One of the greatest challenges food research is facing in the 21st century lies in developing and maintaining sustainable food production while at the same time delivering high-quality food products with added functionality to help prevent lifestyle-related diseases, such as certain cancers, obesity, type 2 diabetes, heart disease, and stroke. Modern food processing encompasses a wide range of preservation technologies that ensure foods are maintained at an acceptable level of quality from their manufacture to consumption. One of the oldest of these technologies is fermentation, a process in which the biological activity of microorganisms produces a range of metabolites that can suppress the growth and survival of undesirable microflora in foodstuffs (1, 39). Fermentation may also be used to enhance the flavor, aroma, shelf-life, texture, nutritional value, and other food properties. The benefits of fermentation in different types of food products are presented in Table I.

Fermentation is a low-cost, economical technique for production and preservation of foods (16), and, as a result, fermented foods are an important part of the diet in many parts of the world. Utilized since ancient times, a wide variety of fermentation methods have been developed and are used around the world. Holzapfel (21) describes the use of starter cultures in traditional small-scale fermentation applications in developing countries with the goal of producing palatable food products from raw or heated raw materials.

In the 19th century the scientific study of microbiology began, and for the first time, the scientific process of fermentation was understood (9). Following the development of microbiology as a science, many new technologies have been developed for the large-scale industrial production of fermented milk, meat, fruit, vegetable, and cereal products (20,35). Several classifications have been used to categorize the diverse array of fermented foods produced based on the different microorganisms, food groups, and types of fermentation involved (7).

In the case of plant-based products the process of fermentation can be used to reduce the content of nondigestible materials, including cellulose, hemicellulose, and polygalacturonic and glucuronic acids. Breakdown of nondigestible compounds can lead to improved bioavailability of certain mineral and trace elements. In addition, during fermentation essential nutrients may be synthesized, such as vitamins, amino acids, and proteins.

The aim of this article is to summarize the production process and nutritional benefits of fermented products made from rice, pulses, barley, and oats.

Role of Fermentation in Food Processing

Fermentation plays several important roles in food processing. The human diet can be enriched through the development of flavors, aromas, and textures in fermented foods and preservation of foods through the use of lactic acid-, alcohol-, acetic acid-, and alkali-based fermentation processes. Food substrates also can be enriched with proteins, essential amino acids, essential fatty acids, and vitamins through the biological activity of the microorganisms used in fermentation. The enzymatic activity of microbial cultures during fermentation also may predigest macronutrients (23). Additionally fermentation may detoxify foods and reduce cooking times and fuel requirements.

Although fermented foods are produced worldwide using a wide variety of manufacturing techniques, raw materials, and microorganisms, there are only four main fermentation processes commonly used: alcohol-, lactic acid-, acetic acid-, and alkali-based fermentation (45). Alcohol fermentation results in the production of ethanol, and yeasts are the predominant microorganisms used (e.g., to produce wines and beers). Lactic acid fermentation (e.g., fermented milk and cereal products)
involves the use of lactic acid bacteria (LAB). Different LAB genera used in cereal fermentation and their shapes are provided in Table II (4). A second important group of bacteria utilized in food fermentation is Acetobacter species. These bacteria produce acetic acid by converting alcohol to acetic acid in the presence of excess oxygen. Alkali fermentation is often used with fish and seeds, the products of which are consumed as condiments (32).

Importance of Cereal Foods Globally
Cereals are grown on more than 73% of the total harvested area worldwide and make up more than 60% of the food produced globally, providing a major source of the dietary fiber, proteins, energy, minerals, and vitamins required for human health (11). The benefits of cereals to human health have been the subject of extensive research and epidemiological studies, and whole grain intake has been linked to the prevention of metabolic syndrome, obesity, and associated chronic diseases such as cardiovascular disease and type 2 diabetes.

