functional foods for addressing specific health needs of certain subpopulations; development of diets that match human nutrient requirements; enhanced health and wellness
Physics, Engineering	Efficient food manufacturing processes to preserve food attributes and ensure food safety; pollution control; environmental protection; waste reduction efforts
Sensory Science	Understanding of chemosenses (for example, taste and odor) to meet different flavor needs and preferences
Toxicology	Assessment of the safety of chemical and microbiological food components, food additives

Controversies about processed foods

Although today the public generally embraces and enjoys key benefits of the food supply—value, consistency, and convenience—some suggest that the cost to society of obtaining these benefits is too high. Negative perceptions about "processed foods" also exist, especially among consumers in the United States. A range of factors contributes to these perceptions. These include uneasiness with technology, low level of science literacy, labeling, and advertising that have at times taken advantage of food additive or ingredient controversies, influence on perception of voluntary compared with involuntary nature of risk, and high level of food availability (Slovic 1987; Clydesdale 1989; Hall 1989). Other factors contributing to negative public perceptions about processed foods include the increasing prevalence of obesity in many industrialized or developed countries, use of chemicals in production or additives in foods, little personal contact between consumers and the agricultural and food manufacturing sectors, food safety issues, and concern that specific ingredients (particularly salt), may contribute to illnesses or impact childhood development (Schmidt 2009).

Some books on food in the popular press have implied that the food industry has incorrectly applied the knowledge of food science and technology to develop processed foods that result in poor dietary habits. The premise of some critics of processed foods is that knowledge of chemistry and the physical properties of food constituents allow the food industry to make processed foods that result in overeating and cause the general population to abandon whole foods. The argument is stretched further to suggest that the development of processed foods is responsible for promoting bad eating habits and is the cause of chronic disease. Such an argument is specious, because personal preferences, choice, will power, and lifestyle factor into the decision of what and how much to eat. The challenge surrounding the connection between lifestyles and health (that is, diet and chronic disease) is discussed in the next section of this review.

The population challenge

During the 2009 World Summit on Food Security, it was recognized that by 2050 food production must increase by about 70%—34% higher than it is today—to feed the anticipated 9 billion people (FAO 2009a). This projected population increase is expected to involve an additional annual consumption of nearly 1 billion metric tons of cereals for food and feed and 200 million metric tons of meat.

Another challenge is the large, growing food security gap in certain places around the world. As much as half of the food grown and harvested in underdeveloped and developing countries never gets consumed, partly because proper handling, processing, packaging, and distribution methods are lacking. Starvation and nutritional deficiencies in vitamins, minerals, protein, and calories are still prevalent in all regions of the world, including the United States. As a consequence, science-based improvements in agricultural production, food science and technology, and food distribution systems are critically important to decreasing this gap.

In addition, energy and resource conservation is becoming increasingly critical. To provide sufficient food for everyone in a sustainable and environmentally responsible manner, without compromising our precious natural resources, agricultural production must increase significantly from today's levels and food manufacturing systems must become more efficient, use less energy, generate less waste, and produce food with extended shelf life.

Although scientific and technological achievements in the 20th century made it possible to solve nutritional deficiencies, address food safety and quality, and feed nearly 7 billion people, further advancements are needed to resolve the challenges of sustainably feeding the growing future population in industrialized and developing nations alike. In fact, to meet the food needs of the future, it is critically important that scientific and technological advancements be accelerated and applied in both the agricultural and the food manufacturing sectors.

Achievements and promises

The next section of this review, "Evolution of the Production-to-Consumption Food System," summarizes the parallel developments of agriculture and food manufacturing from the beginnings of modern society (the Neolithic revolution) to the present; it also addresses the current diet and chronic disease challenge. The subsequent section, "Food Processing: A Critical Element," explains why food is processed and details the various types of food processing operations that are important for different food manufacturing purposes. Then the following section, "Looking to the Future," outlines suggestions to improve our food supply for a healthier population, and briefly discusses the various roles that researchers, consumers, the food industry, and policy makers play in improving the food supply for better health; it also addresses the promises that further advancements and application of technologies in the food system hold for the future.

Evolution of the Production-to-Consumption Food System

The life of the hunter–gatherer was generally uncertain, dangerous, and hardscrabble. Thomas Hobbes, in his *Leviathan* (I561), described life in those times as "the life of man in a state of nature, that is, solitary, poor, nasty, brutish, and short." Agriculture transformed that existence by making available a far larger and generally more reliable source of food, in large part through domestication and improvement of plants and animals.

Domestication leads to civilization

Domestication is the process of bringing a species under the control of humans and gradually changing it through careful selection, mating, and handling so that it is more useful to people. Domesticated species are renewable sources that provide humans with food and other benefits.

At the end of the last Ice Age, humans domesticated plants and animals, permitting the development of agriculture, producing food more efficiently than in hunter-gatherer societies, and improving the human condition. Domestication did not appear all at once, but rather over a substantial period of time, perhaps hundreds of years. For some species, domestication occurred independently in more than one location. For animals, the process may have begun almost accidentally, as by raising a captured young animal after its mother had been killed and observing its behavior and response to various treatments. Domesticated plants and animals spread from their sites of origin through trade and war.

The domestication of plants and animals occurred primarily on the Eurasian continent (Smith 1998). A prominent early site was in the Middle East, the so-called Fertile Crescent, stretching from Palestine to southern Turkey, and down the valleys of the Tigris and Euphrates Rivers, where barley, wheat, and lentils were domesticated as early as 10000 y ago and sheep, goats, cattle, and pigs were domesticated around 8000 y ago. Rice, millet, and soy were domesticated in East Asia; millet, sorghum, and African rice in sub-Saharan Africa; potato, sweet potato, corn (maize), squash, and beans in the Americas; Asiatic (water) buffaloes, chickens, ducks, cattle, and pigs in the Indian subcontinent and East Asia; pigs, rabbits, and geese in Europe; and llamas, alpacas, guinea pigs, and turkeys in the Americas.

The introduction of herding and farming was followed by attempts to improve the wild varieties of plants and animals that had just been domesticated. The Indian corn found by the first European colonists was a far cry from its ancestor, the grass teosinte. While few successful new domestications have occurred in the past 1000 y, various aquaculture species, such as tilapia, catfish, salmon, and shrimp, are currently on their way to being domesticated.

Although the primary goal of domestication (ensuring a more stable, reliable source of animal and plant foods) has not fundamentally changed, the specific goals have become highly specialized over time. For example, we now breed cattle for either beef or dairy production, and cattle and hogs for leaner meat. We breed chickens as either egg layers or broilers. In addition, selection for increased efficiency of producing meat, milk, and eggs is prominent in today's agriculture, as discussed later in this section.

Agriculture, built on the domestication of plants and animals, freed people from the all-consuming task of finding food and led to the establishment of permanent settlements. What we know as civilization—cities, governments, written languages, an expanding base of knowledge, improved health and life span, the arts—was only possible because of agriculture. Along with domestication of plants and animals, people began the journey of discovery of methods to extend the useful life of plant and animal food items so that nourishment could be sustained throughout the year. With a fixed (nonnomadic) population also came primitive food storage and, with that, improvements in food safety and quality.

In July 2009, an important discovery and conjecture was made about the recognition that food security was of paramount importance. Kuijt and Finlayson (2009) reported that they believe they have discovered several granaries in Jordan dating to about 11000 y ago. This would suggest that populations knew the importance of having a dependable food supply before the domestication of plants. The authors further suggested that "Evidence for PPNA (Pre-Pottery Neolithic Age) food storage illustrates a major transition in the economic and social organization of human communities. The transition from economic systems based on collecting and foraging of wild food resources before this point to cultivation and foraging of mixed wild and managed resources in the PPNA illustrates a major intensification of human-plant relationships." Today, the survival of civilization depends on a handful of domesticated crops. Of the roughly 400000 plant species existing today (Pitman and Jorgensen 2002), fewer than 500 are considered to be domesticated.

Selecting for desirable crop traits

The primary force in crop domestication and subsequent breeding is selection, both artificial and natural, described below. Charles Darwin, in developing the theory of natural selection, relied heavily on the knowledge and experiences of plant and animal breeders (Darwin 1859). Crops were domesticated from wild ancestors' gene pools that had been altered by selection imposed by early agriculturalists and by natural selection imposed by biotic and abiotic environmental factors (Harlan and others 1973; Purugganan and Fuller 2010). Selection changes gene pools by increasing the frequency of alleles (genes encoded by a place in the genome and that may vary between individuals and mutant/parent strains) that cause desirable traits and decreasing the frequency of alleles that cause undesirable traits. Modern crop varieties are still shaped by the same forces.

The causes of the bursts of domestication activity have been the subject of much speculation (Smith 1998), but the changes symptomatic of domestication are well established for many species (Harlan and others 1973; Doebley and others 2006). Legumes and the large-seeded grasses collectively known as cereals (for example, maize, wheat, rice, and sorghum) contribute most of the calories and plant protein in the human diet. For these and other annual crops such as sunflower and squash, the initial changes during domestication involved ease of harvesting and the ability to compete with weeds. Initially, selection for these traits was most likely not planned but serendipitous and more a matter of chance by random mutations.

The most significant problem confronting most agriculturalists, both early and modern, is weed competition. Early agriculturalists scattered seeds on ground that had been prepared, most likely by burning or some other disruption of the soil surface. Those seeds that passed their genes onto the next generation (natural selection) were those that best competed with weeds. Selection pressure due to weed competition results in a number of changes, including the reduction or elimination of seed dormancy and larger seeds (Harlan and others 1973; Smith 1998). Dormancy is very undesirable in annual crops, and most domesticated species germinate rapidly upon planting. Selection against dormancy has been so extreme, however, that under certain weather conditions, seeds of modern wheat varieties (*Triticum aestivum*) and barley (*Hordeum vulgare*) sprout while still in the seed head, destroying the value of the grain crop. Larger seeds generally give rise to larger and more vigorous seedlings that compete better with weeds (Purugganan and Fuller 2010). In the grasses, selection for larger seed size is associated with increased starch and decreased protein in the endosperm. For example, the protein content of teosinte (*Zea mays parviglumis*)—the wild ancestor of maize (*Zea mays mays*), which is referred to as corn in North America—is approximately 30%, while the protein content of modern maize is 11% (Flint-Garcia and others 2009).

While the goal of selection is to alter the targeted trait (appearance and/or performance) and the genetic variation underlying the selected trait will be reduced over time, unselected traits will also often change, and these changes may be negative (for example, reduced endosperm protein in grasses that have been selected for larger seeds).

For example, in the United States, the major selection criterion for maize is increased grain yield (Tracy and others 2004), and strong selection pressure for increased grain yield leads to increased starch content and decreased protein content (Dudley and others 2007). Critics focus on such changes as evidence that the quality of our food supply has been "damaged" by modern plant breeding and agricultural practices. But has it? In United States agriculture, maize is grown for its prodigious ability to convert the sun's energy into chemical energy (carbohydrates), while we have abundant sources of plant and animal protein. In other parts of the world, maize is a staple crop, and diets of many people are deficient in protein. To improve the nutrition of the poor whose staple is maize, plant breeders at the Intl. Center for Maize and Wheat Improvement (*Centro Internacional de Mejoramiento de Maíz y Trigo*, CIMMYT) developed quality protein maize (QPM) that has an improved protein content and amino acid profile (Prasanna and others 2001). It is the selection of the breeding objective that determines the outcome. Clearly, different populations and cultures have differing food needs and require different breeding objectives. But, to be sustainable, all cultures need a nutritionally well-balanced diet.

Changes in food animal agriculture and fisheries

Animal food products are good sources of high-quality protein, minerals (for example, iron), and vitamins, particularly vitamin B12, which is not available in plant materials. Livestock production is a dynamic and integral part of the food system today, contributing 40% of the global value of agricultural output, 15% of total food energy, and 25% of dietary protein and supporting the livelihoods and food security of almost a billion people (FAO 2009b). Seafood, including products from a growing aquaculture segment, provides at least 15% of the average animal protein consumption to 2.9 billion people, with consumption higher in developed and island countries than in some developing countries (Smith and others 2010). Except for most of sub-Saharan Africa and parts of South Asia, production and consumption of meat, milk, and eggs is increasing around the world, driven by population and income growth and urbanization (FAO 2009b; Steinfeld and others 2010). The rapidly increasing demand for meat and dairy products has led during the past 50 y to an approximately 1.5-fold increase in the global numbers of cattle, sheep, and goats; 2.5-fold increase in pigs; and 4.5-fold increase in chickens (Godfray and others 2010). The nutritional impact of animal products varies tremendously around the world (FAO 2009b; Steinfeld and others 2010).

The structure of the livestock sector is complex, differs by location and species, and is being transformed by globalization of supply chains for feed, genetic stock, and other technologies (FAO 2009b). The current livestock sector has shifted from pasture-based ruminant species (cattle, sheep, goats, and others having a multi-chamber stomach, one of which is the rumen) to feed-dependent monogastric species (for example, poultry) and is marked by intensification and increasing globalization (Steinfeld and others 2010).

A substantial proportion of livestock, however, is grass-fed (Godfray and others 2010) and small-holder farmers and herders feed 1 billion people living on less than $1 a day (Herrero and others 2010).

The rates of conversion of grains to meat, milk, and eggs from food animals have improved significantly in developed and developing countries (CAST 1999). Technological improvements have taken place most rapidly and effectively in poultry production, with broiler growth rates nearly doubled and feed conversion ratios halved since the early 1960s. In addition to these productivity gains, bird health and product quality and safety have improved through applications of breeding, feeding, disease control, housing, and processing technologies (FAO 2009b). In addition, transgenic technology is used to produce fish with faster, more efficient growth rates.

Meeting the needs of a growing population

As a result of improved public health measures and modern medicine, the population has mushroomed from an estimated 1 to 10 million in 10000 BC to an estimated 600 to 900 million in AD 1750 and an estimated 6.8 billion today. Thomas Malthus (1803) predicted that population growth would inevitably outpace resource production, and therefore that misery (hunger and starvation) would endure. Undoubtedly, application of science and technology in agriculture and food and beverage manufacturing has negated these predictions and fed population growth (Figure 1).

The application of science to agriculture has dramatically increased productivity, but until the Green Revolution of the 1960s and 1970s, productivity was not keeping pace with population growth. Large areas of the world, including the 2 most populous nations, China and India, were experiencing severe food shortages and anticipating worse. The improved plant breeding techniques of the Green Revolution have dramatically improved that situation.

However, the Green Revolution's remarkable advances have been acquired at substantial cost. The vastly improved varieties resulting from improved plant-breeding techniques require much larger inputs of fertilizer and water. Poor farmers often cannot afford the fertilizer, and adequate water supplies are becoming an increasing problem in many areas. Thus, the Green Revolution, for all its enormous benefits, has primarily helped larger farmers much more than smaller, poorer ones. In addition, pesticide applications in the developing world are too often inappropriate or excessive—in some cases because the farmer is unable to read the label—and there is no structure (for example, a regulatory agency such as the Environmental Protection Agency) to regulate their use.

