Microbiology and Technology of Fermented Foods
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Preface

This project started out innocently enough, with the simple goal of providing a resource to students interested in the microbiology of fermented foods. Since 1988, when I first developed a course in fermentation microbiology at the University of Nebraska, there has not been a suitable student text on this subject that I could recommend to my students. Pederson’s *Microbiology of Food Fermentations* had last been published in 1979 and *Fermented Foods*, by A.H. Rose, was published in 1982. Brian Wood’s two volume *Microbiology of Fermented Foods*, published in 1998 (revised from an earlier 1985 edition), is an excellent resource and is considered to be one of the most thorough texts on fermented foods, but it and other handbooks are generally beyond the scientific scope (and budget) of most students in a one-semester-long course. Finally, there are many excellent resources devoted to specific fermented foods. The recently published (2004) *Cheese Chemistry, Physics and Microbiology* (edited by Fox, McSweeney, Cogan, and Guinee) is an outstanding reference text, as are Jackson’s *Wine Science Principles, Practice, and Perceptions* and Steinkraus’ *Industrialization of Indigenous Fermented Foods*. However, their coverage is limited to only those particular foods.

I hope this effort achieves the dual purposes for which it is intended, namely to be used as a text book for a college course in fermentation microbiology and as a general reference on fermented food microbiology for researchers in academia, industry, and government.

In organizing this book, I have followed the basic outline of the course I teach, *Microbiology of Fermented Foods*. Students in this course, and hopefully readers of this text, are expected to have had a basic course in microbiology, at minimum, as well as courses in food microbiology and food science. An overview of microorganisms involved in food fermentations, their physiological and metabolic properties, and how they are used as starter culture provides a foundation for the succeeding chapters. Nine chapters are devoted to the major fermented foods produced around the world, for which I have presented both microbiological and technological features for the manufacture of these products. I confess that some subjects were considered, but then not included, those being the indigenous fermented foods and the natural fermentations that occur during processing of various “non-fermented” foods, such as cocoa beans and coffee beans. These topics are thoroughly covered in the above mentioned texts.

One of my goals was to provide a historical context for how the manufacture of fermented foods evolved, while at the same time emphasizing the most current science. To help accomplish this goal I have included separate entries, called “Boxes,” that describe, in some detail, current topics that pertain to the chapter subjects. Some of these boxes are highly technical, whereas others simply provide sidebar information on topics somewhat apart from microbiology or fermentation. Hopefully, the reader will find them interesting and a pleasant distraction from the normal text.
Finally, in an effort to make the text easier to read, I made a conscious decision to write the narrative portion of the book with minimal point-by-point referencing. Each chapter includes a bibliography from which most source materials were obtained. The box entries, however, are fully referenced.
I am grateful to the many colleagues who reviewed chapters and provided me with excellent suggestions and comments. Any questionable or inaccurate statements, however, are due solely to the author (and please let me know). To each of the following reviewers, I thank you again: Andy Benson, Larry Beuchat, Lloyd Bullerman, Rich Chapin, Mark Daeschel, Lisa Durso, Joe Frank, Nancy Irelan, Mark Johnson, Jake Knickerbocker, David Mills, Dennis Romero, Mary Ellen Sanders, Uwe Sauer, Randy Wehling, and Bart Weimer.

For the generous use of electron micrographs, photos, and other written materials used in this text, I thank Kristin Ahrens, Andeika Bianchini, Jeff Broadbent, Lloyd Bullerman, Rich Chapin (Empyrean Ales), Lisa Durso, Sylvain Moineau, Raffaele de Nigris, John Rupnow, Albane de Vaux, Bart Weimer, Jiujiang Yu, and Zhijie Yang.

For their encouragement and support during the course of this project, special thanks are offered to Jim Hruska, Kari Shoaf, Jennifer Huebner, Jun Goh, John Rupnow, and the SMB group. The editorial staff at Blackwell Press, especially Mark Barrett and Dede Pederson, have been incredibly patient, for which I am very appreciative.

I thank my wife, Charla, and my kids, Anna and Jacob, for being such good sports during the course of this project. At least now you know why I was busier than usual these past two years.

