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Food Fermentation: an essential unit operation towards secure, sustainable, safe, and sustaining food systems

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A Viewpoint on the Frontiers in Science Lead Article
Harnessing agri-food system microbiomes for sustainability and human health

Key points

- Food and feed fermentation improve the palatability and digestibility of plant-based food and feed.
- Fermented foods contribute to food security, particularly in low- and middle-income countries.
- Food and feed fermentation constitutes a low-input processing step, supporting sustainable food production.
- Fermentation can change the nutritional composition of whole plant food ingredients and thereby enhance intake, nutrient digestibility, and gut health.

Introduction

Food fermentation is one of the oldest unit operations in food production, predating the Neolithic revolution. The appreciation for fermented foods stems from their unique sensory and nutritional qualities as well as their enhanced safety. Moreover, many fermented foods are deeply tied to cultural and regional identities (1). Food and feed fermentation is also indispensable for transitioning agri-food systems to more sustainable practices, feeding a growing population in a changing climate (2). This viewpoint aims to outline the contribution of food and feed fermentation to secure, sustainable, safe, and sustaining agri-food production systems (Figure 1).

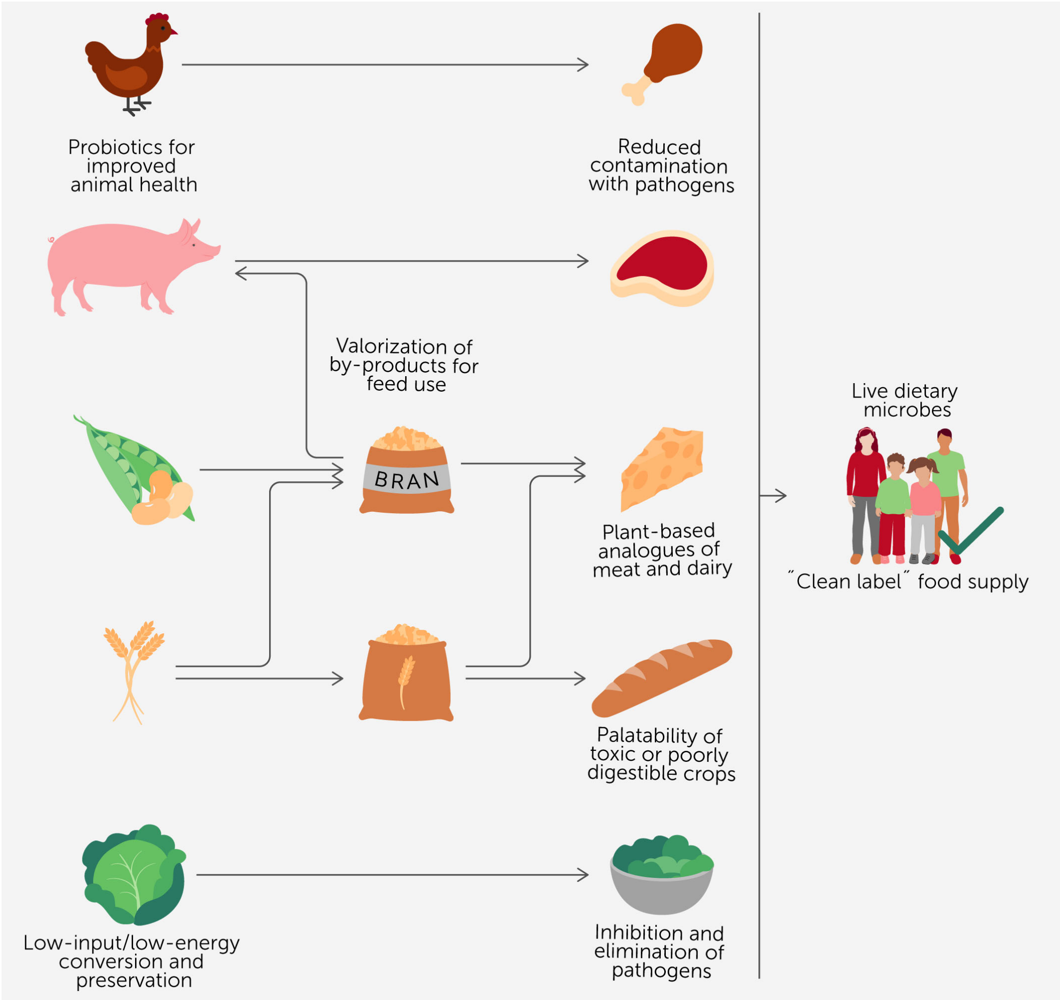

FIGURE 1
Overview of the role of food and feed fermentation in sustainable, safe, food- secure, and health-beneficial food production systems.

Fermented foods and food security

Many staple crops, especially in developing countries, are unpalatable or inedible without processing techniques such as fermentation. For example, cassava and certain yam varieties, staple foods in areas of South America and Africa, contain cyanogenic glucosides, which release cyanide after hydrolysis of the glycosidic bond. Hydrolysis by the intestinal microbiome after ingestion releases cyanide and leads to chronic intoxication or even death. Fermenting the food, however, enables hydrolysis of the cyanogenic glucosides, releasing the cyanide prior to ingestion and making the product safe. *Lacticaseibacillus mannihotivorans* and *Lactiplantibacillus plantarum*, common in cassava fermentations, are particularly effective at this process.

Similarly, vicin and convicin in faba beans can cause favism if not properly hydrolyzed prior to ingestion. The high prevalence of glucose-6-phosphate dehydrogenase deficiency in malaria-endemic areas, such as the Mediterranean and the Middle East, exacerbates the risk.