Problems are not, however, confined to the developing world. Nutrient run off in the United States and other countries leads to algal blooms in lakes and estuaries and to "dead zones" completely lacking in oxygen in lakes and oceans. Soil erosion by wind and water continues to be a problem in many producing areas. Soil quality thus suffers. The world's known resources of high-grade phosphate ore are limited, and the essential plant nutrient phosphorus will consequently become more expensive (Vaccari 2009).

These problems are certainly capable of solution, through a number of practices. Beneficial options include "no-till" agriculture (which leaves the root systems of previous crops undisturbed, thereby retaining organic matter and greatly discouraging erosion), integrated pest management, IPM (which focuses pesticide use where needed, substantially decreasing the amount used), precision agriculture (which site-specifically targets production inputs such as seed, fertilizer, and pesticides where and when needed), drip irrigation (controlled trickling of water), and use of new technology for recovering nitrogen and phosphorus from processing wastewater for use as fertilizer (Bongiovanni and Lowenberg-Deboer 2004; Frog Capital 2009; Gebbers and Adamchuk 2010).

Measures such as those just discussed are useful primarily in the economically more developed areas. Developing countries require other steps adapted to their local areas and focused particularly on improvements for the many millions of small, poor farmers. Improved plant varieties, produced both by conventional breeding and through biotechnology are necessary, as are improved varieties of fish and livestock. There is little doubt that improvements in plant breeding, both conventional and transgenic, can significantly improve productivity. Technological improvements, such as automated plant monitoring via robotics, are "helping plant breeders trim years off the process of developing crop varieties tailored to local conditions" (Pennisi 2010).

The list of such needs is far too long to explore here, but it also must include public health measures. A major problem yet to be addressed is the subsidization of agricultural products in developed nations. Products from small, unsubsidized farmers in developing nations cannot compete in the world market with subsidized products from advanced nations. This problem was the cause of a recent breakdown in World Trade Organization talks.

Some see organic agriculture as an answer to these problems. Organic farming has some clear merits, particularly those practices,

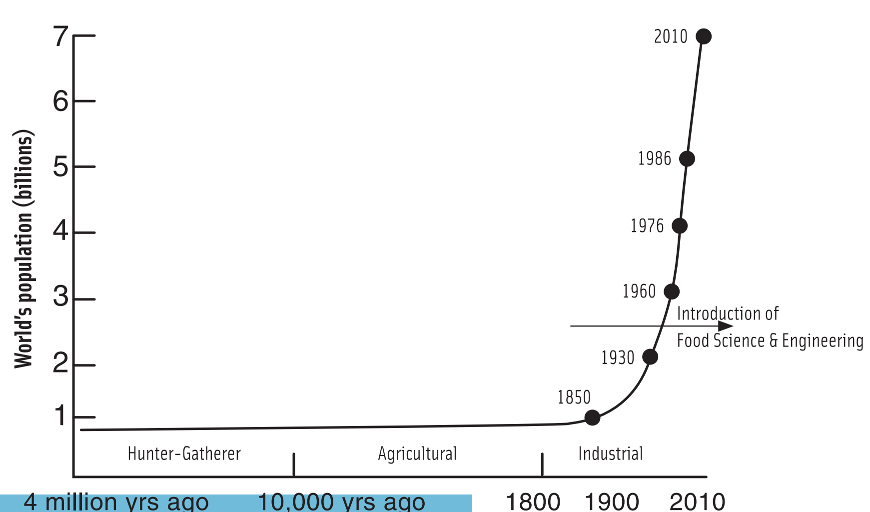

Figure 1–From Foraging and Farming to Food Science and Engineering. Adapted from Henry (1997) © Nutrition Society 1997. Reprinted with the permission of Cambridge University Press.

such as crop rotation and the use of green or natural biocontrol agents and animal manure, which have been used by farmers for millennia (King 1949). The use of degraded plant and animal residues increases the friability (tendency to crumble, as opposed to caking) and water-holding capacity of soil, and nutrients from decaying plants and animal manure are more slowly available than those from most commercial fertilizers. Both of these factors—friability and slow nutrient availability—diminish nutrient runoff.

While organic agriculture continues to grow in response to consumer preferences in the developed world, there are limitations to widespread use of organic practices. Organic agriculture requires substantially more land and labor than conventional practices to produce food, and the resulting yields are not great enough and too expensive to address the needs of the growing population. The supply of composted animal manure is limited and relatively expensive compared to commercial fertilizers. Organic agriculture excludes the use of synthetic pesticides, and the few "natural" ones that are permitted are seldom used (Lotter 2003). Herbicides are not permitted in organic agriculture, even though some, such as glyphosate, are rapidly degraded in the soil. These exclusions require more manual labor for weed and pest control. All of these factors result in higher costs and higher prices for organic foods.

Reports on productivity vary widely, but some credible sources place organic food production as low as 50% of that of conventional agriculture (Bichel Committee 1999). Yield differences may be attributable to a number of factors such as agro-ecological zone (for example, temperate and irrigated compared with humid and perhumid), crop type, high-input compared with low-input level of comparable conventional crop, and management experience (Zundel and Kilcher 2007). In addition, current organic methods exclude the use of the products of modern biotechnology—recombinant DNA technology—essential to future increases in agricultural productivity. Nevertheless, the more useful practices of organic agriculture must be part of the agriculture of the future.

Although poverty and malnutrition exist in all countries, by far the most severe problems in achieving availability, safety, and nutritive value of food and beverages occur in the developing world (IFPRI 2009). Water shortages and contaminated water, poor soil, destruction of forest for fuel, use of animal manure for fuel, the spread of plant and animal diseases, and the complete lack of a sound food safety infrastructure are among the most vexing problems. Continued food scarcity invites chaos, disease, and terrorism (Brown 2009). The gap between developing and developed nations is not only in economics but also in science, governance, and public information. Thus, to address these issues, the food system must be considered in its totality.

Eighty percent of agricultural land is used for grain fed to meat animals and yields only 15% of our calorie intake. Many have suggested that world food shortages could be greatly alleviated by consuming less meat and using the grain supplies now consumed by animals more directly. Reduction in meat intake, particularly red meats, would confer some health benefits, but the potential effects on world food supplies are less clear and quite possibly much less than many presume. If developed nations consume much less meat, the price of meat will fall and poorer nations will consume more. If more grain is consumed, grain prices will rise, to the detriment of populations that already rely heavily on grain. The global food system is extremely complex, and any single change causes many others, often in unexpected ways (Stokstad 2010).

Clearly, the solution to the challenge of meeting the food demands of our future world population lies in these principal thrusts:

- Increased agricultural productivity everywhere, but particularly among poor farmers, of whom there are hundreds of millions.
- Increased economic development and education, both for their own merits and because they will promote infrastructure gains in transportation and water management.
- Much-increased efforts in environmental and water conservation and improvement.
- Continued improvements in food and beverage processing and packaging to deliver safe, nutritious, and affordable food.
- Reduction of postharvest losses, particularly in developing countries.

We must achieve all of these goals. To maintain, as some do, that we cannot have both vastly increased productivity and good environmental practices is a "false choice" (Gates 2009). Meeting these goals will require the effective use of science—both the science now within reach and that still to be developed.

Preserving the food supply

Postharvest losses occur between harvest and consumption as a result of spoilage of raw agricultural commodities, primarily during storage and transportation, before they can be stabilized for longer-term storage. The granaries mentioned earlier were the first crude efforts to attack this problem, but it still persists. Postharvest losses due to rodents, insects, and microbial spoilage in some areas amount to 30% or more of the harvested crop. This results in wasted seed, water, fertilizer, and labor. Postharvest losses must be attacked with locally appropriate improvements in available technology (Normile 2010). It is not enough merely to increase and conserve the supply of raw food; it must be conserved against further loss by processing and be packaged, distributed to where it is needed, and guaranteed in its safety, nutritional value, and cultural relevance. That is the role of science and technology and engineering applied to the processing of foods and beverages.

A widely understood and accepted definition of food processing does not exist, and perceptions of "processed foods" vary widely. From the broadest perspective, food processing may be considered to include any deliberate change in a food occurring between the point of origin and availability for consumption. The change could be as simple as rinsing and packaging by a food manufacturer to ensure that the food is not damaged before consumer accessibility, or as complex as formulating the product with specific additives for controlling microorganisms, maintaining desired quality attributes, or providing a specific health benefit, followed by packaging that may itself play a role in microbial control or quality preservation. Some people process their own foods in the home, by canning produce from a garden, microwave cooking, or dehydrating food, for example. Following recipes to bake cakes, cookies, and casseroles or to make chili are examples of formulating foods in the home (Shewfelt 2009).

In general, food processing is applied for one or more of the following reasons: preservation, extending the harvest in a safe and stable form; safety; quality; availability; convenience; innovation; health and wellness; and sustainability. Although the private sector carries out these processes and delivers the final product to the consumer, public investment in generating the science and engineering base necessary to continue the creativity and ultimate application of new technologies is clearly warranted.

Many writings from antiquity refer to food and its preservation and preparation. Major advances in food preservation accelerated with the development of canning, which proceeded from the investigations of Nicolas Appert in France and the subsequent activities of Peter Durand in England in the early 19th century. Appert used corked glass bottles to preserve food, and Durand introduced the concept of metal cans. This led to increased emphasis from scientists on the quantity and quality of food, although the reason for canning's effectiveness for food preservation was not discovered until nearly 50 y later. Louis Pasteur reported to the French Academy of Sciences in 1864 on the lethal effect of heat on microorganisms. W. Russel of the Univ. of Wisconsin and Samuel Cate Prescott and William Lyman Underwood of the Massachusetts Inst. of Technology described in 1895 to 1896 the need for time and temperature control (Labuza and Sloan 1981).

"Mr. Appert found the art of fixing seasons; he makes spring, summer and fall live in bottles similarly to the gardener protecting his tender plants in greenhouses against the perils of the seasons." (From the *Courrier de l'Europe* of February 10, 1809; Szczesniak 1992).

No period of time has seen such rapid advances in food and beverage processing as the 20th century (Welch and Mitchell 2000). Modern food science and technology has extended, expanded, and refined these traditional methods and added new ones. Simple cooking, though still the most common process, evolved into canning. Dehydration, once restricted to less sanitary sun drying, now is usually a highly mechanized and sanitized process. Refrigeration has evolved from cool storage to sophisticated refrigerators and freezers, and the industrial techniques of blast freezing and individual quick freezing (IQF) are less detrimental to nutritional quality and sensory quality (for example, taste, texture). All of these developments contributed to increased nutritional quality, safety, variety, acceptability, and availability of foods and beverages. Many of these techniques are now combined into more effective preservation technologies through the concept of "hurdle technology," combining techniques to create conditions that bacteria cannot overcome, such as combining drying with chemical preservatives and packaging, or mild heat treatment followed by packaging and refrigerated storage (Leistner and Gould 2002).

Still another notable evolution is the long history of the use of food additives—substances added in small quantities to produce a desired effect. Of the 32 "technical effects" (functional purposes) listed by the Food and Drug Administration in the *Code of Federal Regulations*, 24 can be recognized in the few cookbooks and recipe compilations that have survived from more than 150 y ago.

Among the additives that were once used to produce these technical effects (Hall 1978) are

- Pearl ash (from wood ashes) and vinegar as leavening agents.
- Sodium silicate (water glass) for dipping eggs to preserve them.
- Lye for hulling corn.
- Sulfur dioxide from burning sulfur as a fumigant and preservative.
- Unlined copper utensils for making pickles greener.
- Saltpeter and roach alum as curing and pickling agents.
- Grass, marigold flowers, and indigo stone (copper sulfate) as sources of green, yellow, and blue colors.

Before the days of widespread industrial production of food and before the advent of modern chemistry and toxicology, these and many other crude additives were used confidently within the family without any knowledge of the risks they presented.

Regulatory oversight

In the 20th century, the development of the science of toxicology permitted the careful evaluation of the safety of substances added to food. The advent of modern chemistry permitted the detection of intentional adulteration of foods by purveyors using deceitful practices, and led to the passage and enforcement of modern food laws. Frederick Accum's "Treatise on the Adulteration of Food," published in 1820, marked the beginning of this effort. In the United States, the Pure Food and Drugs Act of 1906 prohibited adulteration and misbranding of food, issues that continued to be addressed in the United States via federal statutes. Prior to 1958, the burden of proving that a substance posed an unacceptable risk rested with the government. In that year, the Food Additives Amendment to the 1938 Federal Food, Drug, and Cosmetic Act changed that by advancing the concept of "adulteration" and imposing on food manufacturers the task of proving prior to marketing that an additive is safe under the conditions of its intended use.

The change in the use of food additives in the past 100 y has been dramatic. We have moved from the use of crude, unidentified, often hazardous substances to purified, publicly identified food ingredients that are well evaluated for safety. Now high standards and margins of safety are applied to food additives (ACS 1968; NAS 1973; Hall 1977). Today, because of modern means of detection, intentional food adulteration in industrialized countries is considered uncommon, occurring more often in foods imported from countries without effective food safety infrastructure. Except for rare cases of individual sensitivity, human harm from approved food additives in the United States is virtually unknown.

Advances in food science and technology

Drying, canning, chemical preservation, refrigeration (including chilling and freezing), and nutrient conservation and fortification were the significant advances of the 19th and 20th centuries and permitted population growth in more developed countries. Such population growth could only occur if there was sufficient food. The industrial revolution could not have occurred without a food delivery system that allowed people to leave the farms, migrate to the cities, and engage in useful production of goods and services for society.

Among the important developments during the early part of the 20th century were the discovery of vitamins and the realization of the importance of other micronutrients such as iodine, iron, and calcium. Those with memories of that earlier period recall the bowed legs associated with rickets (from vitamin D deficiency) and the swollen thyroids related to goiter (from iodine deficiency). With the introduction of the draft just before World War II, the army discovered widespread malnutrition among young American males. This led to the foundation of the Food and Nutrition Board of the Inst. of Medicine of the Natl. Academies and also the development in 1941 of the Recommended Dietary Allowances (RDAs) for essential nutrients. The difficulty of achieving these RDAs from available foods, especially among the poor, led manufacturers to fortify common foods with vitamins and other micronutrients, beginning with iodized salt in 1924. Today, fortified foods, defined by federal Standards of Identity, include such staples as pasta, milk, butter, salt, and flour.

Technological innovations in food preservation were dependent on advances in the sciences, especially chemistry and microbiology. How these sciences and technologies are applied within each society depends on the economic, biological, cultural, and political contexts for each society. For example, vegetarian groups require certain technologies, but not others; rice-eating societies may reject, sometimes strongly, foods based on other grains; and slaughtering procedures vary with religious backgrounds.

Advances in agriculture and food science and technology have led to reduction in nutrient deficiency-related diseases; a generally safe food supply with consistent high quality available independent of seasons; food choices that do not require preparation time; a wide range of delicious foods; reduced food waste; lower household food costs than ever before; convenience foods requiring much less preparation time than before, a benefit for working families; and efficient global food distribution that can be exploited in times of natural and man-made disasters.

