



Fermented foods are produced by using microbes and their enzymes to transform components of the food to new substances, thus giving fermented foods their characteristic taste, smell, and mouthfeel. In North America and Europe, fermented foods are mainly associated with fermented dairy products, pickles and sauerkraut, and fermented meats. The diversity of fermented foods worldwide is, however, much greater. For example, all alcoholic beverages are fermented, as are the breakfast staples coffee and bread: for coffee production, microbes help to separate the coffee beans from the pulp and to improve flavor; most bread is made with baker's yeast, or with yeast in combination with lactic acid bacteria. Even dessert favourites chocolate and vanilla ice cream are fermented or made with fermented ingredients.

The Periodic Table of Fermented Foods aims to provide an overview of the global diversity of fermented foods. The products are sorted in groups depending on the fermentation substrate. Just about any agricultural crop produced on the globe is also consumed as a fermented food. The table is incomplete - fermented foods are as diverse as human cultures and societies. For example, most European and Asian cultures in temperate climates with cold winters ferment vegetables to preserve the vegetable harvest in fall as a source of nutrients, including vitamins, over winter. The best known product is sauerkraut, but an innumerable variety of products with a comparable fermentation process but different recipes and names is produced globally. To provide a second example, most fermented foods are produced in households – this means that each family has its own special recipe, fermentation process and product. In industrialized countries, food fermentations have been industrialized but many large-scale fermentations still rely on traditional knowledge systems for fermentation control. In the last years and particularly during COVID-19 pandemic, the interest in fermenting foods at home has increased and many households produced their own sourdough bread, sauerkraut, or fermented vegetable juices, to name just a few.

Why are foods fermented?

To answer this question, it is best to start with an overview how microbes convert food components.

1. First, most food components, such as proteins, starch and non-starch polysaccharides, are polymers: strings of monomers of amino acids and sugars, respectively. While most monomers can be imported – taken up – into cells, where they can be metabolized, most polymers are too large to enter most cells. Therefore, polymers must be broken down into monomers outside of the cell by means of extracellular enzymes that are transported out of the cell and onto the polymer. The two groups of organisms that are best suited to produce extracellular enzymes are mycelial molds and bacilli. The release of amino acids from the proteins and sugars from the polysaccharides provides nutrients for other microbes, particularly yeasts and lactic acid bacteria, but also enhances the taste of the product. For example, fungi in combination with yeasts and lactic acid bacteria are used to convert bland-tasting wheat and soy beans to soy sauce, which is very rich in amino acids and organic acids with umami and sour taste. Gochujang (element 81) combines fermented rice with hot pepper, thus combining the spiciness of pepper with umami taste. Kharoli (element 13) is a fermented mustard seed product that combines the spiciness of mustard with umami taste.

2. Second, simple sugars are converted to ethanol by yeast, or to lactic acid and other organic acids by lactic acid bacteria. These two groups of organisms occur in most fermented foods (see Periodic Table). During vinegar production, acetic acid bacteria convert ethanol to acetic acid.

3. Third, bioactive plant components are converted to metabolites with higher or lower biological activity or toxicity. To provide two examples: Cassava contains cyanogenic glucosides, which release cyanide if the molecule is hydrolysed after ingestion. As a consequence, Cassava tubers are toxic to humans unless the cyanogenic glucosides are removed by a processing step such as fermentation (group 5). Vanillin, the most important flavor compound in vanilla, is produced by vanilla beans as a glucoside that is not volatile and has no flavor. Curing of vanilla beans recruits bacilli, which hydrolyse the glucoside and thus release the flavor compound

(element 93). Last but not least, many microbes produce flavor volatiles that contribute to the smell of the final products.

4. Fourth, microorganisms produce flavor volatiles during growth. The smell and the taste of fermented products is therefore often very different from the raw material.

Major biochemical conversions during food fermentations:

1. Conversion of starch and proteins to sugars and amino acids (mycelial molds and bacilli)
2. Conversion of sugars to ethanol (yeast) or lactic and acetic acids (lactic acid bacteria) or ethanol to acetic acid (acetic acid bacteria)
3. Conversion of bioactive or toxic plant components to metabolites with higher biological activity, or lower toxicity.
4. Formation of flavor volatiles

What is the motivation for fermentation, then? If we cover the periodic table from left to right, we obtain four main reasons for fermenting food:

1. Humans fermented cereals or fruits to produce intoxicating alcoholic beverages. The production of alcoholic beverages from cereals dates back to the time when humans shifted from hunter-gatherer societies to sessile agricultural societies about 14,000 years ago.