Finally, I would not be in a position of writing an acknowledgment section, much less this entire text, were it not for my graduate mentors, Robert Marshall, Larry McKay, Howard Morris, and Eva Kashket. Role models are hard to find, and I was fortunate to have had four. My greatest inspiration for writing this book, however, has been the many students, past and present, that have made teaching courses and conducting research on fermented foods microbiology such a joy and privilege.
Microbiology and Technology of Fermented Foods
Introduction

“When our souls are happy, they talk about food.”
Charles Simic, poet

Fermented Foods and Human History

Fermented foods were very likely among the first foods consumed by human beings. This was not because early humans had actually planned on or had intended to make a particular fermented food, but rather because fermentation was simply the inevitable outcome that resulted when raw food materials were left in an otherwise unpreserved state. When, for example, several thousands of years ago, milk was collected from a domesticated cow, goat, or camel, it was either consumed within a few hours or else it would sour and curdle, turning into something we might today call buttermilk. A third possibility, that the milk would become spoiled and putrid, must have also occurred on many occasions. Likewise, the juice of grapes and other fruits would remain sweet for only a few days before it too would be transformed into a pleasant, intoxicating wine-like drink. Undoubtedly, these products provided more than mere sustenance; they were also probably well enjoyed for aesthetic or organoleptic reasons. Importantly, it must have been recognized and appreciated early on that however imperfect the soured milk, cheese, wine, and other fermented foods may have been (at least compared to modern versions), they all were less perishable and were usually (but not always) safer to eat and drink than the raw materials from which they were made. Despite the “discovery” that fermented foods tasted good and were well preserved, it must have taken many years for humans to figure out how to control or influence conditions to consistently produce fermented food products. It is remarkable that the means for producing so many fermented foods evolved independently on every continent and on an entirely empirical basis. Although there must have been countless failures and disappointments, small “industries,” skilled in the art of making fermented foods, would eventually develop. As long ago as 3000 to 4000 B.C.E., for example, bread and beer were already being mass produced by Egyptian bakeries and Babylonian breweries. Likewise, it is clear from the historical record that the rise of civilizations around the Mediterranean and throughout the Middle East and Europe coincided with the production and consumption of wine and other fermented food and beverage products (Box 1–1). It is noteworthy that the fermented foods consumed in China, Japan, and the Far East were vastly different from those in the Middle East; yet, it is now apparent that the fermentation also evolved and became established around the same time.

Fermentation became an even more widespread practice during the Roman Empire, as
new raw materials and technologies were adopted from conquered lands and spread throughout the empire. Fermented foods also were important for distant armies and navies, due to their increased storage stability. Beer and wine, for example, were often preferred over water (no surprise there), because the latter was often polluted with fecal material or other foreign material. During this era, the means to conduct trade had developed, and cheese and wine, as well as wheat for bread-making, became available around the Mediterranean, Europe, and the British Isles.

Although manufacturing guilds for bread had existed even during the Egyptian empire, by the Middle Ages, the manufacture of many fermented foods, including bread, beer, and cheese, had become the province of craftsmen and organized guilds. The guild structure involved apprenticeships and training; once learned, these skills were often passed on to the next generation. For some products, particularly beer, these craftsmen were actually monks operating out of monasteries and churches, a tradition that lasted for hundreds of years. Hence, many of the technologies and

Box 1–1. Where and When Did Fermentations Get Started? Answers from Biomolecular Archaeologists

Although the very first fermentations were certainly inadvertent, it is just as certain that human beings eventually learned how to intentionally produce fermented foods. When, where, and how this discovery occurred have been elusive questions, since written records do not exist. However, other forms of archaeological evidence do indeed exist and have made it possible to not only establish the historical and geographical origins of many of these fermentations, but also to describe some of the techniques likely used to produce these products.

For the most part, investigations into the origins of food fermentations have focused on alcoholic fermentations, namely wine and beer, and have been led primarily by a research group at the University of Pennsylvania Museum of Archaeology and Anthropology’s Museum Applied Science Center for Archaeology (http://masca.museum.upenn.edu). These “biomolecular archaeologists” depend not so much on written or other traditional types of physical evidence (which are mostly absent), but rather on the chemical and molecular “records” obtained from artifacts discovered around the world (McGovern et al., 2004).