The diet-and-disease challenge

Food is central to human health, not only in terms of quantity, but also quality as well. The past few decades have seen alarming rates of increase in chronic diseases such as diabetes, cardiovascular disease, and cancer, as well as autoimmune diseases such as inflammatory bowel disease and autism. A growing body of epidemiological, clinical, and basic research shows that food and diet are important factors involved in the etiology of these and other chronic diseases, and that dietary patterns have a profound effect on the risk for chronic diseases. Anand and others (2008), for example, describe the substantial role of environment lifestyle risk factors (such as sun exposure, diet, obesity, and physical inactivity) for cancer and provide evidence that cancer could be preventable for some people but that this would require major lifestyle changes. Hence, whether it is food safety and security, or nutrient deficiency and disease prevention, food is intricately connected to human health and well-being.

Dietary guidelines are produced to provide advice on good dietary habits that will promote health and reduce risk for major chronic diseases. The 2005 *Dietary Guidelines for Americans* includes recommendations to increase consumption of fruits, vegetables, whole grains, and low-fat milk, and to limit consumption of *trans* fats, saturated fats, cholesterol, and sodium. Many food companies have responded to these recommendations. For example, more bread and cereal products are now available that are made from whole grains and have higher fiber contents. The introduction of baby carrots doubled intake of carrots. Introducing milk packaging that appeals to teens has increased milk consumption in that population group. Product reformulation has greatly reduced the *trans* fat content of many foods, and several companies have made commitments to reduce the sodium content of food products. Convenient and innovative toddler foods made from a variety of fruits, vegetables, whole grains, and dairy are now available. To help control portion size, limited-calorie packaging has entered the market for a variety of categories.

Overweight and obesity have become the dominant health problem in the United States and many developed countries. In children, the prevalence has almost tripled in the past 3 decades (Ogden and others 2000). This is of particular concern because overweight children have a high likelihood of becoming overweight adults, with all the associated diseases such as metabolic syndrome and diabetes. Recent research suggests that childhood obesity is determined by age 2 (Harrington and others 2010), which supports the earlier set-point theory that body weight is regulated at a predetermined or preferred level by a feedback-control mechanism (Harris 1990). The obesity issue is a scientifically complex issue of behavior and may be economically driven; some of the lowest priced foods are the more calorie-dense and palatable products (Drewnowski 2004; MacAulay and Newsome 2004).

Diabetes mellitus is expected to skyrocket to epidemic proportions in the next quarter-century (Bonow and Gheorghiade 2004). Lifestyle interventions are the 1st step in the management of diabetes and metabolic syndrome (Stone 2008).

Even in the midst of an abundance of energy from food, however, many people do not meet their nutrient requirements, sometimes because of the types of foods available to them, other times because of the kinds of foods they select. The report of the 2010 Dietary Guidelines Advisory Committee (DGAC 2010) recommended focus on achieving energy balance through the current nutrition and physical activity guidelines.

Food Processing: A Critical Element

As indicated above, food processing has evolved from merely a need to preserve foods from the time and location of harvest or assembly until the product reaches the consumer, to possibly complex activities that may include sourcing raw materials and ingredients from different parts of the world that can improve nutritional and other desirable qualities for better overall health and wellness of consumers.

Objectives of food processing

Food processing frequently serves multiple objectives. For example, freezing or cooking and freezing both preserve and provide convenience. Heating or fermentation of soy is necessary both to achieve edibility and to remove the hemagglutinens that would be mildly toxic. Processing operations are conducted under controlled conditions to ensure that the process is completed in the most effective and efficient manner. The resulting products include ingredients delivered to food manufacturers to be used in producing foods for consumers, as well as ingredients (for example, flour) for consumers to use in food preparation.

The development and implementation of new technologies enhances food quality and safety. New and innovative products, some with unique product attributes, have been developed through the use of new processing technologies.

> Processing is accomplished by using one or more of a range of operations, including washing, grinding, mixing, cooling, storing, heating, freezing, filtering, fermenting, extracting, extruding, centrifuging, frying, drying, concentrating, pressurizing, irradiating, microwaving, and packaging.

The formulation, processing, and packaging of a food or beverage is accomplished for several clearly definable purposes, with numerous benefits to the consumer and society:

- **Preservation.** This is the oldest and perhaps still the most common purpose, and the one most familiar to consumers. The purpose of preservation is to extend the shelf life of a food or beverage.
- **Safety.** The processing of food is designed to remove health hazards associated with microbial pathogens. Processing operations dealing with raw food materials or ingredients carrying pathogens have significant controls and regulations to detect and inactivate food-borne microorganisms that can cause illness. Pasteurization of milk is just one of many examples of processes that eliminate a health hazard for the consumer and extend the life of the product.

Managing food safety, however, goes beyond microbiological risks. Good agricultural and manufacturing practices and other principles address chemical and physical hazards as well. In addition, plant breeding has contributed to reduction of some of the toxicants that occur naturally in foods in small amounts (ACS 1968; Hall 1977) and have been the source of common and sometimes widespread human illness and occasionally death. Processing is, however, still necessary in some instances. For example, manioc must be crushed and soaked—or crushed, heated, and treated with acid—to remove hydrogen cyanide from cyanogenic glycosides before the resulting starch (tapioca) is safe to consume.

• **Quality.** Processes to ensure the delivery of foods and beverages of the highest quality to the consumer continue to evolve. Quality attributes include taste, aroma, texture, color, and nutrient content. In most cases, these attributes begin to decline as soon as a raw food material or ingredient is harvested or collected. The goal of the processes is to ensure that the decline in quality attributes is minimized. For example, blanching and freezing vegetables immediately after harvesting ensures that the nutrients remain at their peak level. In some cases, the quality attributes are enhanced by processing. For example, processing of soybeans greatly improves their flavor.

• **Availability.** Food processing helps to ensure that the consumer has access to a wide variety of foods and food ingredients at any time, including those that help to improve the retention of quality attributes for the period of time required for delivery of the product to the consumer. For example, controlling the composition of the atmosphere surrounding apples and other fruits leads to extended freshness.

• **Sustainability.** Food processing ensures that the resources required to produce raw food materials and ingredients for food manufacturing are used most efficiently. Responding to the goals of sustainability requires the maximum utilization of all raw materials produced and integration of activities throughout all the production-to-consumption stages. To maximize the conversion of raw materials into consumer products, efforts begin at the production stage, with activities to reduce postharvest losses and increase use of by-products. Efforts continue, through food manufacturing and beyond, to ensure that energy, water, and other resources are used most efficiently and environmental impacts are minimized. Refrigeration of fresh produce is an example of an action that reduces loss and increases the edible life of the product.

• **Convenience.** Many processed foods and beverages are developed to allow them to be consumed after limited amounts of preparation. For example, a frozen or refrigerated entree is delivered to the consumer in a form ready for microwave heating. Snack foods are ready to eat when delivered to the consumer.

• **Health and Wellness.** At a fundamental level, food is viewed as a source of nutrition to meet at least the minimum daily requirements for survival, but there is an ever-greater focus on the desire for health optimization from food. Processing can enhance the nutritional value of foods in a number of ways. For example, refining—separation of the antinutritional components—is the best means of improving the nutritional quality of many foodstuffs of vegetable origin, and processing of fresh tomatoes (for example, into catsup) improves the bioavailability of the carotenoid lycopene.

Some products are specifically designed to enhance individual health and wellness—the focus of many current trends—requiring specific unique ingredients and an array of processes to ensure desired product attributes. Many products are fortified or enriched with vitamins and minerals (for example, orange juice fortified with calcium for bone health) and other nutrients (for example, margarine enriched with plant stanols and sterols for heart health) in response to defined nutritional needs of consumers. The success of these products—often referred to as "functional foods"—requires that flavor and texture also meet consumer expectations.

Typical technologies, processes, and operations

The mechanical operations, processes, and technologies typically used to achieve these benefits in preparing and using raw materials in manufacturing foods and beverages (Potter and Hotchkiss 1995) are briefly described below:

• **Mechanical Operations.** There are many mechanical operations used throughout the food system, including simple conveying of raw materials from one location to another, as well as more intense operations to change the physical structure of the material. All or most of these operations are larger scale versions of operations that have been used to prepare foods for centuries. The cracking and grinding of cereal grains to manufacture the flour used in bakery products is a very visible example. Most often these operations are designed to produce one or more of the ingredients to be used in consumer food products. The extraction of oil from soybeans and other oilseeds requires a mechanical operation before efficient separation of the oil can be accomplished. In most cases, these operations are a component of series of steps needed to ensure the most efficient use of the raw material, often including the manufacturing of an array of by-products for consumers to utilize. Another typical mechanical operation is dry mixing, involving the blending of various ingredients to ensure homogeneous and uniform distribution of the various ingredients before a final stage of manufacturing.

• **Heating**. The use of thermal energy to increase the temperature of a raw food or ingredient is the most recognized and widely used approach to preservation of food. By increasing the temperature to appropriate levels and holding for an appropriate time that is dependent on both the nature of the food and the objective of the process, pathogenic or spoilage microorganisms are significantly decreased in number or eliminated.

Thermal processes applied to foods in food manufacturing are based on the same principles as those governing traditional cooking of foods during preparation. The impact of heating—thermal processing—on components of the food is the same as that during cooking and often results in the enhancement of flavors and texture, as well as some modest losses of heat-sensitive nutrients. Many shelf-stable foods are available to consumers as a result of thermal processing. Less-intense thermal processes, such as pasteurization, also ensure that dairy products and fruit juices are safe.

Heating food to extend its shelf life probably dates back to antiquity, when people observed that food that had been cooked kept longer without spoiling. However, it was not until Appert and others investigated heating foods in containers that it was discovered that immediate recontamination of heated food from the environment did not occur. Since those meager beginnings, advances in mathematics, chemistry, biology, and engineering, coupled with their application to food science and technology, have resulted in development of equipment and procedures to optimize the application of heat to foods for the purpose of extending their shelf life and enhancing their edibility (texture, flavor, and visual appearance).

There are basically 3 types of heat processes that are applied to food, other than cooking: blanching, pasteurization, and canning. The latter 2 are tightly regulated by federal—and in some cases, state—agencies to ensure proper application of the technology and prevention of food-borne illness.

Blanching is a mild heat treatment (usually accomplished at temperatures below 212°F for less than 2 to 3 min) applied to foods that are to be subsequently canned, frozen, or dried. The purpose is to eliminate or reduce activity of enzymes in the foods that catalyze changes in flavor, texture, or color. Other benefits include removal of air from the food tissue to reduce oxidation, softening of the plant tissue to facilitate packing into packages, and inactivation of antinutritional properties (such as trypsin inhibitor in soybeans, a naturally occurring chemical that reduces dietary protein breakdown in the human gastrointestinal tract).

The process is usually carried out in hot water or steam, although there are processes based on hot air or microwave heating. Since the process is relatively mild, there is relatively little effect on nutrients, although when hot water is used as the heating medium some nutrients, especially water-soluble nutrients, are leached into the water.

"Pasteurization" is named after Pasteur, who demonstrated that wine spoiled because of the presence of microorganisms and that a mild heat treatment could be used to inactivate the microorganisms and thereby extend the shelf life. Pasteurization is most well known for its application to milk, which is strictly regulated through the U.S. Public Health Service/FDA's Pasteurized Milk Ordinance.

Pasteurization is most generally applied to liquids, although it is also applied to semisolid and solid foods. As applied to liquids, the temperature is elevated to 140 to 212°F for a short period of time (usually less than 1 min) to inactivate microorganisms that can cause illness (pathogens). As originally applied, the liquid was heated after it was put into the container; but by applying advances in food engineering, such as the understanding of flow dynamics and heat transfer to flowing liquids, continuous processes were developed using heat exchangers, machines used to transfer heat from a hot fluid to a colder one. Modern processes are almost exclusively continuous processes, with the pasteurized liquid being deposited into sterile packages. Most pasteurized foods are subsequently kept in refrigerated storage to extend the shelf life because not all spoilage organisms present have been inactivated.

"Canning" is primarily used to inactivate microorganisms that cause food-borne disease such as botulism, but it also inactivates microorganisms that cause food spoilage. This thermal process is commonly accomplished by holding the product at temperatures well above 230°F for several minutes. Canned food is not absolutely sterile (devoid of all viable microorganisms) but rather is commercially sterile (devoid of all viable microorganisms that could grow under normal storage conditions).

There are 2 major methods: heating the food after it has been sealed in a container (referred to as *canning*) and sterilizing the food, then depositing it in a sterile container within a sterile environment and sealing the container (referred to as *aseptic processing*). These processes can also be optimized for retention of nutrients and quality factors such as taste, flavor, and color. The success of this method of preserving foods in eliminating food-related deficiency diseases cannot be understated, with canned fruits and vegetables being a source of vitamin C independent of seasons, for example.

> Prescott and Proctor (1937), of the Massachusetts Inst. of Technology, described the importance of canning as follows: "No technologic advance has exerted greater influence on the food habits of the civilized world than the development of heat treatment and the use of hermetically sealed (air-tight closure) containers for the preservation of foods."

• **Refrigeration and Freezing.** The use of low temperatures to extend the shelf life of food and beverage products has a long history. The use of ice to reduce the temperature of foods and prevent spoilage has been recognized for centuries. Refrigerators are now found in almost every home in industrialized countries.

Although the reduction of temperature does not eliminate microbial populations, it reduces the rate of microbial growth enough to prevent product spoilage and extend the shelf life of most food products. Most fruits and vegetables are refrigerated to extend their freshness. In addition, refrigeration also reduces the reaction rates of enzymes that cause deterioration of most quality attributes of a food or beverage, making high-quality products available to the consumer for extended periods of time (Heldman and Hartel 1997).

Some foods and beverages receive a mild heat treatment to inactivate enzymes and eliminate microorganisms that can cause disease but still require refrigeration to control the growth of surviving microorganisms that can cause spoilage. Pasteurized milk is probably the best example, but many other foods and beverages are also pasteurized and then refrigerated. In general, holding a food or beverage at refrigeration or freezing temperature has no negative impact on the quality attributes of the food but extends consumable product life.

"Freezing" is a more intense use of refrigeration to reduce the temperature of a product to levels below the freezing temperature of water in the product. Lower temperatures cause the liquid water to change phase to ice. At these reduced temperatures (−0.4 to −14°F), the deterioration rates for product quality attributes are reduced to below those at refrigeration temperature, and microbial growth is reduced to negligible levels.

It is not unusual for frozen fruits, vegetables, and some meat products to maintain high quality for as much as 1 y while frozen. Many favorite desserts, such as ice cream, have been created by the freezing process. Most nutrients are not affected by freezing; however, it is difficult to freeze a food product without impact on the some of its more evident quality attributes. The formation of ice crystals within the structure of a plant or animal food results in a series of reactions with potential impact on texture and flavor. Thus, careful control of the time to freeze the product and the temperature of the frozen product during distribution and storage is important to minimize such reactions and ensure the best possible quality attributes over time (Erickson and Hung 1997).

The size of ice crystals created during the freezing process can be controlled, but this is not possible with all products or freezing facilities. For example, small pieces of fruits or vegetables can be frozen very rapidly, and the product structure is preserved with uniform distribution of small ice crystals. In contrast, a large portion of beef or any product in a large package will require a longer time to freeze and will result in a less-uniform distribution of larger ice crystals. The extent of the impact on product quality depends on an array of factors occurring after freezing, including control of temperature during storage and distribution and final preparation of the food. For many foods, the quality attributes of refrigerated and frozen foods compare favorably to those of the fresh counterparts (Mallet 1993).