2. Humans fermented foods to remove anti-nutritive or even toxic compounds in plant foods. One of the most important examples, presented above, is the presence of toxic cyanogenic glycosides in cassava. Cereals and beans also contain compounds that either prevent absorption of minerals during digestion, or can irritate the human intestine more or less severely. Grains and seeds are not meant to be eaten but grinding, fermentation and cooking or baking reduces the content of anti-nutritive compounds and makes starch and proteins more easily digestible. In baking, fermentation additionally leavens the dough to provide a lighter texture. Most products in groups 5 to 10 and 12 are fermented for these reasons. Archeological evidence also dates the first bread production to the same time as fermentation of “beer”, and the production of bread thus likely also predates cereal agriculture.

3. Humans fermented foods to preserve perishable agricultural raw materials. This motivation is most important for fermented vegetables (group 11), fermented dairy products, fish, and meats (groups 14 to 18). The main mechanism of preservation is the production of organic acids by lactic acid bacteria, which reduces the pH and makes the foods unsuitable for growth of spoilage microbes, or for survival of pathogenic microbes. In many products, e.g. cheeses, fermented meats, and in Fu-Tsai (element 111), the preservative effect of a high content of acids is increased by the effect of a low water content, which also inhibits growth of unwanted microbes. In many European societies, e.g. Switzerland, Holland and the British Isles, cheese production was a means for farmers of extending the life of one of their main products, milk, and enabled them to sell it in distant markets. Fermented foods also helped James Cook to travel to Vancouver Island, Australia and multiple other far-away locations as the first European: he was the first to use sauerkraut as food for his crew, which prevented scurvy and allow ship voyages over several months.

4. Humans fermented foods to produce delicacies that please the palate. Vanilla and chocolate have already been mentioned, but vinegars and condiments, and sauces produced from soy, cereals or fish, also rely on fermentation. We have a perception that healthy foods are not tasty and that comfort foods are not healthy. The periodic table of fermented foods provides multiple examples that this perception is not always true: many of the fermented and healthy (plant) foods are very delicious.

Major motivations for food fermentations

1. To produce alcoholic beverages
2. To remove anti-nutritive or even toxic compounds in plant foods
3. To preserve perishable agricultural raw materials
4. to produce delicacies that please the palate

Which microbes are used to ferment foods?

Very diverse groups of microbes are used in food fermentations (see bottom of Periodic Table figure), the most frequently used of which are yeasts, lactic acid bacteria, acetic acid bacteria, mycelial molds, bacilli, staphylococci and propionibacteria. The contribution of some of these major organisms to food quality is outlined above. Yeasts and molds additionally produce flavor compounds, particularly when growing on the surface of cheese, fermented meats, or tofu. Acetic acid bacteria convert ethanol to acetic acid, which is necessary for production of vinegars, and contribute to the smell and the taste in many other fermented foods including kefir, coffee and chocolate and some alcoholic beverages. Staphylococci produce flavors in fermented foods with a high content of protein but a low content of sugar and water, e.g. fermented fish, meats, and some plant-based condiments. Propionibacteria are used almost exclusively in cheese production, where they produce gas to form holes and contribute to the characteristic taste of Swiss cheese.

While some foods are fermented only with one organism, e.g. in beer production with brewer's yeast, or dairy fermentations with only lactic acid bacteria, most food fermentations recruit several groups of microbes. As a general rule, a higher diversity of the community of microbes that is involved in the fermentation results in a higher intensity of flavor and taste. For example, Lambic beer (element 71), fermented with brewer's yeast and lactic acid bacteria, is more flavorful than lager beer or ale, which is fermented with brewer's yeast only; Sourdough bread (group 8) is more flavorful than bread produced with baker's yeast only; and surface ripened cheeses (group 16) are more flavorful than cheese produced with lactic acid bacteria only. "More flavorful", however, does not necessarily correspond to "more preferred" by all consumers. For example, the Swedish Surströmming is certainly more flavorful than fish but most of those that are not used the product would likely designate it as rotten fish. And the strong smell of red-smear cheese (elements 34 and 116) is appreciated by some but not by all consumers.

How do we recruit microbes for food fermentation?

The microbes that we use for food fermentations either originate from the raw materials and the processing environment (spontaneous fermentation), or from a previous batch of fermentation in a processed termed "backslopping" (see below).

In both cases, the composition of the communities of microbes that contribute to the fermentation can be controlled by the right choice of the recipe, e.g. addition of water or salt, fermentation temperature and fermentation time. Vegetable fermentations and many cereal fermentations rely on microbes that are associated with plants. Plants are colonized by bacilli, enteric bacteria, and lactic acid bacteria. Macerating plant tissues and grinding/milling seeds, followed by addition of water or brine, releases nutrients for bacterial growth. Bacilli grow only if acidification by other microbes is delayed as a result of the sugar content of the substrate being low (examples in group 5, 12 and 13). In most spontaneous fermentations, enteric bacteria, which are facultative anaerobes and the most abundant bacteria in plant materials, grow first. Lactic acid bacteria grow later and reduce the pH by production of lactic acid to a point where enteric bacteria can no longer survive and growth of spoilage microbes is inhibited.