Specifically, they have extracted residues still present in the ancient clay pottery jars and vessels found in excavated archaeological sites (mainly from the Near East and China). Because these vessels are generally porous, any organic material was adsorbed and trapped within the vessel pores. In a dehydrated state, this material was protected against microbial or chemical decomposition. Carbon dating is used to establish the approximate age of these vessels, and then various analytical procedures (including gas chromatography-mass spectroscopy, Fourier transform infrared spectrometry, and other techniques) are used to identify the chemical constituents.

The analyses have revealed the presence of several marker compounds, in particular, tartaric acid, which is present in high concentrations in grapes (but is generally absent elsewhere), and therefore is ordinarily present in wine, as well (Guash-Jané et al., 2004; McGovern, 2003). Based on these studies (and others on “grape archaeology”), it would appear that wine had been produced in the Near East regions around present-day Turkey, Egypt, and Iran as long ago as the Neolithic Period (8500 to 4000 B.C.E.).

Recent molecular archaeological analyses have revealed additional findings. In 2004, it was reported that another organic marker chemical, syringic acid (which is derived from malvidin, a pigment found in red wines), was present in Egyptian pottery vessels. This was not a real surprise, because the vessels were labeled as wine jars and even indicated the year, source, and vintner. What made this finding especially interesting, however, was that one of the vessels had originally been discovered in the tomb of King Tutankhamun (King Tut, the “boy king”). Thus, not only does it now appear that King Tut preferred red wine, but that when he died (at about age 17), he was, by today’s standards, not even of drinking age.
manufacturing practices employed even today were developed by monks. Eventually, production of these products became more privatized, although often under some form of state control (which allowed for taxation).

From the Neolithic Period to the Middle Ages to the current era, fermented foods have been among the most important foods consumed by humans (Figure 1–1). A good argument can be made that the popularity of fermented foods and the subsequent development of technologies for their production directly contributed to the cultural and social evolution of human history. Consider, after all, how integral fermented foods are to the diets and cuisines of nearly all civilizations or how many fermented foods and beverages are consumed as part of religious customs, rites, and rituals (Box 1–2).

### Box 1–1. Where and When Did Fermentations Get Started? Answers from Biomolecular Archaeologists (Continued)

As noted above, the origins of wine making in the Near East can be reliably traced to about 5400 B.C.E. The McGovern Molecular Archaeology Lab group has also ventured to China in an effort to establish when fermented beverages were first produced and consumed (McGovern et al., 2004). As described in Chapter 12, Asian wines are made using cereal-derived starch rather than grapes. Rice is the main cereal used. Other components, particularly honey and herbs, were apparently added in ancient times.

As had been done previously, the investigators analyzed material extracted from Neolithic (ca. 7000 B.C.E.) pottery vessels. In this case, the specific biomarkers would not necessarily be the same as for wine made from grapes, but rather would be expected to reflect the different starting materials. Indeed, the analyses revealed the presence of rice, honey, and herbal constituents, but also grapes (tartric acid). Although domesticated grape vines were not introduced into China until about 200 B.C.E., wild grapes could have been added to the wine (as a source of yeast). Another explanation is that the tartric acid had been derived from other native fruits and flowers. Additional analyses of “proto-historic” (ca. 1900 to 700 B.C.E.) vessels indicate that these later wines were cereal-based (using rice and millet). Thus, it now appears clear that fermented beverage technology in China began around the same time as in the Near East, and that the very nature of the fermentation evolved over several millennia.

### References


### Fermented Foods: From Art to Science

It is difficult for the twenty-first century reader to imagine that fermented foods, whose manufacture relies on the intricate and often subtle participation of microorganisms, could have been produced without even the slightest notion that living organisms were actually involved. The early manufacturers of fermented foods and beverages obviously could not have appreciated the actual science involved in their production, since it was only in the last 150 to 200 years that microorganisms and enzymes were “discovered.” In fact, up until the middle of the nineteenth century, much of the scientific community still believed in the concept of spontaneous generation. The very act of fermentation was a subject for philosophers...
and alchemists, not biologists. Although the Dutch scientist Antonie van Leeuwenhoek had observed microorganisms in his rather crude microscope in 1675, the connection between Leeuwenhoek’s “animalcules” and their biological or fermentative activities was only slowly realized. It was not until later in the next century that scientists began to address the question of how fermentation occurs.