• **Dehydration.** Drying is intended to halt or slow the growth of microorganisms and rate of chemical reactions. The removal of water provides food processors excellent opportunities to reduce volume and weight, extend shelf life, and convert liquids to powdery products, such as instant coffee or a vegetable soup base mix. This process is one of the oldest techniques used to preserve foods, one of the most utilized, and the most energy intensive (von Loesecke 1943; Saravacos 1965; King 1968; Thijssen 1979).

Water removal is usually performed via evaporation, vaporization, or sublimation (drying while frozen) by means of a simultaneous heat, mass, and momentum transfer mechanism (Whitaker 1977). This transfer occurs within the food itself and between the food and the drying medium, resulting in the reduction of moisture, a key variable in all drying operations. In addition to water removal, chemical reactions occur, such as Maillard browning (nonenzymatic browning) of amino acids/reducing sugars such as glucose, caramelization of sugar, denaturation/degradation of cross-linking proteins, and pyrolysis (decomposition or transformation of a compound caused by heat) of the various organic constituents. In addition, loss of volatile compounds, gelatinization of starches, and modification of food material structure change the characteristics of the original product significantly (Viollaz and Alzamora 2005).

Many types of dryers, dehydration methods, and associated equipment are applied to a very wide range of foods. Sun drying on trays, mats, or platforms is the traditional method and is still used today. Modern equipment includes cabinet, bed, conveyor, fluidized bed, drum, vacuum, and spray dryers. Freeze drying (lyophilization), osmotic dehydration, microwave, and innovative light-driven refractance-window dryers are also in use. With continuous technological advances in different fields, drying is constantly evolving to offer better quality and novel products.

Mathematical modeling and process simulation have significantly contributed to the understanding of the intricacies of this very complex process and the design of new dryers and drying systems. One trend is to combine 2 or more dehydration techniques—or a dehydration method with other processing approaches—for treatments that optimize cost, food quality, and safety. Examples of these combinations include microwave–vacuum drying, ultrasound-assisted air drying, and encapsulation and flavor impregnation to add value.

- **Acidification.** Raw foods and beverages vary significantly in levels of acid they contain. Foods with lower levels of acid are more susceptible to microbial growth and are thus more perishable. The intentional adjustment in the level of acid in a food has been a preservation method for centuries, in making pickles, for example. This approach to preservation is based on the inability of many spoilage microorganisms and pathogens to grow at high levels of acid. Increasing the acidity prevents growth of many microorganisms and extends the shelf life of the product, while maintaining many of its attributes. This preservation method can be accomplished by addition of acid to adjust the overall acidity level of the product, or biologically through fermentation. Since acid alone may not be sufficient to fully protect the product, adjustments in acidity are frequently used in combination with other techniques such as heat, additives, or refrigeration to accomplish preservation and safety.
- **Fermentation.** The use of microorganisms to change a perishable food into a less-perishable product is another very old way of preservation that has been used around the world by societies without access to refrigeration to extend the edible life of a fresh food. Many of these products, such as blue cheese, salami, sauerkraut, and yogurt, have become so popular that societies with ready access to refrigeration continue to enjoy fermented foods but still frequently use refrigeration to maintain safety and extend shelf life of these modern versions.

Although some microorganisms lead to food spoilage and others cause food poisoning, specific microorganisms that can induce desirable changes in foods are used to overpower those that can lead to unappealing or unsafe foods. Fermentation microorganisms primarily work to change the chemical makeup of a product, making it less likely that undesirable microorganisms will reproduce and compromise product safety or quality. Beneficial microorganisms synthesize natural preservatives, such as lactic acid and other acids (increasing the acidity of the food), carbon dioxide (lowering the oxygen content), and ethanol (discouraging growth of undesirable microorganisms). Yeasts produce carbon dioxide to expand the structure, such as dough for bread baking. They are also responsible for the production of ethanol to produce beer, wine, and other alcoholic beverages.

Fermented dairy products include yogurt and a host of ripened cheeses. Fermented cucumbers are called pickles in Western countries, but pickling is another word for fermenting and is used to produce pickled eggs, pig's feet, and even snakes in certain countries. Many countries and cultures have their own favorite types of fermented products, such as injera from Ethiopia, kimchi (fermented cabbage) from Korea, salami and other fermented sausages from Italy and Germany, and sauerkraut from northern Europe. Harvested cacao beans are fermented before cleaning and roasting, making all chocolate products the result of at least one fermentation step.

- **Water Activity.** A very important and useful tool in the control of food quality attributes and food safety is water activity (a_W). Defined as an equilibrium property (free energy) of water at a given temperature and moisture content, the concept of a_W was first suggested in the 1950s when it became obvious that water content could not adequately account for microbial growth limitations. During the 1960s, researchers demonstrated that a_W is also important in controlling the rates of chemical deterioration in foods, and then in the 1980s it was also found to relate to the texture of crisp dry foods and caking of powders such as instant coffee. a_W is not the same as water content, or the quantitative amount of water in a sample, nor is it a measure of free compared with bound water in a food, an early misconception that is now abandoned.

Through the research of hundreds of food scientists, a number of a_W paradigms have been established and used by food manufacturers to create safe, tasty, and nutritious dry and semimoist foods such as crispy snacks and breakfast cereals, semimoist cookies, and creamy confections. For example, it is known that at a_W values between about 0.3 and 0.65, changes in product texture occur (for example, loss of crispness and onset of stickiness, caking, or hardening), and that at a_W values around 0.85 and greater, significant growth of microorganisms, including illness-causing bacteria, occurs. In fact, the concept of a_W is used in regulation of food processing to ensure food safety. The *Code of Federal Regulations* (21 CFR 110.80 [b][14]) requires that "Foods such as but not limited to dry mixes, nuts, intermediate moisture foods, and dehydrated foods that rely on the control of a_W for preventing the growth of microorganisms shall be processed to and maintained at a safe moisture level. Compliance . . . may be accomplished by any effective means including (i) monitoring the a_W of ingredients and finished product, (ii) controlling the soluble solids-water ratio, (iii) protecting finished foods from moisture pickup . . . so that the a_W does not increase to an unsafe level . . . ." In addition, a_W is the key to control of enzyme activity, lipid oxidation, and many other reactions that have an impact on food quality, such as degradation of vitamins and changes in color, flavor, and aroma (Labuza and others 1970). Figure 2 depicts the water content and a_W of a few common foods.

Specific knowledge of the relationship of a_W to moisture content, such as that shown in Figure 2, is useful to food manufacturers for choosing specific ingredients, such as in making a high- or intermediate-moisture food that will maintain a safe a_W level (generally below 0.85). This information is also important in

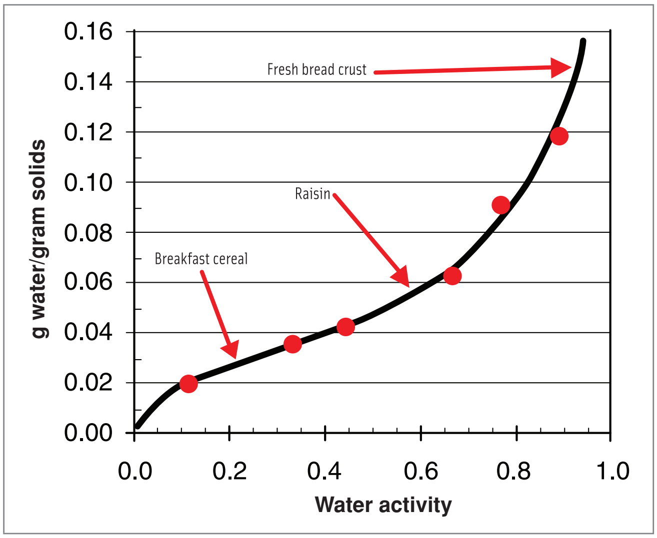

Figure 2–Moisture sorption isotherm relating water activity to moisture content at a specific temperature.

predicting and controlling textural changes and ingredient stability. Foods such as dry mixes, nuts, and dehydrated foods rely on control of a_W for preventing the growth of microorganisms. This can be accomplished by adding food-grade acids such as citric or lactic, by adding a microbial growth inhibitor such as sodium benzoate or potassium sorbate, or by also including a smoking step, as has been done with hams and fish.

The systematic control of a_W through product formulation ensures the maximum quality and shelf life for dry and intermediate-moisture foods (Labuza and others 1970), such as beef jerky, gummies, dried raisins and cranberries, or chewy granola bars. Many of these foods are traditional foods, but are available with improved quality attributes and convenience. Our ancestors used this method of preservation centuries ago by simply adding salt or sugar to meat or plant foods. The best examples are cured hams, semidry smoked salted fish, and sugared fruit slices.

• **Smoking.** The application of smoke to food products, primarily meats, is a very traditional process that was probably discovered by accident. It has been speculated that when ancient cave dwellers learned to cook food over open fires, it quickly became obvious to them that the smoke from the fire helped reduce the spoilage of perishable food products such as meat and also imparted a very distinctive, desirable flavor. Over time, the smoke process was expanded to include not only meat, fish, and poultry but also, more recently, sausage products, ham, bacon, cheeses, and many other foods for which a unique smoked flavor and increased shelf life are desired. Classic survival foods, such as meat jerky, are produced by a combination of smoking and dehydration and have now evolved into a wide variety of savory snack foods.

The smoke application process has evolved dramatically from open campfires to a highly controlled, scientific process, but the benefits have remained the same. Smoke achieves 4 different functions when applied to food, all of which contribute to safer, more palatable products:

Food safety. Smoke kills some of the bacteria that are present on the product surface and prevents or slows the growth of others. While this has been one of the most important roles of smoke for food preservation in the past, this effect is less critical today because several other antimicrobial processes are available. Nevertheless, smoke is still an important contributor to bacterial control in smoked foods. The antibacterial effect of smoke is due to several components of wood smoke, specifically acids and alcohol, which are formed during combustion of wood and deposited on the product surface. Furthermore, most smoke processes are done with application of heat at the same time, and the combination of smoke with mild heating increases the control of both spoilage and pathogenic bacteria. Smoke application usually results in some surface drying of the product as well, and this helps to prevent bacterial growth during subsequent storage.

Quality—flavor and aroma. Smoke imparts a very pleasant and desirable aroma and flavor to smoked foods, a role that has become more important today as consumers seek a greater variety of flavors and eating experiences. Wood smoke can be derived from a variety of wood sources, including hickory, apple, mesquite, and others, to add to the variety of flavors that can be achieved.

Quality—visual appeal. Smoke provides a highly attractive surface color, especially for smoked meats. The deep, rich mahogany color of a smoked ham is easily recognized by consumers and communicates assurance that the associated aroma and flavor expected of a smoked ham will be delivered.

Preservation. Smoke functions as an antioxidant or flavor protector. Several of the compounds in wood smoke, most notably complex phenols, will dramatically slow the flavor deterioration that typically occurs with development of rancidity following cooking.

Despite the advantages, 3 criticisms have occasionally been leveled at the use of smoke for food preservation. First is that atmospheric emissions result from combustion of wood to generate smoke. Second is that it degrades some food nutrients; this has been demonstrated to be of very minor importance—smoke has been shown to not significantly alter the nutrient value of food under normal circumstances. Third is that combustion of wood can generate undesirable compounds (polycyclic hydrocarbons) shown to be toxic and/or carcinogenic.

Of note is that this process results in smoke deposition almost exclusively on the surface of the product, with relatively little penetration below the surface—smoke deposition is limited to the outer $\frac{1}{4}$ to $\frac{1}{2}$ inch of the product. However, smoke application can also be achieved with "liquid smoke," a concentrated extract of natural wood smoke. Liquid smoke contains all of the important functional components of natural smoke and results in the same effects on color, flavor, and bacterial control, but it is much more consistent in composition than natural smoke and therefore more reproducible in effect.

Other significant advantages to liquid smoke are that no atmospheric emissions are generated during smoke application, the undesirable toxic/carcinogenic components of natural smoke are not included in the extract, and the liquid smoke can be mixed into a product during manufacturing for a more uniform smoked flavor. Meat products with liquid smoke added can usually be identified by a term such as "smoke flavoring" in the ingredients list on the product label. Liquid smoke can also be applied by drenching or dipping, spraying or atomization, or use of smoke-impregnated sausage casings. These application methods result in surface deposition of smoke components with product effects that are very similar to those produced by the surface application of natural smoke.

• **Irradiation.** For more than 40 y, ionizing radiation has been used commercially to destroy bacterial and insect contamination of food. Common sources of ionizing radiation today are electron beams, X-rays, and, more often, gamma rays (with the radioactive isotope cobalt-60, the same source used for radiation therapy in hospitals). Elaborate physical safeguards assure worker safety.

Irradiation is particularly effective in reducing microbial contamination of hamburger meat and poultry, which can be contaminated by pathogens such as *Escherichia coli* O157:H7, *Salmonella*, and *Campylobacter* and result in food-borne illness. Irradiation also may be applied to eliminate insects in a wide variety of foods, for example, flour, spices, fruits, vegetables, and grains (IFT 2004), to prevent seeds from sprouting, and to control pathogens in fresh shell eggs, seeds for sprouting, fresh or frozen molluscan shellfish (for example, oysters, clams, mussels, and scallops), and fresh iceberg lettuce and fresh spinach (Morehouse and Komolprasert 2004, FDA 2008). Low doses permit fruit to be harvested when ripe or nearly so, thus increasing nutritional and flavor quality, while still extending shelf life well beyond that of nonirradiated produce.

Irradiation works by damaging the DNA of living organisms; the targets are typically bacteria and insects, but the DNA of the plant or animal food is of course also affected. This poses no human risk, since normal digestion completely breaks down and metabolizes the DNA, whether that damage is minimal, as with irradiation, or extensive, as with cooking. Low doses of irradiation can achieve sprout inhibition and insect de-infestation; medium doses are required for reduction of spoilage and pathogenic bacteria; and high doses are required for sterilization. Irradiated foods must be labeled as such (21 CFR 179.26[c]). Irradiation is also used at high doses and in far higher volume to sterilize joint implants, bandages, sutures, drugs, cosmetics, and wine and bottle corks (Crawford and Ruff 1996; UW Food Irradiation Education Group 2010).

The effects of irradiation on nutritional quality vary depending on nutrient, food, and irradiation conditions (for example, dosage, temperature, and atmospheric conditions). Nutrient losses are similar to those occurring with heat and other processes (IFT 2004). Thiamin (vitamin B1) is sensitive to irradiation, but loss can be minimized with packaging techniques (Thayer 1990; Fox and others 1995, 1997).

Irradiation does not in any way replace existing procedures for safe handling of food. Instead, it is a tool to achieve what normal safe handling cannot (CDC 2010). Irradiation cannot make food safe that is already spoiled (UW Food Irradiation Education Group 2010).

