Fermented foods

How can microbes turn flour into pizza?

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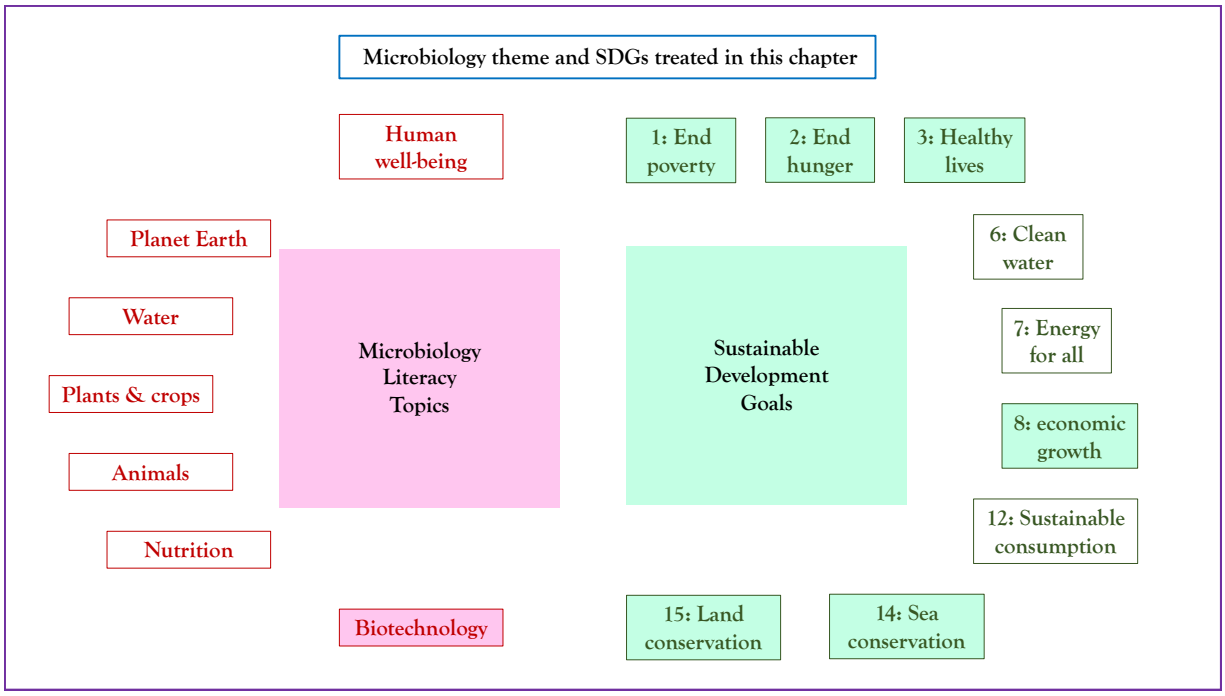
Storyline

In a world in which the gut microbiome and its relationship with human health is a hot topic, fermented foods are becoming increasingly popular, with consumption increasing 149% in 2018 according to FORBES. But fermented foods are not just associated with a healthier gut: fermentation can also create flavors that cannot be accomplished any other way. According to the Rockefeller University, "fermentation is a culinary exploitation of a microbial system". Even more, fermented foods are rich in nutrients, have a longer shelf-life, and display unique textures and organoleptic properties. Nevertheless, fermented foods must be manufactured and stored in a controlled environment to ensure safety, quality and constant organoleptic properties in the final product. Fermented foods are associated with multiple sustainable development goals.

The Microbiology and Societal Context

The microbiology: fermentation by bacteria, yeast and fungi; probiotics; microbial-derived metabolites; food pathogens; fermentation pathways; spoilage. *Sustainability issues:* poverty; hunger; health; industry, economic growth and employment; life below water; life on land.