Initially it was chemists who began to study the scientific basis for fermentation. In the late 1700s and early 1800s, the chemists Lavoisier and Gay-Lussac independently described the overall equations for the alcoholic fermenta-
Improvements in microscopy led Kützing, Schwann, and others to observe the presence of yeast cells in fermenting liquids, including beer and wine. These observations led Schwann to propose in 1837 (as recounted by Barnett, 2003) that “it is very probable that, by means of the development of the fungus, fermentation is started.” The suggestion that yeasts were actually responsible for fermentation was not widely accepted, however; and instead it was argued by his contemporaries (namely Berzelius, Liebig, and Wöhler) that fermentation was caused by aerobic chemical reactions and that yeasts were inert and had nothing to do with fermentative
processes. The debate over the role of microorganisms in fermentation was brought to an unequivocal conclusion by another chemist, Louis Pasteur, who wrote in 1857 that “fermentation, far from being a lifeless phenomenon, is a living process” which “correlates with the development of . . . cells and plants which I have prepared and studied in an isolated and pure state” (Schwartz, 2001). In other words, fermentation could only occur when microorganisms were present. The corollary was also true—that when fermentation was observed, growth of the microorganisms occurred.

In a series of now famous publications, Pasteur described details on lactic and ethanolic fermentations, including those relevant to milk
fermentations, beer, and wine. He also identified the organism that causes the acetic acid (i.e., vinegar) fermentation and that was responsible for wine spoilage. The behavior of yeasts during aerobic and anaerobic growth also led to important discoveries in microbial physiology (e.g., the aptly named Pasteur effect, which accounts for the inhibitory effect of oxygen on glycolytic metabolism). Ultimately, the recognition that fermentation (and spoilage) was caused by microorganisms led Pasteur to begin working on other microbial problems, in particular, infectious diseases. Future studies on fermentations would be left to other scientists who had embraced this new field of microbiology.

Once the scientific basis of fermentation was established, efforts soon began to identify and cultivate microorganisms capable of performing specific fermentations. Breweries such as the Carlsberg Brewery in Copenhagen and the Anheuser-Busch brewery in St. Louis were among the first to begin using pure yeast strains, based on the techniques and recommendations of Pasteur, Lister, and others. By the

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**Box 1–2. Fermented foods and the Bible.**

The importance of fermented foods and beverages to the cultural history of human societies is evident from many references in early written records. Of course, the Bible (Old and New Testaments) and other religious tracts are replete with such references (see below). Fermented foods, however, also serve a major role in ancient Eastern and Western mythologies.

The writers, who had no scientific explanation for the unique sensory and often intoxicating properties of fermented foods, described them as “gifts of the gods.” In Greek mythology, for example, Dionysus was the god of wine (Bacchus, according to Roman mythology). The Iliad and the Odyssey, classic poems written by the Greek poet Homer in about 1150 B.C.E., also contain numerous references to wine, cheese, and bread. Korean and Japanese mythology also refers to the gods that provided miso and other Asian fermented foods (Chapter 12).

### Fermented foods and the Bible

From the Genesis story of Eve and the apple, to the dietary laws described in the books of Exodus and Leviticus, food serves a major metaphoric and thematic role throughout the Old Testament. Fermented foods, in particular, are frequently mentioned in biblical passages, indicating that these foods must have already been well known to those cultures and civilizations that lived during the time at which the bible was written.

In Genesis (9:20), for example, one of the first actions taken by Noah after the flood waters had receded was to plant a vineyard. In the very next line, it is revealed that Noah drank enough wine to become drunk (and naked), leading to the first, but certainly not last, episode in which drunkenness and nakedness occur. Later in Genesis (18:8), Abraham receives three strangers (presumably angels), to whom he offers various refreshments, including “curds.”

Perhaps the most relevant reference to fermentation in the Bible is the Passover story. As described in Exodus (12:39), once Moses had secured the freedom of the Hebrew slaves, they were “thrust out of Egypt, and could not tarry.” Thus, the dough could not rise or become leavened, and was baked instead in its “unleavened” state. This product, called matzoh, is still eaten today by people of the Jewish faith to symbolically commemorate the Hebrew exodus.

Ritual consumption of other fermented foods is also prescribed in Judaism. Every Sabbath, for example, the egg bread, Challah, is to be eaten, and grapes or wine is to be drunk, preceded by appropriate blessings of praise.