Red and brown sorghum varieties are highly pest resistant owing to their high content of phenolic compounds, including deoxyanthocyanidins. In Sub-Saharan Africa and parts of Asia, sorghum is commonly cultivated due to its pest resistance and superior agronomic properties. However, the (poly)phenolic compounds also impart a bitter taste and inhibit starch and protein digestion. From relying on sorghum as a staple crop, a mutation of the bitter taste receptor that reduces its sensitivity has become highly prevalent in peoples living in these regions (3). While processing African sorghum through malting or fermentation reduces the bitter taste of the phenolic, the underlying molecular mechanisms remain unclear.

Feed fermentation may improve the digestibility and palatability of food processing co-products. This contributes to more sustainable food production systems by using the fermented feed instead of human-edible plant crops (4). Such fermentation technologies can then become an important part of sustainable food production systems that are built on circularity. Fermentation is especially attractive as a tail-end process in industrial plants for liquid co-products, as it allows transportation without the need for drying. Fermentation can also serve to create novel protein feedstuffs such as single-cell proteins.

Fermentation for sustainable food and feed production

Fermentation is a low-input/low-cost, resource-efficient process that requires minimal input beyond raw materials and fermentation vessels. While industrial production of meat, dairy, and alcoholic beverages generally use starter cultures to standardize fermentation, traditional and household fermentations typically do not.

Food fermentation helps to produce plant-based analogues for meat and dairy. This reduces environmental impacts related to land use, water consumption, and greenhouse gas emissions, particularly for ruminant meat and, to a lesser extent, for pork, chicken, and milk (5).

Plant-based analogues of animal protein foods are formulated with refined ingredients or are produced by fermentation with the use of whole plant ingredients. While several life cycle assessments have compared the environmental impact of (fermented) dairy products and their plant-based analogues, a comparison of products that are produced with fermented whole plant ingredients versus formulated refined ingredients is not currently available. Starter cultures suitable for the transformation of plant-based raw materials into analogues of fermented dairy products with appealing textures, taste, and appearances are being developed. An increasing body of literature assessing the suitability of starter cultures for plant-based analogues of fermented dairy products is becoming available. The poor sensory quality of many current plant-based analogues of dairy products limits their consumer acceptance; however, the use of appropriate fermentation microbes to generate products with improved sensory attributes increases their consumption and thus helps to shift protein intake from an animal-based one to one which is predominately plant-based, which has been recommended by many food and health institutions (6).