Fermented foods: the Microbiology

1. ***Fermented foods have been around for thousands of years, and they are present in our daily lives.*** Several studies have shown evidence of dairy fermentation in North Africa 10.000 BCE; of fermented beverages made of fruit, rice and honey in China 7.000 BCE; of dough fermentation in Egypt 3.500-3.000 BCE; and of fermented vegetables in the Middle East 2.000 BCE.

Although used for thousands of years, the scientific basis of fermentation was unknown until relatively recently. The actual role of microorganisms in this process was first demonstrated in 1856 by Louis Pasteur, who described fermentation as «la vie sans l'air» or life without air, as fermentation is a metabolic process in which microorganisms extract energy from carbohydrates in the absence of oxygen. Pasteur showed that yeast cells are responsible for transforming glucose from grape juice into ethanol, thereby producing wine.

Nowadays, fermented foods and beverages are produced both in traditional contexts, and in industrial settings in which controlled microbial growth conditions are used. Some of the most common fermented foods are yoghurt, kefir, sourdough bread, kombucha, kimchi, miso, sauerkraut, wine and beer (see the Fermented Food Stars Portrait Gallery for enticing details)

2. ***Fermentation can be carried out by bacteria, yeast and fungi.*** Lactic Acid Bacteria (LAB) are frequently used for fermentation of food and beverages, thanks to their production of several metabolites of interest, such as lactic acid, acetic acid, ethanol, bacteriocins, aromas, exopolysaccharides and enzymes. Examples of products obtained by fermentation with LAB are yoghurts and fermented vegetables (kimchi, olives, cucumber, etc.).

In the case of yogurts, the added bacteria (commonly *Streptococcus thermophilus* and *Lactobacillus delbrueckii*) produce lactic acid (among other acids), and this decreases the pH, causing the milk proteins to coagulate and giving the yogurt its characteristic texture and tartness.

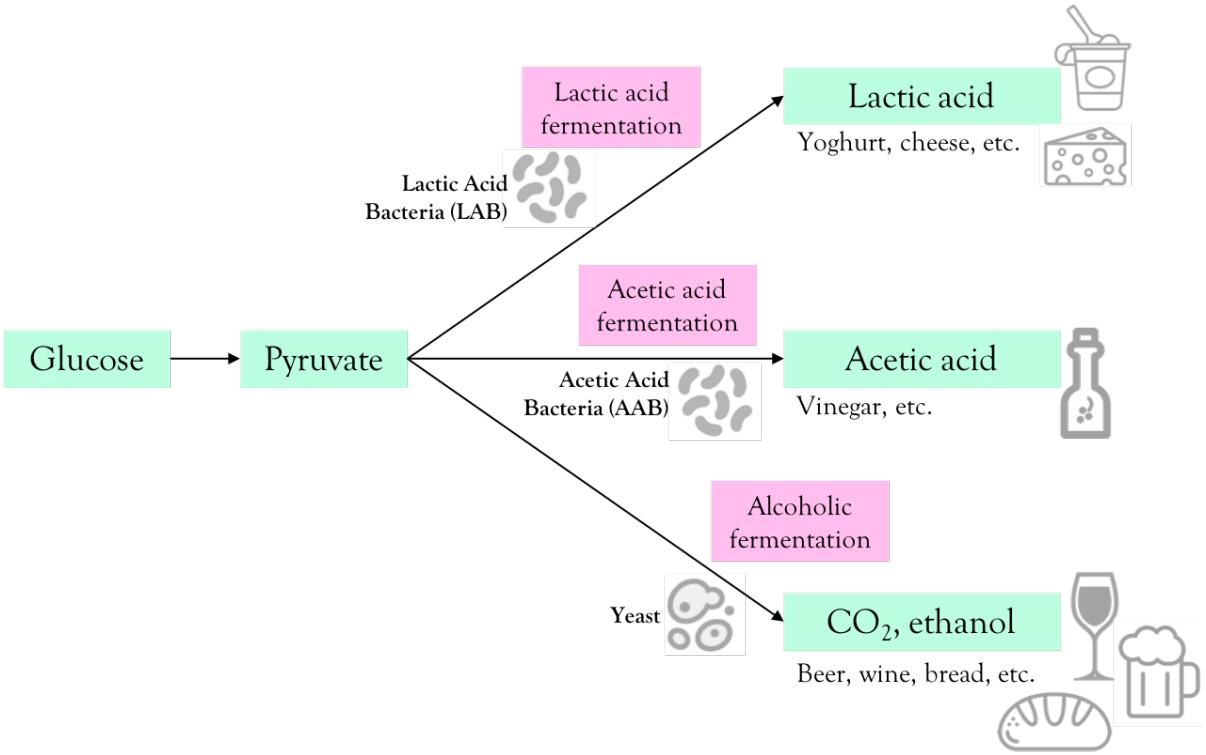
A similar thing occurs with fermented vegetables: LAB produce several acids which cause a reduction in pH, leading to a longer shelf life and to the characteristic aromas, flavors and textures of these vegetables.