Fermented foods are also featured prominently in the New Testament. At the wedding in Cana (John 2:1–11), Jesus’ first miracle is to turn water into wine. Later (John 6:1–14), another miracle is performed when five loaves of bread (and two fish) are able to feed 5,000 men. The Sacrament of Holy Communion (described by Jesus during the Last Supper) is represented by bread and wine.
early 1900s, cultures for butter and other dairy products had also become available. The dairy industry was soon to become the largest user of commercial cultures, and many specialized culture supply “houses” began selling not only cultures, but also enzymes, colors, and other products necessary for the manufacture of cheese and cultured milk products (Chapter 3). Although many cheese factories continued to propagate their own cultures throughout the first half of the century, as factory size and product throughput increased, the use of dairy starter cultures eventually became commonplace. Likewise, cultures for bread, wine, beer, and fermented meats have also become the norm for industries producing those products.

The Modern Fermented Foods Industry

The fermented foods industry, like all other segments of the food processing industry, has changed dramatically in the past fifty years. Certainly, the average size of a typical production facility has increased several-fold, as has the rate at which raw materials are converted to finished product (i.e., throughput). Although small, traditional-style facilities still exist, as is evident by the many microbreweries, small wineries, and artisanal-style bakery and cheese manufacturing operations, the fermented foods industry is dominated by producers with large production capacity.

Not only has the size of the industry changed, but so has the fundamental manner in which fermented foods are produced (Table 1–1). For example, up until the past forty or so years, most cheese manufacturers used raw, manufacturing (or Grade B) milk, whereas pasteurized Grade A milk, meeting higher quality standards, is now more commonly used. Manufacturing tanks or vats are now usually enclosed and are constructed from stainless steel or other materials that facilitate cleaning and even sterilization treatments. In fact, modern facilities are designed from the outset with an emphasis on sanitation requirements, so that exposure to air-borne microorganisms and cross-contamination is minimized.

Many of the unit operations are mechanized and automated, and, other than requiring a few keystrokes from a control panel, the manufacture of fermented foods involves minimal human contact. Fermented food production is now, more than ever before, subject to time and scheduling demands. In the so-called “old days,” if the fermentation was slow or sluggish, it simply meant that the workers (who were probably family members) would be late for supper, and little else. In a modern production operation, a slow fermentation may mean that the workers have to stay beyond their shift (requiring that they be paid overtime), and in many cases, it could also affect the entire production schedule, since the production vat could not be turned over and refilled as quickly as needed. Although traditional manufacturing practices may not have always yielded consistent products, lot sizes were small and economic losses due to an occasional misstep were not likely to be too se-

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<th>Traditional</th>
<th>Modern</th>
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<td>Small scale (craft industry)</td>
<td>Large scale (in factories)</td>
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<td>Non-sterile medium</td>
<td>Pasteurized or heat-treated medium</td>
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<td>Septic</td>
<td>Aseptic</td>
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<td>Open</td>
<td>Contained</td>
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<td>Manual</td>
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<td>Insensitive to time</td>
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<td>Minimal exposure to contaminants</td>
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<td>Varying quality</td>
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<td>Safety a minor concern</td>
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rious. Besides, for every inferior cask of wine or wheel of cheese, there may have been an equally superior lot that compensated for the one that turned out badly. Even the absolute worst case scenario—a food poisoning outbreak as a result of an improperly manufactured product—would have been limited in scope due to the small production volume and narrow distribution range.

Such an attitude, today, however, is simply beyond consideration. A day’s worth of product may well be worth tens, if not hundreds of thousands of dollars, and there is no way a producer could tolerate such losses, even on a sporadic basis. Food safety, in particular, has become an international priority, and there is generally zero tolerance for pathogens or other hazards in fermented foods. Quality assurance programs now exist throughout the industry, which strive to produce safe and consistent products. In essence, the fermented foods industry has evolved from a mostly art- or craft-based practice to one that relies on modern science and technology. Obviously, the issues discussed above—safety, sanitation, quality, and consistency—apply to all processed foods, and not just fermented foods. However, the fermented foods industry is unique in one major respect—it is the only food processing industry in which product success depends on the growth and activity of microorganisms. The implications of this are highly significant.