Because of the usefulness of irradiation in dealing with microbial risks, the Centers for Disease Control and Prevention and other public health authorities have endorsed its use (CDC 2010). The same conclusions on safety and effectiveness have been reached by international agencies (WHO 1997; Morehouse and Komolprasert 2004). Codex Alimentarius, the international food standard-setting agency, has published a *General Standard for Irradiated Foods* (CAC 2003a) and a *Recommended International Code of Practice* (CAC 2003b). Although regulations of irradiation of food vary from country to country, regulations in several countries have been or are being harmonized through compliance with the Codex *General Standard* (Morehouse and Komolprasert 2004). In the United States, food irradiation is regulated as a food additive, because in the Food Additives Amendment of the Federal Food, Drug, and Cosmetic Act of 1958 Congress defined radiation sources as food additives.

The safety of irradiated food, which has been tested extensively, has been clearly demonstrated (Diehl 1995; Crawford and Ruff 1996; WHO 1997; Morehouse and Komolprasert 2004; CDC 2010). Foods made sterile by irradiation to inactivate bacterial spores (at the highest doses) have been fed for years to patients with reduced immunity and to astronauts (CDC 2010; UW Food Irradiation Education Group 2010). Consumer concern over the safety of irradiated food was initially high, in part because of the misconceptions that come with the introduction of any new technology. Arguments against irradiation are similar to those voiced against pasteurization of milk, when it was introduced 100 y ago (UW Food Irradiation Education Group 2010). Concern still exists but has gradually declined as information on irradiation and its advantages have become more widely known (Conley 1992; Bruhn 1995; Morehouse and Komolprasert 2004; IFIC 2009).

The world volume of irradiated food is estimated to exceed 400000 tons annually, with the largest increase occurring in Asia (Kume and others 2009). The food industry has been slow to adopt food irradiation in the more developed nations because of the large capital investment required; there is little incentive to invest in irradiation equipment because of funds already allocated for refrigeration, canning, and other major processes. The situation is very different in developing areas, where existing processes are much less extensive and postharvest losses and the risks of food-borne illness are far greater. Some argue that this is where the need for irradiation is greatest and the ability to afford it is the lowest. In the United States, irradiation could reduce *E. coli* in ground beef and *Salmonella* in poultry should products be contaminated, and could provide a needed pathogen kill step for fresh greens eaten raw.

- **Extrusion.** This process pushes a material through a specially engineered opening to give a desired shape and texture through increases in temperature, pressure, and shear forces. The pushing force is applied by using either a piston or a screw. In food applications, screw extrusion is predominant. Examples of traditional extruded foods are pasta, noodles, vermicelli, and breakfast cereals. Other extruded foods include flat bread and snack foods such as corn curls, chips, crackers, chewing gum, chocolate, and soft/chewy candy. Extrusion is also used to create flavors and encapsulate them for heat stability in processing. Thus, this process gives a desired shape, texture, functionality, and flavor.

Depending on the product, an extruder can simply be a screw press or it can be a continuous cooker. In the case of a screw press, the product is usually further processed extensively, such as by frying, baking, flaking, coating, or drying, as in the extrusion process to produce cornflakes. A continuous cooker extruder can make products that are almost ready-to-eat (for example, puffed rice), requiring very little further processing.

Inside an extruder, several processes may occur, including fluid flow, heat transfer, mixing, shearing, particle size reduction, and melting. In pasta manufacturing, for example, the main objective of the extrusion process is to partially gelatinize starch, compact the dough, and give it the desired shape. In the case of chocolate manufacturing, however, the extruder is used as a reactor to generate key flavor attributes. And, in the case of flat bread, an extruder is used to develop the desired expanded and porous structure.

Food extrusion is generally considered a high-temperature, short-time (HTST) process. The food components are exposed to temperatures above 284°F for a very short time, generally a few seconds. This gives a distinct advantage over conventional pressure cooking, in which the exposure could be several minutes at temperatures near 212 to 248°F.

Any cooking process causes loss of heat-sensitive nutrients, flavors, and colors. A combination of higher temperature and shorter time is desirable because it retains nutrients better than a combination of lower temperature and longer time. It has been found that vitamins A, C, E, B1, and folic acid are very sensitive to extrusion, whereas the B-complex vitamins B2, B6, B12, niacin, calcium pantothenate, and biotin are stable during extrusion.

Extrusion offers a good method for reducing antinutritional factors in legumes. For example, in peas, extrusion has been found to be more effective than germination for reducing tannins, polyphenols, and trypsin inhibitors. Extruders have been used as bioreactors for pretreatment of cereal grains for subsequent ethanol fermentation, enzymatic conversion of starch to glucose and maltose, and sterilization of ground spices such as black pepper, white pepper, and paprika. Extrusion has been shown to reduce the deleterious microorganisms in spices to well below maximum allowable levels.

Extrusion is an environmentally friendly process that uses heat and power efficiently and does not produce effluents. In addition, the same equipment can be used to make a variety of products. Extruded products are safe to consume, with no known harmful effects.

- **Modified/Controlled Atmosphere.** The shelf life of many fresh foods has been extended by controlling the composition of the gas environment in direct contact with the product. For products with shelf life limited by chemical or enzymatic reactions involving oxygen, reducing or eliminating the oxygen content of the environment provides significant extension of the product shelf life (Floros 1990).

The shelf life of fresh fruits and vegetables is extended by controlling both the oxygen and carbon dioxide composition of the atmosphere surrounding the products, which are still actively undergoing respiration and continue to convert oxygen to carbon dioxide. Large-scale controlled-atmosphere storage of fruits and vegetables has become a standard approach to maintaining the highest product quality between the time of harvest and delivery to the consumer. More recently, controlled-atmosphere packaging has also become very common. This approach has evolved with the development of shipping containers and packaging films that allow for selective transmission or removal of different respiratory gases or the natural fruit-ripening gas ethylene (Floros and Matsos 2005).

The modification of product atmosphere must be approached with caution, because of the response of certain microbial populations. The most serious concerns are with anaerobic pathogens, such as *Clostridium botulinum*, that have the potential to grow and produce toxins in an oxygen-free environment. Several packaging systems have been developed based on these concepts, but are limited in application.

- **Additives.** Food additives are adjuncts to food processing. They extend the range and flexibility of the relatively few food processes available, and they improve the economics of the processes. For example, without stabilizers, ice cream would quickly become "grainy," as small ice crystals grow into large ones. Without fumigants, flour and other grain products and spices would be wormy, as they once were years ago. Without fortification of milk and flour and the addition of iodine (in the form of iodate) to salt, rickets and goiter would still occur. Without artificial colors, many foods, such as gelatin, would be unattractive because natural colors lack the stability and coloring power of the synthetics. Without nonnutritive sweeteners, a great many sweetened beverages, desserts, and confections would have unacceptable calorie contents or contain levels of sugar that cannot be consumed by certain individuals, such as people with diabetes and many others. Anticaking agents, enzymes, preservatives, emulsifiers (which allow immiscible liquids such as oil and water to form a stable mixture), humectants (which affect moisture retention through their affinity to water and stabilizing action on water content), and many other additives add significantly to the safety, nutritive value, attractiveness, convenience, and economy of our modern food supply.

The practical definition of a food additive—not the far longer, involved legal definition—is "Any substance added to food in small amounts to achieve a particular technical effect." The *Code of Federal Regulations* (21.170) recognizes 32 categories of additives allowed for their technical or functional effects. Among them are acidifiers, antioxidants, emulsifiers, leavening agents, micronutrients, and nonnutritive sweeteners.

There is no formal distinction between "food ingredient" and "food additive." Common usage would suggest that an ingredient used at less than perhaps 1% of a food would be an "additive." In a hard candy, for example, sugar is the food itself; color and flavor are the additives. In a lightly sweetened beverage, however, sugar could be an "additive." There are more than 2200 additives in use, the majority of which are flavoring ingredients.

Figure 3 displays the distribution of additives in use during the recent decade, ranked by per capita annual consumption in the United States food supply. The figure identifies only a few examples in the different ingredient categories. The graph shows *use*, the amount that disappears into the food supply. Actual

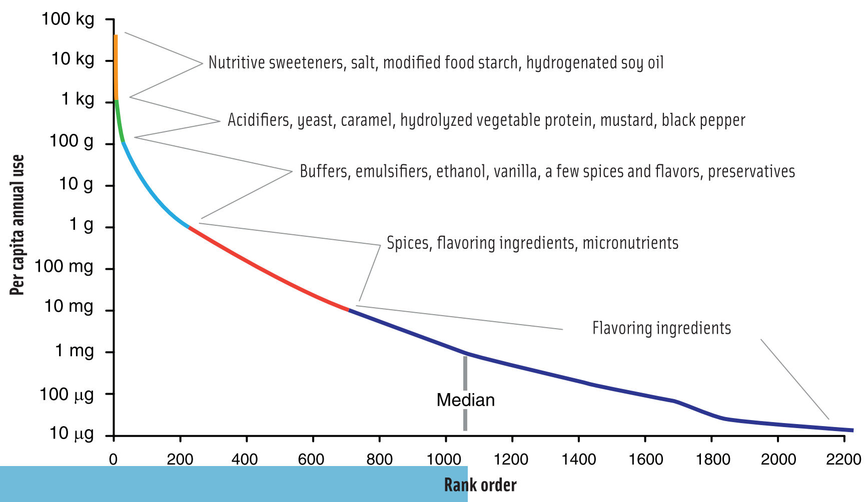

Figure 3–Substances intentionally added to food in decreasing order of per capita annual use.

consumption is significantly lower because of plate waste and, in the case of volatile additives such as flavors, volatilization. Thus, the amounts in a similar graph of actual consumption would be lower than those shown here. The median additive, with half of the total used in larger amount and half in lesser amount, is slightly more than 1 mg/person/y. The per capita consumption of a heavily used substance, such as a nutritive sweetener, frequently exceeds the per capita consumption of an ingredient in a much less used category. For example, a flavoring ingredient that because of its potency is used at very low levels will have a per capita consumption much lower than almost all other ingredients added to food.

• **Packaging.** Many different types of food packages are used for several different reasons. Food is packaged primarily to contain the product, protect the product from contamination, enable convenience, and provide information (Paine 1991; Robertson 1993; Yam and others 2005; IFT 2008).

Most food products are delivered to the consumer in some type of package. Foods that have received some type of preservation process are placed in a package to ensure that the product attributes enhanced by the process are maintained. Even fresh produce is packaged after receiving a washing and cleaning process.

Packaging offers a critical component of food safety by preventing contamination from pathogens. In addition, packaging extends the shelf life of the product by providing a physical barrier to or protection from atmospheric oxygen and moisture, light, and other agents that would accelerate deterioration of the product. Finally, packaging is the vehicle by which legally required information is presented to the consumer in the form of the label bearing information about the product identity, quantity, ingredients, nutrient content, expiration date, and commercial source.

Packaging has advanced from glass bottles, paperboard cartons, tin-plated soldered side-seam steel cans, and aluminum foil to 2-piece aluminum cans with "pop tops;" plastic, flexible, rigid, semirigid, and multilayer containers; microwave safe packages; and active and intelligent packaging (Floros and others 1997, 1998; Suppakul and others 2003; Ozdemir and Floros 2004; Yam and others 2005; Han and Floros 2007; IFT 2008). Innovations were driven by a number of forces, including convenience, consumer desire for minimally processed foods, changes in retail and distribution practices; foodservice needs; trend toward more sustainable packaging; and demands for global and fast transport of food (Suppakul and others 2003; IFT 2008).

Aseptic packaging is a major area of food packaging that has significantly increased the safety, quality, availability, and convenience of certain foods around the world, while reducing the amount of energy needed to preserve and store such foods. The major difference between aseptic packaging and traditional methods of food packaging is that in aseptic packaging the product and the packaging material are continuously sterilized separately. Then, under aseptic conditions that prevent recontamination of the product, the sterile package is filled with the cooled sterile product and hermetically sealed to produce a shelf-stable final product with extended shelf life and no need for refrigerated storage. This technique has allowed for substantial improvements in the quality of the final product, mainly due to the much milder heat treatment that the product undergoes compared to the traditional thermal process (Floros 1993). Large-scale aseptic bulk processing and packaging, combined with aseptic storage and transportation, contributes significantly to reduction of postharvest fruit and vegetable losses and greater availability of these food products around the world.

Many advances in the packaging of food took place in the past 20 to 30 y, producing a wide variety of new materials and processing technologies. The steady accumulation of research developments indicates that food packaging will continue to evolve and respond to the changing needs of the food system and the increased demands of consumers.

Emerging novel processes

To meet consumers' growing demands for fresh-like and highly nutritious foods with guaranteed safety, several alternative preservation technologies have been developed during the past 15 to 25 y for application to food products. These technologies include both (1) novel thermal processes such as microwave and ohmic heating, which are much faster than the currently widespread canning method to produce shelf-stable foods and (2) other physical methods that do not use heat as a primary mode of inactivating microorganisms in foods, such as ultra-high pressure (UHP), pulsed electric fields, ultrasonic waves, high-intensity pulsed light, and others.

Each of these alternative technologies has unique characteristics and potential for expanded applications in different categories of food products. The goal of all the new processes is to reduce the overall time and temperature exposures of the foods so that they are safe and more like fresh or freshly cooked items. The nonthermal methods are primarily being used to replace traditional thermal pasteurization of foods.

• **Microwave Heating.** This method of heating prepared foods and beverages and cooking raw foods is well known and accepted by consumers, but applications for food preservation are still evolving. Some microwave-processed foods are marketed in Europe and Japan. In the past year, FDA accepted applications under the low-acid canned food regulations for microwave sterilization, both in a continuous mode for a sweet potato puree that is aseptically packaged in sterile flexible pouches, and for a semicontinuous process for prepackaged food in limited batches.

• **Ohmic Heating.** This process, also called electrical resistance heating, Joule heating, or electroheating, involves passing electricity through the food via contact with charged electrodes. The electrical energy results in rapid, uniform heating, in contrast to the slow conduction and convection heating of conventional thermal processing, thereby allowing for greater quality than canned counterparts. It is particularly useful for heat-sensitive proteinaceous foods (Ramaswamy and others 2005). Ohmic heating has been applied in limited situations to such foods as cut and whole fruit and liquid eggs, but applications may expand to soups and similar items in the future.

• **High-Pressure Processing.** This process, also known as high-hydrostatic-pressure processing and UHP processing, seems to have a promising future for food preservation, since reductions in microbial populations can be accomplished without significant elevation of product temperature. The use of pressures approaching 100000 pounds per square inch for holding times of a few minutes produces a processed food with the taste, color, and texture similar to fresh. Following the successful introduction of a pressure-treated guacamole product in 1997, a growing number of ready-to-eat meats and other refrigerated items, including raw oysters, have been treated by high pressure to meet food safety standards for such products and have increased their high-quality shelf life.

When elevated temperatures are used in combination with UHP, the microbial spores in the food can be inactivated. In 2009, a pressure-assisted thermal sterilization process developed by a consortium of Army and industrial researchers at the Natl. Center for Food Safety and Technology was accepted under the low-acid canned food regulations by FDA (NCFST 2009). This process is more rapid and less damaging to several food quality attributes than traditional thermal sterilization because application of pressure rapidly and uniformly heats packaged food in the pressure vessel to the desired end temperature, and then, when pressure is released after a few minutes the product returns to the original temperature.