As part of a general trend, the cereal-processing industry has been challenged in recent years to produce new ingredients and foods with added health benefits. Poutanen et al. (36) report that new bioactive metabolites in cereals can be produced during fermentation from the starter components present in raw materials. In addition, modification of the cereal matrix during fermentation can be tailored to increase the bioaccessibility of bioactive compounds. Nout (34) describes how the nutritional properties of traditional fermented cereal products can be enhanced by increasing their nutrient and energy densities and mineral status through a combination of mineral fortification and dephytinization. In addition, fermentation may be used to improve the flavor and aroma of cereal-based foods (8). Formation of several volatile compounds during cereal fermentation contributes a complex blend of flavors to food products. Aromas produced by diacetyl, acetic acid, and butyric acid also may increase the appeal of fermented cereal-based products. The following is a list of compounds formed during fermentation of cereals (8):

- **Organic Acids:** Acetic, Benzoic, Butyric, Caproic, Caprylic, Formic, Isobutyric, Lactic, Lauric, Myristic, Palmitic, Pelargonic, Propionic, Pyruvic, Succinic, Valeric
- **Alcohols:** Amyl alcohol, Ethanol, Isoamyl alcohol, Isobutanol, n-Propanol
- **Aldehydes and Ketones:** Acetaldehyde, Acetoin, Acetone, Butanone, Diacetyl, Formaldehyde, n-Hexaldehyde, Methyl ethyl ketone
- **Carbonyl Compounds:** Furfural, Glyoxal, Hydroxymethylfurfural, Methional, 3-Methyl butanol

**Table I. Benefits of fermentation in different types of food products**

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Stability</th>
<th>Safety</th>
<th>Nutritive Value</th>
<th>Acceptability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat</td>
<td>++</td>
<td>+</td>
<td>–</td>
<td>(+)</td>
</tr>
<tr>
<td>Fish</td>
<td>++</td>
<td>+</td>
<td>–</td>
<td>(+)</td>
</tr>
<tr>
<td>Milk</td>
<td>++</td>
<td>+</td>
<td>(+)</td>
<td>(+)</td>
</tr>
<tr>
<td>Vegetables</td>
<td>+</td>
<td>(+)</td>
<td>–</td>
<td>(+)</td>
</tr>
<tr>
<td>Fruits</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Legumes</td>
<td>–</td>
<td>(+)</td>
<td>(+)</td>
<td>+</td>
</tr>
<tr>
<td>Cereals</td>
<td>++</td>
<td>–</td>
<td>(+)</td>
<td>+</td>
</tr>
</tbody>
</table>

* Data source: Holzapfel (21). ++ = definite improvement; + = usually some improvement; (+) = occasionally some improvement; – = no improvement.

**Fermented Foods from Rice and Pulses**

Rice and pulses are the main ingredients in many fermented foods consumed in Asia and India (Table III). Rice proteins are hypoallergenic, and rice contains high levels of lysine, making it suitable for use in infant food formulations and the diets of children with food allergies (13). Pulses constitute an important source of dietary proteins for large segments of the world’s population, particularly in countries in which consumption of animal proteins is limited by nonavailability or religious and cultural habits (27). Pulses also provide energy, dietary fiber, minerals, and vitamins. Recent research studies suggest that consumption of pulses may have potential health benefits, including reduced risk of cardiovascular disease, certain cancers, type 2 diabetes, osteoporosis, hypertension, gastrointestinal disorders, and adrenal disease and reduction of LDL cholesterol (22).

**Dhokla.** Dhokla is a lactic acid fermented cake originating in Gujarat, India (24). It is prepared with Bengal gram and rice or with a mixture of rice and chickpea flour used as the substrate for the fermentation. Dhokla is prepared from a batter of coarsely ground rice (Oryza sativa L.) and Bengal gram dhal (Cicer arietinum L.), fermented at low temperature, steamed in a pie dish, cut, and seasoned (4). As with other indigenous fermented foods, significant improvement in the nutritional value and net protein utilization due to fermentation has been reported for dhokla (30,41). During fermentation microorganisms such as Lactobacillus fermentum, Leuconostoc mesenteroides, Pichia silvica, Streptococcus faecalis, Torulopsis sp., Candida sp., and T. pullulans (2) produce vitamins at a higher rate. The thiamine and riboflavin content is increased by ≈50% by fermentation. There also is an almost twofold increase in batter volume and a drop in pH from 5.2 to 4.5. Yeast produces folic acid and increases the volume of the batter, imparting sponginess to the product (44). In contrast, the bioaccessibility of zinc decreases by 23% upon heat processing of the fermented batter (19).