Yeasts are commonly used as leavening agents, with *Saccharomyces cerevisiae* being one of the most popular options. When making bread with yeast as a leavening agent, the yeast cells convert their food (sugars) into alcohol and carbon dioxide through fermentation, and it is the carbon dioxide that makes the dough rise. Yeast is also responsible for the production of ethanol in fermented beverages, such as beer and wine.

Finally, filamentous fungi are used commonly to produce cheeses, including *Penicillium roqueforti* for blue cheeses (i.e., Gorgonzola or Roquefort) and *Penicillium camemberti* for mouldy soft cheeses (e.g. Brie or Camembert: see below). Other foods fermented by fungi include tempeh.

Brie, a soft cheese with an external layer of white mould that is the filamentous fungi *Penicillium camemberti* (image: Karolina Grabowska, Pexels)

3. ***Fermentation preserves food, leading to an improved shelf life and the generation of less waste.*** As previously mentioned, during fermentation, microorganisms break down complex compounds (i.e., carbohydrates) and transform them into different products depending on the fermentation route used. The three most frequent fermentation pathways relevant to fermented foods are: lactic acid fermentation (end product: lactic acid), acetic acid fermentation pathway (end product: acetic acid), and alcoholic fermentation pathway (end products: ethanol and carbon dioxide). These end products are in fact the reason that fermentation contributes to the preservation of food: they all inhibit the growth of microorganisms that cause food spoilage.



Another means of preventing food spoilage through fermentation is the high abundance of the fermenting microorganisms, that dominate the microbial communities and limit the growth of other undesirable microorganisms by occupying a specific ecological niche and, in some cases, by producing bacteriocins, that directly inhibit the growth of other bacteria. The improved preservation of fermented foods is of particular interest in low- and middle-income countries that have limited access to refrigeration.

4. ***Fermentation plays a very important role in the flavor, smell and texture of fermented foods.*** During fermentation, the microbial metabolic pathways that are engaged lead to the synthesis of molecules that can enhance the existing flavors and aromas and create new ones. For example, the breakdown of sugars and the production of acid by LAB during fermentation leads to a reduced amount of sugars and a lower pH, resulting in a decrease in sweetness and an increased sourness.

Furthermore, the microorganisms involved in fermentation can produce volatile components that can lead to the development of new aromas and flavors, but also inhibit the generation of volatile compounds present in the raw material. This is the case, for example, with fermented cucumbers. The aroma of fresh cucumber results from the presence of aldehydes; the drop in pH during fermentation inactivates the enzymes synthesizing these aldehydes, which are therefore no longer formed.

In the case of sourdough bread, it has been shown than fermentation causes 7- to 9-fold increases in the concentrations of different compounds involved in aroma.

And fermentation can result in important changes in the physical properties of foods, influencing their texture, structure, consistency and viscosity, through the production of exopolysaccharides and other biopolymers.

Fermenting vegetables is a relatively easy process (Photo by Maria Verkhoturtseva; Pexels).

5. ***Fermented foods have many health benefits.*** Many studies conducted in recent years have shed light on the health benefits associated with the consumption of fermented foods.