- **Pulsed Electric Fields.** Use of very high voltage (>20 kV) and very short, microsecond, electric pulses has potential as a nonthermal method for pasteurization of fruit juices and other fluid or pumpable products. The process is being optimized, but more information needs to be evaluated on the impact of the process on food components, first to assure microbiological safety and then to determine the impact on sensory quality as well as content of key nutrients (Sanchez-Moreno and others 2009).

Recent research has shown not only that some of these alternative novel processes allow production of very high quality items, but also that those items may have a higher nutritive value than similar items produced by traditional thermal processes because the novel processes result in less chemical damage of key micronutrients.

To achieve acceptance first by the regulatory authorities and then by consumers will require an overall evaluation of each of these novel processes.

Food waste management

Approximately 30 to 40% of raw food materials and ingredients are lost between the points of production and consumption. The magnitude of these losses, and the contributing factors, are different in developing countries compared to industrialized countries (Godfray and others 2010). For example, food losses in the developing world are primarily due to the lack of an infrastructure, as well as lack of knowledge of or investment in the means to protect from losses arising from damage and spoilage attributable to rodents, insects, molds, and other microorganisms. Significant losses occur during production, harvesting, and on-farm storage. In contrast, in industrialized countries, food losses are more significant in retail and foodservice establishments and in the home. The losses in developed countries are attributable to several factors, including the relatively low costs of food and the lack of incentives to avoid wastes (Godfray and others 2010).

Commercial food manufacturing operations are more efficient in the conversion of raw materials into consumer products than home processing and preparation. Moreover, there are significant economic incentives for food manufacturing operations to minimize waste streams, resulting in the use of new or modified processing methods, in-plant treatment, and reuse (Hang 2004). Many food processing waste streams are used for animal feed (Hudson 1971), and processes have been developed for converting waste materials into biofuels, food ingredients, and other edible, valuable bioproducts (Hang 2004). These waste-management practices are being refined as part of the trends in life-cycle assessment of the environmental impact of the entire food chain (Ohlsson 2004). Through such assessments, the food industry is identifying the steps in the food chain that have the greatest environmental impact. The assessments become the basis for selection of alternative raw materials, packaging materials, and other inputs, and an overall improvement in waste-management strategies (Ohlsson 2004).

Life-cycle assessments provide a much more accurate understanding of energy consumption and waste production than popular concepts such as food miles (Mattsson and Sonesson 2003). An example of life-cycle assessments is the comparison of high value added products, such as pork, with a highly productive crop, such as potatoes. The analysis indicates that for the high value added product, the largest energy consumption and production of emissions and other wastes is in the agricultural sector (that is, on the farm). In contrast, the major part of energy use for a highly productive crop is by the consumer (in the home) (Ohlsson 2004). Thus, to reduce energy contributions to global warming and generation of pollutants, it would be appropriate to target reductions where they would have the greatest effect (for example, on the farm for items such as pork and in the home for items such as potatoes) rather than simply focusing on food miles or food processing.

Numerous benefits

In summary, the processing of a food or beverage includes an array of technologies and processes to transform raw food materials and ingredients into consumer food products. The primary purpose of these processes is for preservation (for example, transforming perishable fruits and vegetables with the highest quality outcome possible into products available throughout the year around the world) and to ensure food safety.

The processing of a food does create some changes in the quality attributes of the product. In some cases, these changes are intentional and provide improvements in the nutritive quality, texture, appearance, and flavor of the product. In other cases, the changes may simply make the product different, without improving or changing its quality.

Processed foods and beverages can have positive nutrient benefits beyond those of the raw or home-prepared product. Nutrient retention is highly variable, depending on commodity, cultivar, timing of harvesting, storage conditions, nutrient type (for example, sensitivity to heat or oxygen, and water solubility), and processing method. Depending on these variables, processed foods may have more nutritional value (due to greater bioavailability of beta-carotene or lycopene, for example) than the fresh product (Rickman and others 2007a, 2007b). In addition, some processed products (for example, canned and frozen fruits and vegetables) are often a better value for the consumer than the "fresh" or raw product.

Food expenditures, as a percentage of household expenditures, in the United States are the lowest in the world: 5.6% compared to 9.1% in Canada, 11.4% in Germany, 24.1% in Mexico, and 44.1% in Indonesia (ERS 2008). Cost is an extremely important variable to most consumers in making food and other purchases, particularly to those with low incomes. Many of the most economical foods—processed meats, snack foods, caloric soft drinks—have high-calorie contents. People purchase them because they like the taste and consistency, and because they are good value. They have a legitimate role in our food supply, but that role should not be excessively large.

Looking to the Future

The future of the agriculture and food system will be largely determined by the trajectory of 3 major trends: the population and its associated demographics; availability and type of energy resources; and climate as it influences available land, water, and air quality. Population is the most important by far, since it drives the others (given the impact on demand for arable land, for example) through its multiplier, the standard of living (consumption rate). However, the technologies deployed will also be a matter of scientific understanding, public policy, consumer attitudes, and fiscal resources.

Historical perspectives and future development

Assuming that the goal is a sustainable future, Warren Belasco (2006) considered in his book *Meals to Come: A History of the Future of Food* the perspectives of 3 people living in the 1790s: Thomas Malthus, who was concerned about population growth; the enlightenment philosopher Jean-Antoine-Nicolas de Condorcet; and William Godwin, who believed that inequitable distribution was the problem. From these historical perspectives, Belasco proposed 3 possible cornucopian futures: (1) the classical, based on expansion into new areas (for example, expand food production and processing); (2) the modern, the belief in scientific and technological solutions; and (3) the recombinant, a blend of the radical modern with the familiar classical (for example, share resources more efficiently).

Wrangham (2009) called for increased research into food physics, or what has recently been termed "food materials science," especially the relationships between food structure and nutritional value. While Michael Pollan (2008), in his book *In Defense of Food: An Eater's Manifesto*, laments modern "nutritionism," he points to the need for more science as well.

Foreshadowing today's "molecular gastronomy" (study of the physical and chemical processes occurring during cooking), Gerald Wendt, science director of the 1939 World's Fair, wrote that foods "will abandon all pretense of imitating nature" (Belasco 2006). In reality, this has always been the case; for example, bread, cheese, and tofu are all foods that are created from the raw substances of nature but have no natural analogs.

Food culture evolves, albeit slowly. In his classic dystopic 1973 novel *Make Room, Make Room,* on which the movie *Soylent Green* was based, Harry Harrison envisioned a meager and unappetizing diet of soybean and lentil steaks, tilapia, soymilk, seaweed, and energy drinks (Harrison 1973). Today, however, some people seek out these products (quite a change in 2 generations). Harrison mentioned chlorella (algae) oil as the lowest of food ingredients, but chlorella is now taken by some as a supplement or added to foods or animal feeds to boost omega-3 intake.

Surimi is an example of technology applied to increase both stability and distribution of a raw commodity (fish) but that also increases the value of the product, as in surimi-based imitation crab. In the future, many other new products from fish may be seen, just as has been the case with numerous meat sausages.

Not only can the conversion of macronutrients (for example, proteins and carbohydrate polysaccharides) to calories be modulated by processing (such as the effect of high-pressure processing on protein conformation and hence conversion to calories), but also micronutrients bound up in the cellular structure of foods can be made more bioavailable by appropriate novel processing methods, such as high-pressure processing and pulsed electric fields (Sanchez-Moreno and others 2009). Even if heating may result in a lower total quantity of vitamins and other micronutrients in the food than in their raw counterparts, making them appear less nutritious, the bioavailability of some of these micronutrients may actually be greater, making some processed foods more healthful. Novel emerging processes not totally relying on heat seem to offer the potential to increase bioavailability of classic micronutrients and to spare many of the labile phytochemicals (plant metabolites, some of which are known to have human health benefits) that are a major advantage of fresh fruits and vegetables.

Solving the diet-and-disease challenge

The solutions to the diet-and-disease problem are complex and require a multipronged strategy from both the public and private sectors. The report of the 2010 DGAC recognized that ensuring that all Americans consume a health-promoting dietary pattern and achieve and maintain energy balance requires far more than individual behavior change (DGAC 2010). The DGAC's report contained 4 primary recommendations:

- Reduce the incidence and prevalence of overweight and obesity of the U.S. population by reducing overall calorie intake and increasing physical activity;
- shift food intake patterns to a more plant-based diet and increase the intake of seafood and fat-free and low-fat milk and milk products and consume only moderate amounts of lean meats, poultry, and eggs;
- significantly reduce intake of foods containing added sugars and solid fats, reduce sodium intake, and lower intake of refined grains; and
- meet the 2008 Physical Activity Guidelines for Americans.

The report expressed an urgent call to action and recommended that a strategic plan be developed that focuses on the behaviors and actions needed to successfully implement these 4 key recommendations.

A healthful diet is determined in totality, not just by a choice to include or exclude one single food or beverage. Decision-making and priority setting should be made in this context. Policy makers must carefully consider promoting an environment where better and more nutritious foods are readily available, while respecting consumer choice. Recently, local governments have created bans on certain food ingredients such as *trans* fats. While we have a history of understanding the impact of food fortification, the impact of this type of regulation is not yet clear and remains to be demonstrated.

Consider salt as an example. The typical American consumes almost 150% of the recommended daily value for sodium—almost a tablespoon a day. A recent report by the Inst. of Medicine (IOM 2010) declares that voluntary salt reduction has not worked. The IOM recommendations include modification by FDA of the Generally Recognized as Safe status of ingredients containing sodium and national standards to lower consumption, stepwise reduction in salt content of processed foods and menu items in restaurants to allow American consumers to adapt their tastes to foods with lower levels of sodium, enhanced monitoring and surveillance of compliance with the recommended new FDA standards, increased funding for research that links salt consumption to consumer preferences at different stages in human life, and development of programs that increase consumer awareness of elevated salt consumption.

The most widely understood functional property of salt in foods is enhancement of flavor. Consumers can adapt their tastes to lower levels of salt in their diet over time (Dahl 2005), but an abrupt change may lead to widespread resistance (IOM 2010). Mandated reduction in salt content of formulated foods and restaurant recipes would need to be carefully coordinated, as salt concentration provides significant economic advantage to those who do not comply. Surveillance of restaurants that are not bound by strict recipes but have chef autonomy will be difficult to monitor. Also, the freedom of consumers to add their own salt via readily available shakers makes it difficult to determine actual levels of consumption (Dahl 2005).

Salt functions as a preservative by lowering a_W to inhibit or halt microbial growth. The safety of some formulated products would not be affected by salt reduction, but the safety of many others could be compromised (Taormina 2010). Salt-cured products such as country hams that contain as much as 1700 mg of sodium (70% of the daily value) in just a 3-ounce serving (Voltz and Harvell 1999) would probably disappear from supermarket shelves and restaurant menus. Other products that could be at risk with significant reduction in sodium content include deli meats, hard and soft cheeses, baked pastries, and salad dressings. Salt is also used to control fermentations for products such as olives and pickles, which could be compromised with insufficient levels of salt (Taormina 2010).

Overconsumption of total calories coupled with very low physical activity and too much sedentary time is the driving force behind the obesity epidemic, rather than the macronutrient distribution of a person's diet (DGAC 2010). Consumers must make more healthful choices of diet and exercise. Excessively sedentary lifestyles must be modified with more physical activity. Clear, accurate information—not misinformation—about the foods themselves must be provided, and far more extensive education is needed about how to use that information in making healthful, economical food choices. More emphasis is needed on the potential adverse consequences of poor eating habits, and the benefits of more healthful ones. Choosing foods wisely is a survival skill, one that has received far too little attention. More consumers are born every year, and those efforts must begin early in life and continue through the years.

Many resources are still being devoted to increasing the availability of indulgent foods that do not contribute to meeting the nutrient needs of consumers. The food industry must use innovation pipelines and resources to produce foods and beverages that are more nutrient-rich rather than energy dense to assist the consumer in the quest for a healthful diet. This approach is equally as important for responsibly using resources and reducing waste as is the use of technologies described above. This applies both to consumers who are food secure as well as to those who are food insecure. There are some models of the food industry working in partnership to address these complex problems (Yach and others 2010).

Responsible marketing is also part of the solution to a healthful diet. Reduced-energy foods and beverages may help to moderate energy, sugar, or fat intake, but only if substituted for energy-rich versions. Simply including them in the diet may fail to reduce energy balance. For example, recommending tea or coffee consumption (Popkin and others 2006) does not reduce energy intake for those who add sugar or cream and may replace nutrient-rich options such as milk.

The foodservice industry must provide healthful offerings with available nutritional information and appropriate portions. Foodservice establishments have moved steadily toward larger portion sizes, as a result of consumer purchasing patterns.

Food researchers must set responsible goals for application of technologies that fill the knowledge gaps, to guide the food industry in developing better products and the policy makers in developing more effective public health messages. There is still much to be learned about the relationship of diet composition and energy balance, the effect of reduced-energy versions of foods and beverages on signaling systems, and the connection between reduced-energy products with enhanced palatability and energy intake. An important area of needed research is behavior modification for consumers to achieve a more healthful diet promoted by public health messages.

Addressing future challenges

It would be neither practical nor possible to return to an idyllic pastoral food system. Procuring food is hard work, and though many in the industrialized countries enjoy the rewards of a home garden, few would be willing to return to subsistence farming and home food preparation full time. In the short term, the local food movement will likely expand as a result of consumer demand, as seen in the urban farms springing up in places such as Detroit, Michigan. But the local food movement has its limits, since many consumers will continue to demand out-of-season and exotic foods that cannot be grown locally, and climate conditions prevent the efficient growth of food year round in all regions. Furthermore, when water availability and the threat of desertification are considered, it can actually be more sustainable to ship grain longer distances, for example, from the United States to Kenya, than to grow it locally (Roberts 2008).

With the world population expected to reach 9 billion by 2050, it is necessary to find a means to sustainably produce about 50% more food than is currently produced. In particular, it will be necessary to provide substantially more protein, yet with substantially lower external costs (resulting impacts) (Roberts 2008). Also, application of simple and appropriate processing technologies (for example, drying) and packaging and shipping methods close to food production sites to counter the large percentage of waste (up to 50% by some estimates) in less-developed areas must be fostered. Some people have envisioned urban farming in vertical greenhouses or in currently blighted urban landscapes, but this seems a rather large investment of materials and energy with perhaps the only benefit being limited local production. Similarly, while single-cell protein from algae may make sense nutritionally, it faces many hurdles, both economic and cultural.

Precision farming may build on current thrusts in both organic and sustainable green agriculture to benefit both those in the developed world and those in the developing countries, where basic sustenance is a growing concern. Ronald and Adamchak (2010) stated in *Tomorrow's Table* that "the judicious incorporation of 2 important strands of agriculture—genetic engineering and organic farming—is key to helping feed the growing population in an ecologically balanced manner." Mixed crop and livestock production systems, used to produce about half of the world's food supply, offer important synergies, such as using livestock draft power to cultivate land and manure to fertilize soil, crop residues to feed livestock, and income from livestock products to buffer against low crop yields (Herrero and others 2010). It has been suggested that the small-holder farmers in these systems should be the first target for policies to sustainably intensify production by carefully managed inputs of fertilizer, water, and feed to minimize waste and environmental impact, supported by improved access to markets, new varieties, and technologies (Herrero and others 2010).