**Idli.** Idli is a low-calorie, starchy cereal- and pulse-based fermented food that is particularly popular in southern India. The acidity of the batter protects against pathogenic organisms. Globally idli is formulated using a variety of cereal grain and pulse combinations. In India idli traditionally is prepared with rice and black gram (Phaseolus mungo L.) that have been soaked separately. After draining the water, the rice and black gram are ground independently, with occasional addition of water during the process. The rice is coarsely ground, and the black gram is finely ground. The resulting rice and black gram batters are mixed together (2:1 ratio), with the addition of a little salt, and allowed to ferment overnight at room temperature (≈30°C). The fermented batter is placed in special idli pans and steamed for 5–8 min (14). Steamed idli contains approximately 3.4% protein, 20.3% carbohydrate, and 70% moisture (33,47).

**Table II. Lactic acid bacteria genera and their cell structures**

<table>
<thead>
<tr>
<th>Lactic Acid Bacterium</th>
<th>Cell Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactobacillus</td>
<td>Rods</td>
</tr>
<tr>
<td>Streptococcus</td>
<td>Spheres in chains (cocci)</td>
</tr>
<tr>
<td>Pediococcus</td>
<td>Spheres in tetrads (cocci)</td>
</tr>
<tr>
<td>Lactococcus</td>
<td>Cocci</td>
</tr>
<tr>
<td>Leuconostoc</td>
<td>Spheres in chains (cocci)</td>
</tr>
<tr>
<td>Bjfifdobacterium</td>
<td>Branched rods</td>
</tr>
<tr>
<td>Enterococcus</td>
<td>Cocci</td>
</tr>
</tbody>
</table>

* Data source: Blandino et al. (4).
Today, several food producers are producing idli on a large industrial scale and selling ready mixes. The LAB Streptococcus faecalis, Leuconostoc mesenteroides, Lactobacillus delbrueckii, L. fermenti, L. lactis, and Pediococcus cerevisiae are responsible for the fermentation process. The microbiological, physical, and biochemical changes in idli batter during fermentation, as well as its nutritive values, have been investigated (2,37,47). Fermentation processes appear to have a significant effect on elimination and/or reduction of antinutrients (phytic acid and enzyme inhibitors), as well as flatulence-causing components. A reduction in phytic acid of 35.0–40.0% was reported during idli preparation. Fermentation and steaming also resulted in an appreciable reduction (33.8%) in oligosaccharides (verbascose, stachyose, and raffinose) (46).

**Dosa.** Dosa is a fermented food product with origins in southern India. It is prepared with rice and black gram and commonly consumed as part of the breakfast meal or as a snack. Dosa batter is very similar to idli batter, except that the rice and black gram are finely ground and, instead of being steamed, the fermented suspension is fried with a little oil on a flat plate. Dosa batter is prepared by grinding wet rice and black gram separately with water. The two suspensions are then mixed and allowed to undergo natural fermentation, usually for 8–20 hr. The fermented batter is spread in a thin layer (1–5 mm thick) on a flat, heated plate that is smeared with a little oil or fat. A transformation from solid to gel occurs during heating, and within a few minutes, a circular, semisoft to crisp product resembling a pancake is obtained and ready for consumption (3). Leuconostoc mesenteroides, Streptococcus faecalis, Torulopsis candida, and Trichosporon pullulans are involved in the dosa fermentation process.