Fermented foods frequently contain large amounts of live microorganisms, and these can transiently affect the gut microbiota, increasing its diversity, improving its health and reducing the risk of dysbiosis-associated disease. Many of these microorganisms can in fact be probiotic strains, that are known to protect the gut against pathogenic microbes, produce molecules of interest such as Short-Chain Fatty Acids (SCFAs), or metabolize bile acid salts. Probiotics have also been seen to alleviate the symptoms associated with irritable bowel syndrome and can stimulate the immune system.

Fermentation can also lead to the elimination of several compounds (i.e., polyphenols, phytates, oxalates, mycotoxins, etc.) that are present in the raw materials and that can be toxic or impede the intestinal absorption of certain nutrients. It can also lead to the synthesis of vitamins, minerals and biologically-active compounds that enhance the nutritional and functional properties of the food. And fermented food can also contribute to improvement of human health for example through its antioxidant and/or anti-inflammatory activities.

Finally, fermentation of substrates the host cannot digest, such as dietary fibers or complex carbohydrates, can make them available to the host.

Yoghurt is a fermented food made by adding live bacteria (usually *Streptococcus thermophilus* and *Lactobacillus delbrueckii*) to milk. These produce lactic acid (and other acids) which decreases the pH, causing the milk proteins to coagulate and giving the yogurt its characteristic texture and tartness (Photo Cats Coming; Pexels).

6. ***Fermented food can have negative effects on health when the fermentation and conservation are not properly controlled.*** The lack of Good Manufacturing Practices (GMPs) (i.e. an absence of proper hygiene conditions during manufacturing, use of poor-quality ingredients, or inadequate quality control mechanisms) can lead to the presence of pathogenic microorganisms and/or toxins in fermented foods, leading to illness and even outbreaks.

In addition, correct storage conditions are also essential: even though fermentation can improve preservation, fermented foods can also spoil. Ways of detecting spoilage include the appearance of undesired mold on the materials, the presence of a rotten smell or the bad taste of the food. Interestingly, the appearance of mold is not always associated with food spoilage: dry fermented sausages often display a layer of filamentous fungi growing on the surface of casings which improve the aroma and flavor of the product. It must be noted though, that this layer of fungi can also lead to the production of antibiotics and mycotoxins, that may prove to be hazardous for human health.

7. ***There are regulations to ensure that fermented foods are correctly prepared and stored to prevent infections.*** Although there are still some traditional fermented foods that depend on naturally occurring fermentations, larger scale commercial productions tend to remove the natural microbial flora present on the raw materials and then add in defined starter cultures – well characterized microbes that carry out the fermentation and that outcompete and prevent the growth of any other organisms that may accidentally enter the process – and perform the process in a controlled environment. This is of the utmost importance to ensure safety, quality and constant organoleptic properties of the final product.

It must be highlighted that there are some fermented foods in which the microorganisms are not alive in the final product, such as bread (the high temperatures reached when baking lead to the death of the microorganisms). On the other hand, other fermented foods contain a very high count of live microorganisms. This is the case, for example, with yogurt. For a yogurt to be able to display "Live and Active Cultures" on the packaging, it has to contain at least 100 million

Colony-Forming-Units (CFUs) per gram of yogurt at the time of manufacture, according to the International Dairy Foods Association (IDFA).

Relevance for Sustainable Development Goals and Grand Challenges

The microbial dimension of producing and consuming fermented foods relates to several SDGs, including:

- **Goal 1. End poverty.** Poverty is intricately linked with human health, as it restricts access to food, healthcare, and other basic requirements. In this sense, fermented foods are beneficial for human health when the fermentation is controlled, but there is a risk of infection and disease if this microbial growth is not controlled and shifts towards the growth of pathogenic microorganisms. On the hand, it must be noted that fermented foods may contribute to reducing poverty, as they can constitute a source of income and employment if their production is turned into an actual business.
- **Goal 2. End hunger.** Fermentation is an economically viable process that can be used to preserve foods, increase shelf life and hence reduce food wastage, and this can in turn contribute to reducing hunger. Furthermore, fermentation can also be used to salvage food waste and turn it into a nutritional and edible form that otherwise would be thrown away. For example, Tempe-bongkrek is an Indonesian food produced by fermenting coconut presscake or coconut milk residue with the fungi *Rhizopus oligosporus*.
- **Goal 3. Healthy lives**. Fermented foods have improved nutritional qualities as well as increased safety and hygiene. They are also a source of live probiotic microorganisms which, as we have previously seen, can contribute to human health through a variety of pathways.
- **Goal 8. Economic growth and employment.** Production of fermented food and beverages is a relatively simple and inexpensive process that can pose an opportunity for the creation of micro- and small-scale industries. This can boost socio-economic development, but only when done properly: it is important to assess the critical control points to ensure the correct safety and hygiene of the final product.
- **Goals 14 and 15. Conserve the oceans; Protect terrestrial ecosystems.** The biosphere is facing a plastic pollution crisis. Packaging is the main contributor to plastic waste, representing about 63% of the total in Europe. In 2017, more than 27.1 million tons of plastic waste were produced in Europe, with only 31.1% being recycled, 41.6% being incinerated and 27.3% being deposited in landfills. These landfills occupy many hectares worldwide and are responsible for the emission of dangerous gases (including the greenhouse gases methane and carbon dioxide), as well as highly toxic leachates during the decomposition stage, posing a serious threat to the environment, and to human and animal wellbeing. And much plastic waste is exported to other countries for disposal, mostly with an unknown fate. A considerable amount of plastic wastes enter rivers and thence marine systems, giving rise to the "plastic oceans" we now have. The increased shelf life of fermented products leads to a reduction in the waste generated, and this can massively benefit the health of our oceans and terrestrial ecosystems. Importantly, the production of homemade fermented foods, such as bread and yogurts, can also lead to a reduction in waste, as these products will not require plastic packaging like the commercial products in supermarkets.

Potential Implications for Decisions

1. ***Individual***
    a. Health benefits associated with the consumption of fermented foods.

b. Homemade fermented food and the risks involved.

2. ***Community policies***
   a. Reduced waste associated with the purchase and/or homemade production of fermented foods.
   b. Health costs associated with consumption of fermented foods in which undesirable microorganisms have grown.

3. ***National policies***
   a. Especially in developing countries, national policies could aid small and medium businesses that aim to generate income and employment by manufacturing fermented foods. These aids could help with the installation of equipment and the implementation of GMPs.

Pupil participation

1. ***Class discussion of the benefits associated with fermented foods.***

2. ***Pupil stakeholder awareness***
   a. Fermented foods have been seen to contribute to several SDGs. Which of these are most important to you personally and as a class?
   b. Do you think it is safe to make fermented foods at home? What can you do to increase the safety of this process?

3. ***Exercises***
   a. A baking session. Baking homemade bread is an easy, fun and sensory experience that not only allows to reinforce friendship and family bonds, but it contributes to teaching children to be self-sufficient, as it is a process that they can handle from beginning to end with minimum help from an adult, and that will result – hopefully – in an edible product of which the children will be very proud.
   b. Fermented foods and the cultural context. Aside from the commonly consumed fermented food and beverages around the world (yoghurt, bread, cheese, wine, beer, etc.), there are many fermented foods that are traditional of certain countries and regions. Search more on these traditional fermented foods and create a world map with pictures and a short description of each product (you might also consult the Fermented Food Stars Portrait Gallery).

The Evidence Base, Further Reading and Teaching Aids

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Glossary

Acetic acid: weak organic acid that is present in vinegar and is responsible for its characteristic smell and sour taste.

Aldehyde: organic compound, usually sweet-smelling, that contains a -CH=O group at the end of a carbon chain and is formed by the oxidation of alcohols.