Fermentation and food safety

Fermentation ensures the safety of products such as fruit wines, fermented vegetables, and fermented dairy, fish, and meats (1), replacing thermal or non-thermal processing steps that prolong shelf life and inactivate pathogenic microorganisms. In winemaking, ethanol and low pH provide safety, while fermented vegetables rely on acidification to a pH below 4.0. Dairy, fish, and meat preservation typically combines a low pH with low water activity (a_W), often achieved by drying and adding salts. Many products strike a finely tuned balance of pH, a_W, and preservatives such as nitrite to eliminate pathogens. The inactivation of the low infectious-dose pathogens, such as enterohaemorrhagic *Escherichia coli* and *Salmonella enterica*, at a low pH is relatively slow and requires several weeks when the fermentation occurs at a low temperature. Control of fermentation parameters and long ripening or fermentation times nevertheless achieve safe products. Very few studies document pathogen control in fermented fish products as these products are produced in low- and middle-income countries and at the household level. The intrinsic and extrinsic factors that establish the safety of plant-based analogues of dairy products are poorly documented. Outbreaks linked to *Listeria monocytogenes* or *Salmonella* have nevertheless been reported, the latter in a product that included non-pasteurized sprouted pulses (7). The safety of plant-based analogues of fermented dairy products thus remains an emerging field.

Fermentation for health-beneficial foods

Fermented foods such as kimchi, kefir, and yogurt are increasingly recognized for their health benefits, which arise from live fermentation microbes, their metabolites, and substrate-derived bioactive compounds. These may include bioactive peptides and amino acid metabolites in dairy products and phytochemicals and their metabolites in plant products; thus, they cannot be considered across all fermented foods.

Fermented foods that contain live dietary microbes at the time of consumption are a suitable vehicle for probiotic microorganisms. Probiotics are live microorganisms that exert health benefits when consumed in sufficient quantities. The current consensus is that the probiotic activity of microorganisms is strain-specific, i.e., a fermented food has probiotic properties only if the starter culture employed is a probiotic strain with clinically documented health benefits that maintains high viable cell counts until consumption. Consumption of live dietary microbes is also recognized to provide health benefits. Probiotic lactobacilli are suitable fermentation organisms for kefir or sauerkraut/kimchi or as adjunct cultures in cheeses and enable the dual use of lactobacilli as a starter culture and probiotic. Pathogen control in animal production has also relied on feed fermentation to deliver probiotic microorganisms in, for example, silages or swine feed (8).

Most lactobacilli outcompete pathogens such as *Enterobacteriaceae* by rapid acidification, both in spontaneous food fermentation and the treatment of diarrheal diseases, including traveler's diarrhea. In addition, specific lactobacilli, such as *Limosilactobacillus reuteri*, produce a biofilm matrix that prevents adhesion of enterotoxigenic *E. coli* (ETEC) to intestinal mucosae (8). This concept could be used to treat ETEC diarrhea in humans but is unexplored. In developing countries, fermented cereal foods are staples and ETEC is a major cause of childhood mortality.

ETEC and *Salmonella* control through probiotic lactobacilli has seen success in animal production. High piglet mortality affects many of the current swine production systems, compromises profitability, and raises ethical concerns. A major contributor to piglet mortality due to post-weaning diarrhea are ETECs; probiotic lactobacilli, however, can reduce post-weaning diarrhea via competitive exclusion or prevention of pathogen adhesion to the intestinal mucosa (8). In poultry production, *Salmonella* control minimizes pathogen contamination in meat. Probiotic mixtures have also been shown to enhance immune responses in cattle, particularly in the case of *Salmonella* Dublin infections (9).