This succession of microbial communities is comparable in all fermented vegetable fermentations, irrespective of where these are performed and which vegetables is used. A comparable succession of microbial communities is found in spontaneous cereal fermentation, e.g. in most products in groups 6 and 7.

Backslopping

Backslopping is the process whereby a small quantity of material from a completed fermentation is used to start a new one. It provides uniformity in fermentation, because it largely eliminates the involvement of diverse and variable microbes from the environment, and because the fermentation starts immediately because the inoculum is both large and adapted to the fermentation. In the Periodic table figure, the product names are underlined if fermentation microbes are controlled by backslopping.

Back-slopping is generally used in brewing, baking, soy sauce production, and in most dairy fermentations. The process is often continued without interruption over long periods of time: Some sourdoughs have a documented history of more than 100 years of continued back-slopping; many or most dairy starter cultures that are used in the Americas were brought by European immigrants more than 100 years ago. Fungal cultures that are used for fermentation of beer, blue mold cheese and Japanese soy sauce have been cultivated by back-slopping for several hundred years.

How does back-slopping impact the community of microbes in food fermentations?

1. First, addition of even a small proportion of a previous fermentation adds millions of microbes to the new batch and these typically grow much faster than the microbes from the raw material: the fermentation is faster and easier to control by recipe, temperature, and fermentation time.

2. Second, continuous back-slopping over long periods of time makes transmission of microbes from even unlikely sources a possible or even likely event. As outlined above, spontaneous fermentations of plant foods are dominated by plant-associated microbes. Back-slopped fermentations are not. In some cases, we know the origin of the fermentation microbes: bacteria in back-slopped dairy starter cultures and sourdoughs originate from the intestine of domestic animals, or of insects; for others we don't know the origin but we know that the fermentation microbes are not associated with the raw materials. Fermentation with intestinal bacteria does not sound very appetizing but we need to keep in mind that a single transmission

event with very few cells is sufficient to have the gut microbes multiply in food fermentations for decades to follow.

3. Third, continuous back-slopping of fermentation microbes results in domestication of microbes. In the same way humans domesticated pigs, cattle and horses, many of the fungal fermentation microbes are domesticated. They were back-slopped (“bred”) for several hundred years and are genetically and physiologically different from their feral ancestors. Examples include brewer’s yeast, the blue mold used in cheese ripening, and the molds used in production of *koji*, the fungal starter cultures used in production of soy sauce, rice wine, and cereal vinegars in Japan.

Is it difficult to ferment foods at home, or in school?

Food fermentations are ancient, and most food fermentations continue to be carried out at the household level: It takes some skill and experience but not a degree in science to successfully manage a food fermentation. The procedures for production of many fermented foods including yoghurt, fermented vegetable juices, water kefir or kombucha, fermented vegetables or sourdough bread are readily adopted for use at the household level, or in experiments conducted in primary school. In some cases, e.g. kefir, water kefir or kombucha, you need to rely on your social network to obtain a starter culture. Sharing a culture is not difficult because bacteria multiply rapidly and a small amount of starter culture can be used to ferment a large volume of food, and to maintain the culture by back-slopping. Cultures are also available in the supermarket. Yoghurt cultures can be maintained by back-slopping at home if kitchen utensils that maintain the temperature of inoculated milk at 38 – 42 °C are available. The acidic, “Balkan-style” yoghurts with milk as sole ingredient are a better source of fermentation cultures than the less acidic yoghurts that are produced with attenuated lactic acid bacteria. Pickles or fermented cabbage (kimchi or sauerkraut) that are displayed on refrigerated shelves of the supermarket are likely to contain live microbes that can be used to jump-start fermentation of sauerkraut or fermented vegetable juices. The same products kept at ambient temperature are pasteurized and don’t contain live microbes.

Sources for information on how to control different fermentation include the Noma guide of fermentation, which provides guidance on the use of food fermentation in culinary arts, various sites on the internet, which need to be verified as to whether or not they provide reliable information, and even artificial intelligence chatbots. The AI chatbot available at <https://chat.openai.com/chat> was apparently trained with a sufficient number of documents on food fermentations to provide very reasonable and likely successful guidance on the fermentation of sauerkraut, on how to start a sourdough starter, and on how to ferment vegetable juice (accessed May 11, 2023). The most relevant message: if things smell foul, get moldy or otherwise appear to have gone sideways, discard the product and start again. The ability to control food fermentations depends on experience and making mistakes is part of the process.