Anti-inflammatory: property of a substance that reduces inflammation. Inflammation is part of the protective biological response of our body when exposed to harmful stimuli (i.e., pathogens or irritants, among others) but, when expressed at too high a level, it can be harmful.

Antioxidant: property of a substance that inhibits oxidation and, therefore, can protect your cells by preventing or reducing damage caused by free radicals (highly reactive chemicals that contain oxygen). Common examples of antioxidants are vitamins A, C and E.

Bacteriocins: antibacterial substances synthesized by specific strains of bacteria that kill or inhibit the growth of other, closely related, bacterial strains.

Beer: carbonated alcoholic drink made by brewing and fermenting starches with yeast (mainly malt but also others such as wheat, maize, rice or oats). Flavors may be added with hops and/or other flavoring agents.

Bile acid salts: product of a bile acid and a base that are one of the primary components of bile and help with the digestion of fats by functioning as emulsifiers of fatty acids and lipids.

Carbohydrate: large group of organic compounds composed of carbon, oxygen and hydrogen, and that are one of the three main nutrient groups identified in food and drink (carbohydrates, proteins and fats). Dietary carbohydrates include sugars, starches and fibers.

Colony-Forming Units (CFUs): unit used in microbiology to estimate the number of live bacterial or fungal cells in a given sample.

Dietary fibers: parts of plant-derived foods that our body isn't able to digest or absorb, present mainly in vegetables, fruits, whole grains and legumes.

Dysbiosis: imbalance or disruption in the normal gut microbiota, resulting in a reduction in microbial diversity and in the loss of beneficial bacteria, which can lead to negative effects on our health.

Ecological niche: interrelationship of a species with the biotic and abiotic factors in its environment; these relationships define how an organism or a population respond to and can alter the distribution of resources and the presence of competing organisms or populations.

Enzyme: protein that catalyzes or encourages a biochemical reaction, for example, by increasing the speed of the reaction. They are essential for digestion, liver function, and many more biological processes in our body.

Ethanol: colorless volatile flammable liquid that is produced by fermentation of sugars, also known as alcohol. It is the intoxicating agent in liquors and can also be used in fuel and as a solvent.

Exopolysaccharide: mucoid polysaccharide (sugar) matrix produced by microorganisms and secreted to the exterior of the cell where they serve as protection against environmental stressors, such as heat, chemicals or antibiotics.

Fermentation: metabolic process performed by microorganisms (bacteria, yeast or fungi) in which energy is extracted from carbohydrates in the absence of oxygen and can lead to the production of lactic acid, acetic acid, alcohol, carbon dioxide, and others.

Fermented foods: foods produced by the action of fermentation, in which certain components of the raw material are transformed by microorganisms into end products that affect the characteristics of the food (nutrients, taste, texture, preservation properties, etc.).

Filamentous fungi: multicellular fungi that are commonly known as molds. They generally appear forming circular colonies that may display a cotton or wool-like appearance. Their filaments do not organize into fruiting bodies (i.e., mushrooms).

Glucose: simple sugar that is the main type of sugar in our blood and the major source of energy for the body's cells.

Good Manufacturing Practices (GMPs): system for ensuring that products are produced in a consistent and controlled way in accordance with specific quality standards, aiming to minimize the risk associated to the products. It covers all aspects, from starting materials, to adequate premises and equipment, to personal hygiene of the staff.

Gut microbiota: microorganisms that live in the digestive tract.

Irritable bowel syndrome: common disorder that affects the digestive system (in particular, the large intestine) and causes symptoms such as abdominal pain, gas, bloating, diarrhea or constipation.

Kefir: fermented drink, similar to a thin yogurt, with a sour taste that is obtained by fermentation of milk with a symbiotic culture composed of bacteria and yeast. This symbiotic culture is added in the form of kefir grains: microbial clusters that are held together by a polysaccharide matrix.

Kimchi: spicy vegetable dish that consists of picked and fermented vegetables, especially cabbage and radishes with several seasonings.