**Puto.** Puto is a rice-based fermented food product originating in the Philippines. In India it is known as puttu (rice cake). Although a wide variety of rice cake products exist in many cultures around the world, they are particularly prevalent in Asia and countries throughout the Pacific Region where rice is a staple food and the basis of many meals and foods. Puto batter is fermented overnight. The fermented batter is steamed, creating rice cakes that are usually 2–3 in. in diameter. Rice cakes have several nutritional benefits and are low in calories, making them especially popular with consumers who are looking for ways to cut calories from their diet (12).

**Chakuli.** Chakuli is a cereal- and pulse-based fermented food originating in Orissa, India. The most common main ingredients are parboiled rice and black gram. Jackfruit (Artocarpus heterophyllus Lam.) or palmrya palm fruit (Borassus flabellifer L.) juice may be substituted for black gram during the summer. To prepare chakuli, rice is washed, soaked, dewatered, and briefly dried in the sun. Dried rice grains are ground in an iron or wooden mortar and sieved to obtain a fine powder. Black gram is soaked until the seed coat can be removed easily by applying gentle pressure. The seed coat is removed by washing, and the black gram is ground into a smooth paste using a grinder. The paste is beaten repeatedly by hand with a small amount of water and mixed with rice powder, lukewarm water, and salt. The batter is covered and left to ferment for 4–5 hr during the summer or 12–15 hr during the winter (40).

**Siddhu.** Siddhu is a fermented cereal- and pulse-based food that is eaten primarily in Himachal Pradesh, India, for special occasions. Wheat flour is mixed with water and the powdered form of the starter material, malera (yeast), as inoculum and then fermented for 4–5 hr in a warm place. The fermented dough is shaped into an oval and stuffed with spices mixed with a paste of opium seeds, walnut, and/or black gram and steam cooked (48).

**Enduri and Munha Pithas.** Enduri and munha pithas are fermented cereal- and pulse-based foods eaten primarily in Orissa and are popular dishes for festive celebrations. Parboiled rice powder and black gram are the main ingredients in these pithas. The method of cooking enduri pitha is similar to that for chakuli. The fermented batter is placed in a turmeric (Curcuma longa L.) leaf. The leaf is folded along the midvein and stuffed with coconut, chhana (fresh curd cheese), and sugar fillings. The batter-filled folded leaves are then cooked over steam. Munha pitha is

| Table III. Examples of fermented food products and their place of origin, main ingredients, and associated microorganisms |
|---|---|---|---|
| Food | Place of Origin | Main Ingredients | Microorganisms |
| Dhokla | Gujrat, India | Bengal gram or rice and chickpea flour | Lactobacillus fermentum, Leuconostoc mesenteroides, Pichia sibirosa, Streptococcus faecalis, Torulopsis sp., Candida sp., and Trichosporon pullulans |
| Idli | Southern India | Rice and black gram | Streptococcus faecalis, Leuconostoc mesenteroides, Lactobacillus delbrueckii, L. fermenti, L. lactis, and Pediococcus cerevisiae |
| Dosa | Southern India | Rice and black gram | Leuconostoc mesenteroides, Streptococcus faecalis, Torulopsis candida, and Trichosporon pullulans |
| Puto | Asia, predominantly the Philippines | Rice | – |
| Chakuli | Orissa, India | Parboiled rice and black gram | Malera (starter yeast) |
| Siddhu | Himachal Pradesh, India | Wheat and pulses | – |
| Enduri and munha pithas | Orissa, India | Parboiled rice powder and black gram | – |
| Ang kak | China | Rice | Monascus purpureus |
| Brem | Central and East Java, Indonesia | Rice | Mucor indicus and Candida sp. |
| Arem | Bali, Indonesia | Rice | Saccharomyces sp. and Leuconostoc mesenteroides |
| Khnomjaa | Thailand | Rice flour | Lactobacillus sp. and Streptococcus sp. |
| Tapuy | Philippines | Rice | Leuconostoc sp. and Lactobacillus plantarum |
| Bibingka | Philippines | Rice and sugar | Leuconostoc mesenteroides, Enterococcus faecalis, and Pediococcus cerevisiae (in mixed fermentation with Saccharomyces cerevisiae) |
| Pinni | Himachal Pradesh, India | Barley flour | – |
| Buo chang | Himachal Pradesh, India | Barley | – |
| Yoa | Scandinavia, predominantly Finland | Oats | Lactic acid bacteria and bifidobacteria |
prepared from parboiled rice powder and black gram paste mixed in a 3:1 ratio. Sugar or jaggery, minced coconut, raisins, and cashew nuts may be added to the fermented batter to create a delicacy (40).