Microorganisms used to initiate fermentations are, unlike other “ingredients,” not easily standardized, since their biochemical activity and even their concentration (number of cells per unit volume) may fluctuate from lot to lot. Although custom-made starter cultures that are indeed standardized for cell number and activity are readily available, many industrial fermentations still rely, by necessity, on the presence of naturally-occurring microflora, whose composition and biological activities are often subject to considerable variation. In addition, microorganisms are often exposed to a variety of inhibitory chemical and biological agents in the food or environment that can compromise their viability and activity. Finally, the culture organisms are often the main means by which spoilage and pathogenic microorganisms are controlled in fermented foods. If they fail to perform in an effective and timely manner, the finished product will then be subject to spoilage or worse. Thus, the challenge confronting the fermented foods industry is to manufacture products whose very production is subject to inherent variability yet satisfy the modern era demands of consistency, quality, line-speed, and safety.

Properties of Fermented Foods

As noted in the previous discussion, fermented foods were among the first “processed” foods produced and consumed by humans. Their popularity more than 5,000 years ago was due to many of the same reasons why they continue to be popular today (Table 1–2).

**Preservation**

The preservation aspect of fermented foods was obviously important thousands of years ago, when few other preservation techniques existed. A raw food material such as milk or meat had to be eaten immediately or it would soon spoil. Although salting or smoking could be used for some products, fermentation must have been an attractive alternative, due to other desirable features. Preservation was undoubtedly one of the main reasons why fermented foods became such an integral part of human diet. However, even today, preservation, or to use modern parlance, shelf-life (or extended shelf-life), is still an important feature of fermented foods. For example, specialized cultures that contain organisms that produce

<table>
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<th>Table 1.2. Properties of fermented foods</th>
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<tr>
<td>Enhanced preservation</td>
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<td>Enhanced nutritional value</td>
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<td>Enhanced functionality</td>
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<td>Enhanced organoleptic properties</td>
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<td>Uniqueness</td>
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<td>Increased economic value</td>
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specific antimicrobial agents in the food are now available, providing an extra margin of safety and longer shelf-life in those foods.

Nutrition

The nutritional value of fermented foods has long been recognized, even though the scientific bases for many of the nutritional claims have only recently been studied. Strong evidence that fermentation enhances nutritional value now exists for several fermented products, especially yogurt and wine. Fluid milk is not regularly consumed in most of the world because most people are unable to produce the enzyme β-galactosidase, which is necessary for digestion of lactose, the sugar found naturally in milk. Individuals deficient in β-galactosidase production are said to be lactose intolerant, and when they consume milk, mild-to-severe intestinal distress may occur. This condition is most common among Asian and African populations, although many adult Caucasians may also be lactose intolerant.

Many studies have revealed, however, that lactose-intolerant subjects can consume yogurt without any untoward symptoms and can therefore obtain the nutritional benefits (e.g., calcium, high quality protein, and B vitamins) contained in milk. In addition, it has been suggested that there may be health benefits of yogurt consumption that extend beyond these macronutrients. Specifically, the microorganisms that perform the actual yogurt fermentation, or that are added as dietary adjuncts, are now thought to contribute to gastrointestinal health, and perhaps even broader overall well-being (Chapter 4).

Similarly, there is now compelling evidence that wine also contains components that contribute to enhanced health (Chapter 10). Specific chemicals, including several different types of phenolic compounds, have been identified and shown to have anti-oxidant activities that may reduce the risk of heart disease and cancer. That wine (and other fermented foods) are widely consumed in Mediterranean countries where mortality rates are low has led to the suggestion that a “Mediterranean diet” may be good for human health.

Functionality

Most fermented foods are quite different, in terms of their functionality, from the raw, starting materials. Cheese, for example, is obviously functionally different from milk. However, functional enhancement is perhaps nowhere more evident than in bread and beer. When humans first collected wheat flour some 10,000 years ago, there was little they could do with it, other than to make simple flat breads. However, once people learned how to achieve a leavened dough via fermentation, the functionality of wheat flour became limitless. Likewise, barley was another grain that was widespread and had use in breadmaking, but which also had limited functionality prior to the advent of fermentation. Given that barley is the main ingredient (other than water) in beer manufacture, could there be a better example of enhanced functionality due to fermentation?

