

Biotechnology Innovations for Sustainable Food and Feed Production through Biological Resource Utilization and Environmental

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Abstract

The growing demand for food and animal feed, combined with climate change, depletion of natural resources, environmental pollution, and increasing agricultural waste, has created an urgent need for innovative and sustainable approaches to food-system development. Biotechnology provides a multidisciplinary platform for converting biological resources into nutritious foods, functional ingredients, alternative proteins, animal feeds, bio-based inputs, and value-added products while reducing environmental pressures. Recent advances in microbial biotechnology, fermentation, enzyme technology, metabolic engineering, precision fermentation, plant biotechnology, algal biotechnology, biomass valorization, and biological waste treatment have expanded opportunities for sustainable resource utilization. Microorganisms, algae, agricultural residues, food-processing by-products, and underutilized biological materials can be transformed into proteins, enzymes, organic acids, bioactive compounds, feed additives, single-cell proteins, and other high-value products. Precision fermentation is particularly important for producing specific food ingredients and proteins with controlled composition and potentially lower land requirements than conventional livestock-derived production. Biotechnology also contributes to feed sustainability through microbial protein, probiotics, prebiotics, exogenous enzymes, fermented feed, and improved utilization of low-value agro-industrial substrates. Environmental biotechnology complements these approaches by enabling biological treatment of organic wastes, nutrient recovery, bioconversion, bioremediation, and circular bioeconomy development. However, technological costs, regulatory requirements, biosafety, consumer acceptance, scalability, energy requirements, and life-cycle impacts remain important considerations.

Keywords: biotechnology, sustainable food, animal feed, biological resources, fermentation, microbial protein, precision fermentation, waste valorization, environmental biotechnology, circular bioeconomy.

1. Introduction

Global food systems are under increasing pressure to provide sufficient, nutritious, safe, and affordable food while reducing their environmental footprint. Population growth, urbanization, changing dietary preferences, climate variability, land degradation, water scarcity, biodiversity loss, and the increasing generation of agricultural and food-processing waste are collectively challenging the sustainability of conventional food-production systems [1]. The transformation of agrifood systems therefore requires technological approaches capable of simultaneously addressing productivity, resource efficiency, nutritional quality, environmental protection, and economic viability.

The Food and Agriculture Organization has emphasized that agrifood systems generate substantial social and economic benefits but also impose significant environmental, health, and social costs that need to be incorporated into strategies for sustainable transformation. Biotechnology has emerged as an important component of this transformation because it allows biological organisms, cells, enzymes, genes, and metabolic pathways to be used for the production of food, feed, ingredients, bioactive compounds, and environmental services [2]. Traditional biotechnology has long contributed to food production through fermentation of milk, cereals, legumes, fruits, and vegetables. Modern biotechnology has expanded these applications through recombinant DNA technology, genome engineering, metabolic engineering, synthetic biology, omics technologies, and precision fermentation.

One of the most important developments is the ability to convert renewable biological resources and low-value biomass into higher-value products. Crop residues, fruit and vegetable wastes, oilseed press cakes, cereal bran, molasses, whey, spent grains, and other agro-industrial by-products contain carbohydrates, proteins, lipids, minerals, and bioactive compounds that can serve as substrates for microbial and enzymatic processes. Instead of being discarded or inadequately treated, these resources can be integrated into circular production systems [3]. Microbial biotechnology is particularly promising because bacteria, yeasts, filamentous fungi, and microalgae can grow rapidly on diverse substrates and produce proteins, enzymes, vitamins, pigments, organic acids, lipids, and other metabolites. Microbial biomass can also serve directly as a protein-rich feed or food ingredient. Recent research has further expanded the potential of fermentation-based production through precision fermentation, in which selected microorganisms are optimized to produce specific proteins or functional ingredients. Precision fermentation is increasingly being investigated for plant-based and alternative food products, including ingredients intended to improve nutritional and sensory characteristics.

Environmental biotechnology provides a complementary framework by converting waste streams into useful biological resources and reducing the environmental burden associated with food and feed production. Biological treatment processes can recover nutrients, reduce organic pollution, generate useful metabolites, and facilitate nutrient cycling. Consequently, biotechnology should not be considered merely a method for producing individual food products; rather, it can function as a central technology for restructuring food and feed systems around resource efficiency and circularity [4]. This review examines major biotechnology innovations for sustainable food and feed production, with particular emphasis on biological resource utilization, waste valorization, microbial and fermentation technologies, alternative proteins, feed biotechnology, and environmental management.

2. Biotechnology as a Tool for Sustainable Agrifood Systems

Biotechnology has become an important tool for improving the sustainability, efficiency, and resilience of modern agrifood systems. It involves the application of biological organisms, cells, enzymes, genetic materials, and metabolic processes to produce food, feed, agricultural inputs, and environmentally beneficial products. In sustainable food systems, biotechnology can reduce dependence on non-renewable resources, improve the utilization of biological materials, minimize production losses, and convert agricultural and food-processing residues into valuable products. Microbial fermentation, enzyme technology, plant biotechnology, algal biotechnology, and metabolic engineering are increasingly being integrated into food and agricultural production to improve productivity while reducing environmental impacts [5]. One of the major contributions of biotechnology is resource-use efficiency. Conventional food production frequently requires large quantities of land, freshwater, fertilizers, energy, and other inputs. Biological systems can improve the efficiency with which available resources are converted into useful products. Microorganisms such as bacteria, yeasts, fungi, and microalgae can grow rapidly on diverse substrates, including agricultural residues and food-processing by-products.