**Ang-kak and Chao.** Ang-kak is made in China by fermenting rice with certain strains of *Monascus purpureus* in solid-state fermentation. Because of its red color, ang-kak is used as a food coloring agent for cooked dishes, as well as for manufacturing fermented foods such as fish sauce, fish paste, soja, and red wine (50). Chao is a fermented rice paste made in Cambodia (50).

**Brem.** Brem is a solid yellow-white fermented rice product with a sweet/sour flavor that is consumed in Central and East Java, Indonesia. Microorganisms such as *Mucor indicus* and *Candida* sp. are used in the fermentation process. The fermented mixture is pressed, and the liquid is evaporated until it attains the consistency of syrup. The syrup is placed in small cones and after cooling solidifies, producing a solid candy (38).

**Apem, Khanomjeen, and Joongpyun.** Apem, khanomjeen, and joongpyun are fermented rice-based bread and cake products. Apem is a steamed rice bread originating in Indonesia and especially popular in Bali. It is made from white rice flour that is fermented overnight and steamed in cups. The main microorganisms used in the fermentation are *Saccharomyces* sp. and *Leuconostoc mesenteroides* (50). Khanomjeen is a fermented spongy rice cake consumed in Thailand and made from glutinous rice flour. It is a sweet cake that is eaten as a dessert. Microorganisms such as *Lactobacillus* sp. and *Streptococcus* sp. are used in the fermentation process (38). Joongpyun is a fermented rice cake popular in Korea that is prepared by steaming fermented dough made from glutinous rice flour and rice wine (50).

**Fermented Foods from Barley**

In many countries, barley (*Hordeum vulgare* L.) is a staple ingredient in human foods and animal feeds (10). Barley contains antioxidants such as tocopherols, lignans, flavonoids, and phenolic acids; higher concentrations are found in the outer layers of the kernel, which constitute the bran. Barley also contains higher amounts (up to 6 g/100 g of flour) of β-glucan, which has been widely reported to lower blood cholesterol levels (26). Mårtensson et al. (31) have reported on the development of a new fermented nondairy, oat-based product, Yosa (Table III).

**Yosa.** Yosa is a new snack food developed for commercial application (43) that is made from oat bran pudding cooked in water and fermented with LAB and bifidobacteria. The fermented batter is flavored with sucrose or fructose and fruit jam (42). Yosa is mainly consumed in Finland and other Scandinavian countries. It has a texture and flavor similar to yogurt, but it contains no milk or other animal products. Four experimental variants of Yosa were created during product development prior to launching the product in the Finnish market. It is a beneficial addition to the diet because it contains oat fiber and probiotic LAB, which can maintain and improve the environment in the intestines (49). Its sweet flavor is expected to enhance product acceptance in general, especially among younger consumers (15).

**Conclusions**

A diverse array of fermented foods are prepared around the world using a wide variety of locally grown cereals and pulses, as well as flavor-enhancing ingredients. Fermentation can not only make a food more palatable, it can impart added nutritional value by, for example, enriching protein quality and carbohydrate content. Today fermented cereal foods are very popular due in part to their improved antioxidant contents, ability to protect against disease, and anticarcinogenic effects.

Fermented foods are important in the human diet and possess a natural and healthy image that is appealing to health-conscious consumers. Fermentation is also being explored in the development of new foods with beneficial health properties—a trend that is likely to continue in the future. However, there is a need for further research on the technical, microbial, and biochemical characteristics of fermented food products.

**Acknowledgments**

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