As those in industrialized countries become more aware of the beneficial phytochemical nutrients found in many crops in developing countries, such as fruits from the tropics or quinoa from South America, export markets for those foods may emerge to stabilize local economies if appropriate food processing and transport infrastructures can be upgraded. Hurdle technology, using combinations of minimal technologies, has been used in developed countries for manufacturing ready-to-eat products, and may hold considerable potential for preserving certain traditional items in developing cultures. Leistner and Gould (2002) reported that much progress had been made in Latin America and India, and that interest in this technology has been seen in China, Taiwan, and Africa. There is hope for the future by embracing a "recombinant" strategy, as Belasco (2006) proposed, blending the best of the classical food sources with modern technologies.

Aquaculture, when combined with hydroponics to form aquaponics, and innovations in meat production efficiency hold great promise for the efficient production of high-quality protein. Federoff and others (2010) suggested that aquaculture, integrated with agriculture, is part of the answer to meeting the demands for food, feed, fiber, and fuel, given the implications of population growth, arable land and freshwater limits, and climate change.

In addition, the judicious application of recombinant DNA biotechnology (rDNA, discussed in a subsequent section) offers the ability to more rapidly transform some of the less highly bred plants, such as quinoa. Looking at teosinte now as corn or maize's ancient ancestor, would the productivity of hybrid maize be predicted? rDNA biotechnology could be harnessed to improve the protein quality of cereal grains and could also be employed to improve crops such as sorghum and millet to reduce antinutrients and build in drought tolerance. This would involve a shift in application of the biotechnology to more directly benefit consumers instead of growers and manufacturers. A new Green Revolution may include an accelerated mutation breeding program (use of chemical or radiation mutagens to introduce genetic change) to build in traits to better preserve quality and nutrient content of key food commodities.

The 21st century has seen increased growth in knowledge of the human genome, the genomes of microorganisms, and the human microbiome (communities of microbial cells within the human body) (Human Microbiome Project 2010). In the future, as we learn many more of the complex interactions of the thousands of compounds in common foods with the human genome and intestinal microflora, the old adage "You are what you eat" may well evolve into an optimal nutrition strategy to serve the growing human population. It is difficult to make predictions in such a rapidly changing scientific and technological atmosphere, but it is certain that the "designer foods" concept (following the concept of personalized nutrition, which is enabled by knowledge of one's genome and biome) will take on new meaning in coming years, given the accelerating pace of both the science base and technical innovation.

An *ad hoc* committee of the Natl. Research Council was charged with examining the current state of biological research in the United States and recommending how best to capitalize on recent scientific and technological advances to find solutions to 4 major societal needs, including sustainable food production. The committee's main recommendation was for a coordinated, interagency initiative to encourage the emergence of a "New Biology" approach to challenging problems, described in the book *New Biology for the 21st Century* (NRC 2009). The essence of the New Biology is integration, described as a new level of inquiry that reintegrates the subdisciplines of biology and integrates physicists, chemists, computer scientists, engineers, and mathematicians, purposefully organized around problem solving.

With respect to the food challenge, the New Biology requires parallel application of several technologies; computational modeling of plant growth and development at the molecular and cellular levels; cell-type specific-gene expression, proteomic, and metabolomic data; high-throughput visual and chemical phenotyping; methods to characterize the dynamics and functions of microbial communities; and ready access to next-generation sequencing methods. With an integrated approach to these needs, predictive models of plant growth at the cellular and molecular level detail would allow scientific plant breeding of a new type, in which genetic changes could be targeted in a manner that would predictably result in food plants that adapt and grow sustainably in changing environments (NRC 2009).

Emerging areas affecting health and wellness

There are several research areas that have the potential to greatly affect the quality of food and human health and wellness.

- **Personalized Nutrition.** Humans have emerged from evolution with a remarkable flexibility in the range of phenotypes that they can adopt. Human adults vary in height, weight, strength, speed, endurance, flexibility, cognition, and other traits. Furthermore, humans apply these phenotypes to a remarkable range of lifestyles, varying in everything from daily activities such as endurance exercise to recreational pursuits ranging from music, art, and athletics to preference for foods. This basic biological truth means that as science gains more information on the interaction among genetics, environment, and phenotype, people will want to use the controllable variables of their environment—diet and exercise, for example—to guide their own personal phenotype.

One consequence of human diversity relates to the observable variations in disease susceptibility. Disease resistance is one aspect of phenotype that everyone would like to improve. The first priority of life science research, of course, is to understand the basis of varying predisposition to, cures of, and recovery from disease (Collins and others 2003). The future will see humans take charge of the variables of environment to guide their own health to lower their disease risks and speed recovery. Personalizing diet will be essential to their success.

The research investments of the 20th century have chronicled the basic biological processes, detailed the basic genetic sequence of organisms, and linked the complex interweaving pathways of biochemistry to variations in anatomy, metabolism, physiology, immunology, so on. Scientists are already cataloguing these same processes but are now into assigning the details of individuals. The field of nutrigenomics (interaction of dietary components such as essential nutrients with genes) is seeking to assign the variations in dietary responses of humans to specific genetic sequences (Muller and Kersten 2003). In parallel, the field of metabolomics is building the tools to both diagnose individual variations in metabolism and identify the solutions to improve it (German and others 2004, 2005).

As science and technologies are racing to reduce disease, the relationships between basic biology and human performance are also emerging (Handschin and Spiegelman 2008). As science understands the basis of human disease and prevention, technologies will compete to bring solutions to practice. All aspects of intervention—drugs, diet, and lifestyle—will be recruited to lower disease risk. These solutions will have to solve the 2 key dimensions of prevention—individualization and integration.

Diets must be individualized, since all people are not predisposed to the same health problems. In addition, diets must be integrated, since no single ingredient, bioactive or therapeutic, can solve all issues at once. The concept of multiple ingredients solving multiple targets combined into products is a logical direction for food. Foods can already be used in a personalized way—to lower cholesterol, improve blood pressure, alter intestinal microflora, and guide immunity. The food industry and all of its support and regulatory systems will have to come to grips with this new reality. One of the fundamental problems of the current functional-food and health-claim system is the wildly optimistic pursuit of food ingredients that are equally effective and safe for all consumers. Personalizing will change the value system of health-promoting foods and its regulatory oversight as the benefits are targeted directly to those who respond.

Parsing individual response (based on the individual's genotype) is at least as complex a challenge as the task of increasing or decreasing the amount of a specific protein, fatty acid, or other component of the plant itself (Brigelius-Flohe and Joost 2006). Functional-food components are of increasing interest in reducing risk of a number of the leading causes of death: cancer, diabetes, cardiovascular disease, and hypertension. Many food components, such as plant-derived estrogens (phytoestrogens), are known to influence the expression of both structural genes and transcription factors (a sequence-specific DNA binding factor that controls the transfer of genetic information from DNA to messenger RNA) in humans (Kaput and others 2007). Genistein, coumestrol, and zearalenone, for example, bind to the estrogen receptor and may switch on a similar set of genes, such as 17β-estradiol, the physiologic estrogen.

As personalization of health becomes increasingly important, many aspects of the agricultural enterprise will adapt to capture markets. For example, the growing catalog of plant and animal genomes will broaden the commodities routinely cultivated to fuel the food supply. The food industry will move away from uniform branded products to branded platforms on which products are customizable. Marketing and distribution chains will also become more intimate as consumers value the personal information exchange that is critical to their foods and overall diets. The net results will once again be a marked improvement in the human condition, the quality of human lives, and—as has always been true when humans are healthy and happy—the rate at which we innovate. It is a very attractive future.

• **Molecular Biology.** Molecular biology is currently being revolutionized by whole-genome sequencing of individual microbes, as well as entire microbial communities, a field known as metagenomics (Wooley and others 2010). These new advances are also being complemented by our increasing understanding of gene expression and metabolism at the level of individual cells and complex microbial communities, such as those that exist within the human gastrointestinal tract. Sophisticated gene expression arrays based on whole-genome sequences are now allowing us to see for the first time the complex and dynamic regulation of virulence genes (those coding for a pathogen's illness-causing potential) *in vivo* during the various stages of infection (Toledo-Arana and others 2009).

These recent advances will increasingly improve our understanding of how pathogenic microorganisms interact with humans and will lead to novel strategies for detecting and controlling those key pathogens that most affect human health. For example, using special whole-genome "tiling" microarrays—concentrated, orderly arrangements of thousands of gene probes on a glass slide, used to detect all genes present within a microorganism or measure the level of expression of all genes within a microorganism—with overlapping nucleotides, Toledo-Arana and others (2009) were able to demonstrate how expression of various virulence genes dramatically changed as the microorganism switched from being a saprophyte (an organism that lives on dead organic matter) in the environment to a pathogen in infected hosts.

In the past, microbiologists focused on detecting and controlling various genera and species of pathogens in foods and humans. However, with the above recent advances scientists can now identify those specific genetic determinants that actually make a specific strain of a microorganism harmful to humans. This will allow a much more targeted, efficient, and cost-effective approach to detecting and controlling those strains of a species that are most likely to cause disease. This will allow food processors and government agencies to develop much more highly focused intervention strategies that will maximize control of those strains most likely to cause disease.

Also, identification of novel genetic determinants responsible for transmission and virulence will lead to rapid sequence-based approaches for determining the molecular epidemiology of various pathogens (Chen and others 2010). Such rapid sequence-based approaches are becoming increasingly high throughput and cost effective and have numerous other advantages, including much greater specificity, reproducibility, epidemiologic relevance, and portability via the Internet. Such advances will result in a global sequence-based epidemiology network for rapidly tracking and controlling dangerous strains of food-borne pathogens, which increasingly are capable of being quickly spread around the globe as a result of international trade and air travel.

Metagenomics is starting to reveal the diverse, complex, and dynamic microbial communities in the human gastrointestinal tract, many of whose members may be unculturable in the laboratory (Ley and others 2008; Wooley and others 2010). Microbial members of the microbiome in the human gastrointestinal tract actually outnumber their eukaryotic counterparts (organisms whose cells have a nucleus that contains their genetic material) in the human body and may be playing major roles in maintaining and promoting human health (Neish 2009).

Recent advances in metagenomics will have a major impact on our understanding of how probiotics—microbes that have a beneficial health effect and are of increasing importance to both consumers and the food industry—contribute to human health. Probiotics will continue to gain in importance as the population ages and more people become at risk for various pathogenic and chronic diseases and increasingly look for novel probiotics that can prolong health and wellness. Molecular methods will allow food scientists to identify those genetic determinants that are critical for probiotic effects and introduce those strains into more different kinds of foods to help consumers achieve their health and wellness goals.

Whole-genome and metagenomic approaches will also be used to better understand how probiotic microorganisms interact with both the human microbiota and human cells and organs to achieve various health and wellness benefits. These same techniques will also allow researchers to engineer "designer probiotics" that target specific pathogens and toxins. Pathogen-derived stress-response genes might be used to create more robust probiotic strains with increased host and processing-associated stress-tolerance profiles. Also, functional metagenomics may be used to identify novel genes with probiotic attributes from diverse and vastly unexplored environments, such as the human gastrointestinal tract (Culligan and others 2009).

Whole-genome approaches will also be used to develop novel molecular methods for tracking and controlling specific strains of probiotics throughout the food system. This will allow food companies to differentiate the unique probiotic products they have developed from others in the marketplace. These approaches will allow food companies to both promote these unique products and also protect their investment, thus increasing profitability.

• **Microbial Ecology.** With potential impact on food quality and health and wellness, microbial ecology examines the diversity of microorganisms and how microorganisms interact with each other and their environment to generate and maintain such diversity. While microbial ecology is not a new concept, it is of increasing interest to many food microbiologists, because it explains the presence and functioning of microbes in complex and dynamic food environments, both outside and inside the gastrointestinal tract. Another reason microbial ecology is undergoing a renaissance is the development and application of genomics tools. Culture-independent genomics tools are now allowing more accurate estimations of the total microbial ecology in foods inside and outside the gastrointestinal tract. However, genomics tools have also exposed how little we know about the vast diversity of microorganisms that colonize foods and the human gastrointestinal tract.

Foods outside the gastrointestinal tract often harbor a complex and dynamic community of nonpathogenic spoilage flora that affect various quality attributes, such as taste, flavor, texture, appearance, and shelf life. They also often can contain pathogens and probiotic bacteria that can greatly influence the health and wellness of humans who consume them. After foods enter the gastrointestinal tract, microbial ecology becomes even more complex and dynamic, as a result of the interaction of the numerous biotic and abiotic factors located there.

Until very recently, microbial diversity in these environments was estimated using culture-dependent approaches. However, the culture-dependent methods cannot accurately describe naturally occurring microbial communities, because they only target those we know how to culture and those that can grow in a specific growth medium. In the past 20 y, the application of genomics and metagenomics tools has revolutionized microbial ecology studies and drastically expanded our view of the previously underappreciated microbial world, including environments on and in foods and those within the human gastrointestinal tract (Xu 2006).

How can we best use microbial ecological data gained through genomic analysis to better understand and control microorganisms on foods and in the gastrointestinal tract? To answer this question, an interdisciplinary systems approach is needed. This approach will require the integration of the analyses at various levels of ecological organization, from subcellular and cellular levels to those of individuals, populations, communities, and ecosystems. Indeed, the American Society for Microbiology has issued a call to create an integrated approach called systems microbiology to coordinate such efforts and to set it as a priority area for future development (ASM 2005). As we understand more about the complex and dynamic microbial ecology of foods, we will be in a better position to manipulate those biotic and abiotic factors that enhance food quality and/or health and wellness.

Promising technologies

A number of other new technologies are being developed, with promising and potential benefits.

- **Biotechnology.** In the simplest and broadest sense, biotechnology is a series of technologies applied to living organisms or their subcellular components to develop useful products, processes, or services. Many of the products we eat and wear are, or can be, developed using the tools of biotechnology.

The first generation of products commercialized from biotechnology were crops focusing largely on input agronomic traits, primarily in response to biotic stress—pressure from organisms such as viruses, bacteria, and insects that can harm plants—and the vast majority of biotechnology crops have been in the area of pest resistance and herbicide tolerance. Biotechnology-derived papaya, squash, and sweet corn are commercially available in the United States; enzymes produced using recombinant DNA methods are used to make cheese and low-lactose milk, keep bread fresh, and produce fruit juices and wines; and bioengineered *E. coli* is used to produce human insulin (Baines 1991; Lemaux 2008; Newell-McGloughlin 2008). Two varieties of rice—referred to as Golden Rice—having increased levels of beta-carotene, a precursor of vitamin A, have been developed and are in use in the Philippines, India, Bangladesh, China, and Vietnam (Lemaux 2008). Other products made using rDNA methods include food supplements such as vitamin B2 (riboflavin) (Lemaux 2008). Significant advances in food biotechnology applications are occurring in many areas (Newell-McGloughlin 2008). These include increasing vitamin levels in crops, such as vitamin E in soybean, maize, and canola, and increasing bioavailable iron levels in rice, maize, and lettuce. Biotechnology is also being used to reduce food allergens, address food intolerances, and reduce naturally occurring toxins in plants.