Organoleptic

Simply stated, fermented foods taste dramatically different from the starting materials. Individuals that do not particularly care for Limburger cheese or fermented fish sauce might argue that those differences are for the worse, but there is little argument that fermented foods have aroma, flavor, and appearance attributes that are quite unlike the raw materials from which they were made. And for those individuals who partake of and appreciate Limburger cheese, the sensory characteristics between the cheese and the milk make all the difference in the world.

Uniqueness

With few exceptions (see below), there is no way to make fermented foods without fermentation. Beer, wine, aged cheese, salami, and sauerkraut simply cannot be produced any other way. For many fermented products, the
very procedures used for their manufacture are unique and require strict adherence. For example, Parmesan cheese must be made in a defined region of Italy, according to traditional and established procedures, and then aged under specified conditions. Any deviation results in forfeiture of the name Parmesan. For those “fermented” foods made without fermentation (which includes certain fresh cheeses, sausages, and even soy sauce), their manufacture generally involves direct addition of acids and/or enzymes to simulate the activities normally performed by fermentative microorganisms. These products (which the purist might be inclined to dismiss from further discussion) lack the flavor and overall organoleptic properties of their traditional fermented counterparts.

**Economic value**

Fermented foods were the original members of the value-added category. Milk is milk, but add some culture and manipulate the mixture just right, age it for a time, and the result may be a fine cheese that fetches a price well above the combined costs of the raw materials, labor, and other expenses. Grapes are grapes, but if grown, harvested, and crushed in a particular environment and at under precise conditions, and the juice is allowed to ferment and mature in an optimized manner, some professor may well pay up to $6 or $7 (or more!) for a bottle of the finished product. Truly, the economic value of fermented foods, especially fermented grapes, can reach extraordinary heights (apart from the professor market). As noted in Chapter 10, some wines have been sold for more than $20,000 per bottle. Even some specialty vinegars (Chapter 11) sell for more than $1,000 per liter. It should be noted that not all fermented foods command such a high dollar value. In truth, the fermented foods market is just as competitive and manufacturers are under the same market pressures as other segments of the food industry. Fermented foods are generally made from inexpensive commodities (e.g., wheat, milk, meat, etc.) and most products have very modest profit margins (some products, such as “current” or un-aged cheese, are sold on commodity markets, with very tight margins). There is a well-known joke about the wine business that applies to other products as well, and that summarizes the challenge in making fermented foods: “How do you make a million dollars in the wine business? Easy, first you start with two million dollars.” Finally, on an industry-wide basis, fermented foods may have a significant economic impact on a region, state or country. In California, for example, the wine industry was reported to contribute more than $40 billion to the economy in 2004 (according to a Wine Institute report; www.wineinstitute.org). A similar analysis of the U.S. beer industry (www.beerinstitute.org) reported an overall annual impact of more than $140 billion to the U.S. economy.

**Fermented Foods in the Twenty-first Century**

For 10,000 years, humans have consumed fermented foods. As noted above, originally and throughout human history, fermentation provided a means for producing safe and well-preserved foods. Even today, fermented foods are still among the most popular type of food consumed. No wonder that about one-third of all foods consumed are fermented. In the United States, beer is the most widely consumed fermented food product, followed by bread, cheese, wine, and yogurt (Table 1–3). Global statistics are not available, but it can be estimated that alcoholic products head the list of most popular fermented foods in most of the world. In Asia, soy sauce production and consumption ranks at or near the top. Collectively, sales of fermented foods on a global basis exceed a trillion dollars, with an even greater overall economic impact.

Although fermented foods have been part of the human diet for thousands of years, as the world becomes more multicultural and cuisines and cultures continue to mix, it is likely that fermented foods will assume an even more important dietary and nutritional role. Foods such as kimchi (from Korea), miso (from Japan), and kefir (from Eastern Europe) are fast becoming part
of the Western cuisine. Certainly, the desirable flavor and sensory attributes of traditional, as well as new-generation fermented foods, will drive much of the interest in these foods.