Kombucha: fermented, lightly effervescent drink obtained by fermenting sweet black or green tea with a Symbiotic Culture Of Bacteria and Yeast (SCOBY).

Lactic acid/lactate: lactic acid is an organic acid that can be produced from simple carbohydrates (glucose, sucrose, galactose, etc.) via lactic acid fermentation. Lactate is sometimes used as a synonym of lactic acid, but both molecules are structurally different: lactic acid has an extra hydrogen atom bound to an oxygen atom.

Lactic Acid Bacteria (LAB): group of bacteria that produce lactic acid as the major metabolic end product of carbohydrate fermentation.

Leavening agent: biological (i.e., yeast) or synthetic (i.e., baking powder) compounds that are used to make doughs and batters rise via the formation of gas bubbles (i.e., carbon dioxide) that lighten and soften the mixture.

Metabolite: intermediate or end product of metabolism, a process that uses chemical reactions to change food into energy.

Microorganism: organism of microscopic size that can exist in a single cell form or as a colony of cells.

Miso: traditional Japanese seasoning that consists of a high-protein thick paste that is produced by fermenting soybeans with salt and a fungus, sometimes adding also rice, barley, or seaweed.

Mycotoxin: toxic substance naturally produced by a fungi that can cause a variety of adverse effects on health.

Naturally occurring fermentations: fermentations that are carried out by the microorganisms that are present naturally in the raw food or processing environment, without adding external microorganisms.

Nutrient: chemical compounds present in food (i.e., protein, fat, carbohydrates, vitamins or minerals) that are used by the body to maintain a healthy status and function properly.

Organoleptic properties: qualities of food and drinks that create individual experiences via the senses, including taste, smell, sight and touch.

Oxalates: salt or ester of oxalic acid that can be found in plants (i.e., spinach, almonds, beets, etc.) and can form insoluble salts with calcium., interfering with its absorption by the body.

Pathogenic microbe: a microorganism that is capable of causing infection or disease in its host through a variety of mechanisms, such as competition for metabolic resources, direct cell or tissue destruction, or secretion of toxins.

Phytates: salt or ester of phytic acid that can be found in plants (i.e., cereal grains, legumes, nuts and seeds, etc.) and can form insoluble complexes with several nutrients (i.e., calcium, iron, zinc, etc.), interfering with their absorption by the body.

Polyphenols: naturally occurring organic compounds with antioxidant activity that can be found in many plants (i.e. berries, cocoa, beans, artichokes, spinach, etc.) where they provide color to their flowers, fruit and vegetables.

Probiotic: live microorganism that, when consumed, can have a positive impact on health. They are frequently found in yogurt and other fermented foods.

Sauerkraut: finely cut raw cabbage that is fermented by lactic acid bacteria.

Short-Chain Fatty Acids (SCFA): fatty acids with less than six carbon atoms that are crucial for gastrointestinal health and that can be generated by fermentation of indigestible foods (i.e., dietary fiber) by gut microbiota.

Sourdough bread: bread characterized by its sour taste and long shelf life that is made by fermenting the dough with a starter culture (also known as pre-ferment), which is a fermented mixture of flour and water that contains a combination of wild lactic acid bacteria and yeast.

Spoilage: deterioration of food, drinks and other perishable goods, for example, due to the action of specific spoilage microorganisms.

Starter culture: well characterized microbes that are used to assist the beginning of fermentation and that outcompete and prevent the growth of any contaminants that may accidentally enter the process.

Tempeh: traditional Indonesian dish made by a natural fermentation process that binds soybeans into a cake form.

Toxin: poison that is highly toxic for living organisms and that can be produced by plants, certain animals, or pathogenic microorganisms.

Wine: alcoholic beverage made by fermenting grape juice.

Yeast: microscopic single-cell fungus that reproduces by budding and that can be used to produce fermented foods via the alcoholic fermentation pathway.

Yoghurt: semisolid and slightly sour food produced by fermenting milk with two different bacterial species, *Streptococcus thermophilus* and *Lactobacillus bulgaricus*.