Conclusions

Fermented foods are not only among the oldest foods produced by humanity but are also a major contributor to innovations in food science, improving the quality, sustainability, and health benefits of our food supply. Traditional or novel fermented plant foods that replace animal protein enhance food security and food production sustainability. Emerging concepts relate food fermentation to improved human health, including health benefits from bacterial metabolites produced during fermentation or intestinal transit. In addition, the emerging concept of live dietary microbes, which links health benefits not to specific probiotic strains but to the consumption of live bacterial cells, has been gaining traction via an increasing number of successful clinical trials. Food and feed fermentation is thus an essential part of the effort to build secure, sustainable, and safe food systems. The future of food is fermented (10).

Statements

Author contributions

MG: Conceptualization, Funding acquisition, Visualization, Writing – original draft, Writing – review & editing.

JS: Conceptualization, Writing – original draft, Writing – review & editing.

JW: Conceptualization, Writing – original draft, Writing – review & editing.

RZ: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declared that this work was conducted in the absence of financial relationships that could be construed as a potential conflict of interest.

The author MG declared a past co-authorship with the lead article author PC to the handling editor at the time of review.

The authors MG and JS declared that they were an editorial board member of Frontiers at the time of submission. This had no impact on the peer review process and the final decision.

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References

1. Gänzle M. The periodic table of fermented foods: limitations and opportunities. *Appl Microbiol Biotechnol* (2022) 106:2815–26. doi: 10.1007/S00253-022-11909-Y

2. Fernández-Gómez P, Leong D, Berg G, Brennan F, Caruso T, Charles TC, et al. Harnessing agri-food system microbiomes for sustainability and human health. *Front Sci* (2025) 3:1575468. doi: 10.3389/fsci.2025.1575468

3. Wu Y, Guo T, Mu Q, Wang J, Li X, Wu Y, et al. Allelochemicals targeted to balance competing selections in African agroecosystems. *Nat Plants* (2019) 5:1229–36. doi: 10.1038/s41477-019-0563-0

4. Zijlstra RT, Beltranena E. Feeding coproducts to pigs to reduce feed cost and reach sustainable food production. *Anim Front* (2022) 12:18–22. doi: 10.1093/AF/VFAC067

5. Coffey AA, Lillywhite R, Oyebode O. Meat versus meat alternatives: which is better for the environment and health? A nutritional and environmental analysis of animal-based products compared with their plant-based alternatives. *J Hum Nutr Diet* (2023) 36:2147–56. doi: 10.1111/JHN.13219

6. Gänzle MG, Monnin L, Zheng J, Zhang L, Coton M, Sicard D, et al. Starter culture development and innovation for novel fermented foods. *Annu Rev Food Sci Technol* (2024) 15:211–9. doi: 10.1146/annurev-food-072023-034207

7. Schmitt N, Yu G, Greve R, McIntyre L. Outbreak of *Salmonella* Weltevreden linked to fermented cashew nut cheese in Victoria, BC. *Environ Heal Rev* (2018) 61:74–81. doi: 10.5864/d2018-017

8. Chen XY, Woodward A, Zijlstra RT, Gänzle MG. Exopolysaccharides synthesized by *Lactobacillus reuteri* protect against enterotoxigenic *Escherichia coli* in piglets. *Appl Environ Microbiol* (2014) 80(18):5752–60. doi: 10.1128/AEM.01782-14

9. Soto LP, Astesana DM, Zbrun MV, Blajman JE, Salvetti NR, Berisvil AP, et al. Probiotic effect on calves infected with *Salmonella* Dublin: haematological parameters and serum biochemical profile. *Benef Microbes* (2016) 7:23–33. doi: 10.3920/BM2014.0176

10. Hernández-Velázquez R, Flörl L, Lavrinienko A, Sebechlebská Z, Merk L, Greppi A, et al. The future is fermented: microbial biodiversity of fermented foods is a critical resource for food innovation and human health. *Trends Food Sci Technol* (2024) 150:104569. doi: 10.1016/j.tifs.2024.104569