Consumption of these products also will likely be increased as the potential beneficial effects of fermented foods on human health become better established, scientifically and clinically. As noted above, compelling evidence now exists to indicate that red wine may reduce the risk of heart disease and that live bacteria present in cultured milk products may positively influence gastrointestinal health. Armed now with extensive genetic information on the microorganisms involved in food fermentations that has only become available in the last century, it is now possible for researchers to custom-produce fermented foods with not only specific flavor and other functional characteristics, but that also impart nutritional properties that benefit consumers.

### References


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<th>Production</th>
<th>Consumption</th>
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<tr>
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<td>Fermented vegetables</td>
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*aSources: 2001–2004 data from USDA, WHO, and industry organizations  
*bPer person, per year  
*cNot available
Microorganisms and Metabolism

“We can readily see that fermentations occupy a special place in the series of chemical and physical phenomena. What gives to fermentations certain exceptional characters, of which we are only now beginning to suspect the causes, is the mode of life in the minute plants designated under the generic name of ferments, a mode of life which is essentially different from that of other vegetables, and from which result phenomena equally exceptional throughout the whole range of the chemistry of living beings.”

From The Physiological Theory of Fermentation by Louis Pasteur, 1879

When one considers the wide variety of fermented food products consumed around the world, it is not surprising that their manufacture requires a diverse array of microorganisms. Although lactic acid-producing bacteria and ethanol-producing yeasts are certainly the most frequently used organisms in fermented foods, there are many other bacteria, yeast, and fungi that contribute essential flavor, texture, appearance, and other functional properties to the finished foods. In most cases, more than one organism or group of organisms is involved in the fermentation.

For example, in the manufacture of Swiss-type cheeses, thermophilic lactic acid bacteria from two different genera are required to ferment lactose, produce lactic acid, and acidify the cheese to pH 5.2, a task that takes about eighteen hours. Weeks later, another organism, Propionibacterium freudenreichii subsp. shermani, begins to grow in the cheese, producing other organic acids, along with the carbon dioxide that eventually forms the holes or eyes that are characteristic of Swiss cheese.

Even for those fermented foods in which only a single organism is responsible for performing the fermentation, other organisms may still play inadvertent but important supporting roles. Thus, tempeh, a fermented food product popular in Indonesia, is made by inoculating soybeans with the fungal organism Rhizopus oligosporus. The manufacturing process lends itself, however, to chance contamination with other microorganisms, including bacteria that synthesize Vitamin B₁₂, making tempeh a good source of a nutrient that might otherwise be absent in the diet of individuals who consume this product.

A Primer on Microbial Classification

For many readers, keeping track of the many genus, species, and subspecies names assigned to the organisms used in fermented foods can be a challenging task. However, knowing which organisms are used in specific fermented foods is rather essential (to put it mildly) to understanding the metabolic basis for how microbial fermentations occur. Therefore, prior to describing the different groups of microorganisms involved in food fermentations, it is first necessary to review the very nature of microbial taxonomy (also referred to as systematics) and how microbiologists go about classifying, naming, and identifying microorganisms.

Although this might seem to be a thankless task, it is, after all, part of human nature to sort or order things; hence, the goal of taxonomy is
to achieve some sense of order among the microbial world. Specifically, taxonomy provides a logical basis for: (1) classifying or arranging organisms into related groups or taxa; (2) establishing rules of nomenclature so that those organisms can be assigned names on a rational basis; (3) identifying organisms based on the accepted classification scheme and nomenclature rules; and (4) understanding evolutionary relationships of species, one to another.

As will be noted later in this and successive chapters, rules for classification are not permanently fixed, but rather can be amended and re-defined in response to new, more discriminating methods. For the most part, these new classification methods are based on molecular composition and genetic properties, which can also be used to determine phylogenetic or evolutionary relationships between related organisms.

The three domains of life

According to modern taxonomy, life on this planet can be grouped into three branches or domains—the Eukarya, the Bacteria, and the Archaea (Figure 2–1). This organization for classifying all living organisms was proposed and established in the 1980s by Carl Woese and is based on the relatedness of specific 16S rRNA sequences using a technique called oligonucleotide cataloging. This three-branch tree of life displaced the classical taxonomy that had recognized only two groups, eukaryotes and prokaryotes, and that was based primarily on morphology and biochemical attributes. All of the microorganisms relevant to fermented foods (and food microbiology, in general) belong to either the Eukarya or Bacteria. The Archaea, while interesting for a number of reasons, consists of organisms that generally live and grow in