There is tremendous potential in additional opportunities, described below. The Intl. Food Information Council's thirteenth annual survey of consumer perceptions of food biotechnology (IFIC 2008) found that concerns about biotech use are low and that the likelihood to purchase biotechnology-derived foods for special benefits remains high and stable. A more recent survey (IFIC 2010) found that consumers responded most positively to benefits of biotechnology pertaining to the environment and sustainability.

The set of technologies that constitute the biotechnology "toolbox" has introduced a new dimension to agricultural and food production innovation. Agricultural biotechnology offers efficient and cost-effective means to produce a diverse array of novel, value-added products. In addition to the applications already discussed, biotechnology has the potential to increase food production, improve food quality and healthfulness, reduce the dependency of agriculture on chemicals, alleviate biotic and abiotic stress (for example, high salt or temperature extremes), and lower the cost of raw materials, all in an environmentally sustainable manner.

While the scope of biotechnology's influence in the food industry is broad, the tools of this technology have potential for a major impact in 4 principal areas: crop and animal agriculture, bioprocessing, and diagnostics (Newell-McGloughlin 2008). It is possible to enhance the growing season, yield, disease and pest resistance, and other properties of crops and enhance the nutritional content, texture, color, and flavor of foods. Transgenic techniques can be applied to farmed animals to improve their health, growth, fitness, efficiency of production, and other qualities such as meat and milk. Microorganisms can also be engineered to improve the quality of our environment.

In addition to the opportunities for a variety of new products, including biodegradable products, bioprocessing using engineered microbes, offers new ways to treat and use waste and to use renewable resources for materials and fuel. Instead of depending on nonrenewable fossil fuels, organisms can be engineered to convert maize and cereal straw, forest products and municipal waste, and other biomass to produce fuel, plastics, and other useful commodities.

The coming generations of crop plants developed via biotechnology can be generally grouped into 4 broad areas: continuing improvement of agronomic traits such as yield and tolerance to abiotic stress, in addition to the biotic stress tolerance of the present generation; crop plants as biomass feedstocks for biofuels and "biosynthetics;" value-added output traits such as improved nutrition and food functionality; and plants as production sources for therapeutics and industrial products (Newell-McGloughlin 2008). Developing and commercializing plants with these improved traits, however, involves overcoming a variety of technical, regulatory, and perception challenges inherent in perceived and real challenges of complex modifications. Both the panoply of traditional plant-breeding tools and modern biotechnology-based techniques will be required to produce plants with the desired quality traits.

From a health perspective, plant components of dietary interest can be broadly divided into 4 main categories, which can be further broken down into positive and negative attributions for human nutrition: macronutrients (proteins, carbohydrates, lipids/oils) and fiber; micronutrients (vitamins, minerals, phytochemicals); antinutrients; and allergens, intolerances, and toxins (Newell-McGloughlin 2008).

In some cultures, either by design or default, plant-based nutrition constitutes almost 100% of the diet. Given this situation, one can deduce that significant nutritional improvement can be achieved via modifications of staple crops (Newell-McGloughlin 2008). A growing body of evidence indicates that food components can influence physiological processes at all stages of life. Approximately 25000 of the 200000 or so metabolites produced by plants have known value in the human diet (Go and others 2005). Analysis of these metabolites, specifically metabolomic analysis, is a valuable tool in better understanding what has occurred during crop domestication (lost and silenced traits) and in designing new paradigms for more targeted crop improvement that is better tailored to current needs (Hall and others 2008).

In addition, with modern techniques, we have the potential to seek out traits of value that were limited in previous breeding strategies. Research to improve the nutritional quality of plants has historically been limited by a lack of basic knowledge of plant metabolism and the challenge of resolving complex interactions of thousands of metabolic pathways. A complementarity of techniques, both traditional and novel, is needed to metabolically engineer plants to produce desired quality traits.

Metabolic engineering is generally defined as the redirection of one or more reactions (enzymatic and otherwise) to improve the production of existing compounds, produce new compounds, or mediate the degradation of undesirable compounds. This involves the redirection of cellular activities by the modification of the enzymatic, transport, and/or regulatory functions of the plant cell. Significant progress has been made in recent years in the molecular dissection of many plant pathways and in the use of cloned genes to engineer plant metabolism.

With evolving "omics" tools (genomics, proteomics, metabolomics), a better understanding of the totality of effects of metabolic engineering on metabolites, enzyme activities, and metabolic fluxes (rates of turnover of molecules through a metabolic pathway) is beginning to be developed. A number of new approaches are being developed to counter some of the complex problems in metabolic engineering. Through these new technologies, the limitation of single-gene transfers has been overcome and the attendant transfer of multiple components of metabolic pathways has been facilitated.

For example, it is now possible to design "minichromosomes" that carry cassettes of genes, enhancing the ability to engineer plant processes such as the production of complex biochemicals. Paul Christou's laboratory at the Univ. of Lleida in Madrid, Spain, used combinations of genes in a modification that introduced multicomplex metabolic pathways coding for increased beta-carotene, vitamin C, and folate, effectively creating a multivitamin maize cultivar (Naqvi and others 2009).

This system has an added advantage from a commercial perspective in that these methods circumvent problems with traditional approaches which not only limit the amount of sequences transferred but also may disrupt native genes or lead to poor expression of the transgene, thus reducing both the numbers of transgenic plants that must be screened and the subsequent breeding and other related steps required to select a suitable commercial candidate.

Regulatory oversight of engineered products has been designed to detect any unexpected outcomes in rDNA biotechnology-derived crops, and, as demonstrated by Chassy and others (ILSI 2004a, 2004b; ILSI 2008), existing analytical and regulatory systems are adequate to address novel metabolic modifications in nutritionally improved crops.

• **Nanotechnology.** Nanoscale science, engineering, and technology—referred to as nanotechnology—include the fundamental understanding and technological advances arising from the understanding of new physical, chemical, and biological properties of matter at the length of scale of approximately 1 to 100 nanometers (nm). Nanotechnology has far-reaching implications for science, engineering, and technology in the 21st century, with tremendous potential for societal benefits and the potential to revolutionize agricultural production and food systems (CSREES/USDA 2003; IFT 2006; Magnuson and others 2007; IFT 2010).

Nanotechnology is rooted in the vision of Richard Feynman, 1959 Nobel Laureate in physics, who envisioned the ability to closely observe and control phenomena and behaviors of matter at the nanometer scale with atomic precision. His vision became reality in the mid-1980s when instrumentation advancements (for example, scanning tunneling microscopy and atomic force microscopy) enabled seeing nanoscale structure and interactions and manipulation of individual atoms with precision.

Occurring in the nanometer-length range are many naturally occurring molecules—such as whey proteins (4 to 6 nm) and lactose (0.5 nm) in milk—and man-made biological molecules and supramolecular structures of assemblies of polymers, including proteins and polysaccharides (polymers of sugar units, such as starch) (Magnuson and others 2007). Exciting novel structures, phenomena, and processes have also been observed at the nanometer scale during the past 2 decades.

In the past decade, governments around the world launched initiatives and industries, and private sectors ventured into research and development of nanotechnologies for a wide range of applications, from semiconductors, energy, chemicals, and materials to medicine, the environment, and food and agriculture. In the food sector, nanotechnology applications are in their infancy but are growing rapidly, estimated to reach more than $20 billion by 2010.

In agriculture, nanotechnology holds promise for responding to the need for more precise management of resources such as water, fertilizers, and other agricultural chemicals; improving crop and livestock production; controlling pests, diseases, and weeds; monitoring plant disease and environmental stresses; supporting sustainable and precise production; and improving postharvest technology, including waste management. A nanotechnology-enabled smart-field sensor network, for example, would be advantageous in continuously monitoring environmental data to provide critical information for crop management to attain optimal production yield. Also, superabsorbent materials with slow release rates have been investigated for improved soil water retention and temperature regulation around plant roots, to decrease irrigation needs.

The potential benefits of nanotechnology applied in the food system are anticipated for food safety and defense, food processing, food packaging, and ingredient technologies (IFT 2005, 2007, 2010). Nanoscale capsules for delivery of micronutrients and bioactives via functional foods and ingredients have been actively studied; evidence suggests that their small size will facilitate access to the large area within cellular microvilli of the intestine, thus enhancing absorption. Clemson Univ. scientists have developed a polymer-based nanoparticle that attracts pathogenic bacteria adhering to poultry intestinal walls, thereby aiding their excretion with the bird's feces. Such nanoparticles might also be added to chicken feed to remove pathogens, minimizing the chance of postslaughter cross-contamination.

Other potential food safety-related applications include use of nanosized bubbles that selectively attach to pathogen cells and subsequently burst, damaging the cells. Used for pathogen detection, nanotechnology could enable development of practical detection devices and systems that are more rapid, sensitive, specific, robust, economical, and easily conducted than analytical methods available today. Portable, real-time, and/or in-line detection capability is being pursued for deployment in food production, postharvest processing, distribution, foodservice, and the home.

Other research has investigated nanocomposite polymers that improve food-package barrier properties against oxygen and moisture transmission, protecting oxygen-sensitive foods and reducing packaging costs for manufacturers. Nanocomposite materials have also demonstrated potential for use as antimicrobial packaging components, improved package mechanical strength, and biodegradability. Several biodegradable nano-biobarcode technologies have been researched that will aid product traceability, maintenance of product authenticity, identification of product attributes of interest to consumers, and monitoring of product changes relevant to quality and safety.

Responsible research and development of nanoscale food materials for the agricultural and food sectors will involve assessment of the adequacy of existing characterization methods and, where necessary, development of new methods to address critical questions for a science-based approach to understanding the characteristics of the novel engineered substances. Characterization of nanoscale food materials will include study of their stabilities in food matrices and during processing; digestibility and biopersistence; absorption, distribution, metabolism, and excretion properties; ability to translocate across cell membranes; and potential toxicity at the intended application range/exposure level through oral ingestion. Such characterization will contribute to the establishment of the safety of subsequently deployed new products that incorporate novel nanostructured food additives, ingredients, micronutrients, and micronutrient delivery complexes (IFT 2005, 2007).

Recognizing that without consumer acceptance new technologies will not succeed in the marketplace, federal funding agencies and universities are engaged in disseminating through a variety of channels—such as public radio and interactive displays at science centers and museums—information about nanotechnology developments emerging from the laboratory, obtaining public input, and studying consumer responses to nanotechnology food applications. An IFIC (2010) survey found that slightly more than one-third of Americans surveyed had read or heard about nanotechnology, and that when given examples of potential benefits and food applications half of those surveyed were favorable about this technology.

Much of the advance in nanotechnology will depend on the outcome of recently proposed research on its safety, as well as real measures—and communication—of both benefits, such as increased bioavailability of micronutrients, and risks to consumers.

Consumer acceptance

Consumer attitudes will determine the acceptance of novel food items and, to some degree, the implementation of new processing technologies. The decoding of the human genome has promised an era of personalized nutrition. Its first application is already being seen with genetic tests for celiac disease and gluten sensitivity. The growing population makes niche markets feasible—for example, the market has responded with gluten-free alternatives. We have barely scratched the surface of genomics and are already hearing of the influence of epigenetics—changes in gene activity without alteration of the genetic code—and the potential for epigenetic changes brought about by short-term limitation in food availability to influence obesity in future generations (Bygren and others 2001).

Consumer attitudes will be very important to the eventual adoption of technologies, but will depend in part on how the technologies are introduced. Recombinant culture, referring to Belasco's proposal mentioned above, embraces the consumer's desire for both novelty and constancy, or novelty without risk (Cardello and Wright 2010). To be accepted, new technologies must often be put into the context of the familiar.

Conclusions

Our modern food system is very complex and changes continuously in time and space. During the past century, food processing evolved to make food the basis of a healthy civilization, help society overcome hunger and disease, and improve the safety, nutrition, convenience, affordability, and availability of foods. Food processing also changed the perception of foods and beverages.

Through food science and technology, the knowledge of many disciplines is applied to transform raw food materials and ingredients into consumable foods available year round. Advances in agriculture and food science and technology have provided reduction in nutrient deficiency-related diseases; enhanced food safety and consistent quality; decreased home food-preparation time; a large variety of delicious food choices; reduced food waste; lower household food costs than ever before; food and meal convenience options; products specifically formulated to meet the nutritional needs of specific subpopulations; and efficient global food distribution, which can be exploited in times of natural and man-made disasters.

Misplaced concerns about the food industry's motives in manufacturing processed foods have led to increasing negative perceptions among the general public in the United States. It is a fact that scientific and technical achievements throughout the food system—from agriculture and food manufacturing to preparation in the home—allow most people in the developed world to have ready access to a diverse, abundant supply of food that is safer, tastier, more nutritious, more convenient, and relatively less expensive than would otherwise be the case. Many people in the developing world, however, where a substantial portion of food produced is lost, are not able to make choices from such abundance. Further advances in science and technology are critically needed to successfully meet the daunting challenges ahead in feeding the growing world population, especially in the areas of greatest need.

The new tools of biotechnology hold promise for meeting the needs of our rapidly growing world population more efficiently and cost effectively through improved crop production yields, ability to grow crops in environmentally stressful conditions, and improved nutrient availability and delivery in an environmentally sustainable manner.

Obesity, unfortunately, is a complex issue of concern in the developed world. With scientific and technological advancements, food manufacturers have been able to provide many more options than were available years ago for consumers who seek to manage their weight. These options include food and beverage products with reduced caloric density and packaging as a component of portion control. Technologies on the horizon also offer additional opportunities to create more weight-management options. Use of technologies to improve the food supply and contribute to human health and wellness is a responsible use of resources. It is important to recognize that obesity is a complex issue of behavior. Further developments in genomics, metabolomics, and nutrigenomics hold tremendous promise for development of individualistic solutions to obesity.

Through nutrigenomics and metabolomics, personalized nutrition for health and wellness will become better understood and a more practical reality for a larger number of people. Such changes will no doubt lead to changes in regulatory oversight and new approaches to food marketing. Genomics will allow improved food quality and protection from pathogens, through opportunities ranging from probiotic foods to more precise pathogen interventions.

Nanotechnology can be expected to have beneficial impacts throughout the food system, from agricultural production, where it may enable more precise management of resources, to personalized nutrition, which holds potential for enhancing delivery and absorption of nutrients and bioactive substances via functional foods. With continued developments in nanotechnology, we can anticipate new mechanisms for detecting and controlling pathogens, in both the agricultural and food-manufacturing sectors.

Today and in the future, the food system must be flexible and resilient, consumer driven, and sustainable, and it must secure the environment and natural resources and assure the health and wellness of an increasing number of consumers. Food science and technology can help us advance the food system, minimize risks, maximize benefits, and deliver a safe, nutritious, and abundant food supply to all people around the world.

Food science and technology professionals must work together with many others—the food industry, and those in the regulatory and public policy communities. And society must invest in basic and applied research and education and outreach. With science and technology solutions available to address specific issues throughout the food system, our ability to feed a growing population in a sustainable way, while safeguarding both human and planet health, looks not only possible, but also promising. We must, however, remain steadfast and rational about our approach, to help both humanity and nature.

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