These organisms can convert carbohydrates, proteins, and other organic materials into microbial biomass, enzymes, organic acids, vitamins, pigments, bioactive compounds, and other value-added products. Such biological conversion provides an opportunity to produce useful commodities while simultaneously reducing the quantity of material requiring disposal.

A second important contribution is biological conversion and valorization of underutilized resources. Agricultural residues such as cereal bran, crop stalks, fruit peels, vegetable wastes, oilseed cakes, molasses, whey, and other processing residues contain substantial amounts of carbohydrates, proteins, lipids, minerals, and bioactive compounds. Biotechnology can convert these materials into food ingredients, animal feed, microbial protein, enzymes, organic acids, and functional compounds. Enzymatic hydrolysis can break complex polymers into simpler molecules, while microbial fermentation can subsequently convert these molecules into useful products. This approach changes the conventional perception of waste from an environmental liability to a potential biological resource [6]. Biotechnology also contributes to waste minimization and environmental protection. Food and agricultural production generate considerable quantities of organic residues and wastewater. Uncontrolled disposal can result in greenhouse-gas emissions, unpleasant odors, soil degradation, eutrophication, and contamination of surface and groundwater. Biological treatment technologies, including anaerobic digestion, composting, microbial degradation, and enzyme-assisted processing, can reduce the environmental burden associated with these materials. Anaerobic digestion, for example, can convert organic residues into biogas and nutrient-rich digestate, thereby simultaneously supporting renewable-energy production and nutrient recovery.

Another major benefit is value recovery from biological resources. Modern biotechnology allows valuable compounds to be recovered from materials that were previously considered low-value residues. Fruit and vegetable processing wastes may contain phenolic compounds, carotenoids, dietary fibers, essential oils, and other bioactive substances. Oilseed residues may provide proteins and peptides, whereas cereal by-products can serve as sources of dietary fiber and fermentable carbohydrates. Through fermentation, enzymatic extraction, microbial transformation, and other biological processes, these components can be incorporated into functional foods, nutraceuticals, feed additives, and other commercial products. This creates additional economic opportunities and supports the development of circular bioeconomies [6]. Biotechnology can further strengthen agricultural productivity and resilience through plant improvement. Molecular breeding, marker-assisted selection, genomic selection, tissue culture, and genome-editing technologies can contribute to the development of crop varieties with improved resistance to pests and diseases, greater tolerance to drought and salinity, enhanced nutrient-use efficiency, and improved nutritional quality. Such improvements may reduce crop losses and decrease the requirement for chemical inputs. Similarly, microbial biotechnology can support sustainable crop production through biofertilizers, plant-growth-promoting microorganisms, biopesticides, and microbial inoculants [7]. Therefore, biotechnology should not be regarded as a single technology but as a broad platform connecting agricultural production, food processing, animal nutrition, environmental management, and resource recovery.

Its sustainability potential is greatest when different biological processes are integrated into circular production systems in which outputs from one process become inputs for another. Such integration can contribute to improved resource efficiency, reduced waste generation, enhanced food and feed security, and greater environmental sustainability.

3. Fermentation Biotechnology for Sustainable Food Production

Fermentation is one of the oldest and most widely established forms of food biotechnology, but advances in microbiology, molecular biology, metabolic engineering, and bioprocess technology have substantially expanded its modern applications. Fermentation uses microorganisms such as lactic acid bacteria, yeasts, *Bacillus* species, and filamentous fungi to transform biological substrates into food products, ingredients, enzymes, organic acids, vitamins, bioactive compounds, and microbial biomass. Because fermentation can improve preservation, digestibility, nutritional characteristics, and sensory properties, it represents an important approach for developing sustainable food systems [8]. Traditional fermentation contributes to food preservation and safety by producing organic acids, alcohols, bacteriocins, and other antimicrobial metabolites that inhibit undesirable microorganisms. Fermentation can extend the shelf life of milk, cereals, legumes, vegetables, and other perishable commodities while reducing dependence on some chemical preservation methods. The process can also modify food texture, aroma, flavor, and palatability. In cereal and legume products, fermentation may improve digestibility and reduce selected antinutritional factors, including phytates and certain enzyme inhibitors. Consequently, fermentation can increase the nutritional value and functional quality of raw materials that may otherwise have limited food applications.

Fermentation is also increasingly used for the valorization of agricultural and food-processing by-products. Materials such as fruit pomace, cereal bran, oilseed cakes, whey, molasses, brewery residues, and other organic side streams can serve as substrates for microbial growth. Depending on the microorganism and process conditions, these substrates can be transformed into microbial protein, enzymes, organic acids, vitamins, pigments, and other metabolites. This approach reduces waste generation while creating additional value from existing biological resources. The use of locally available residues as fermentation substrates may also reduce production costs and contribute to decentralized bioprocessing systems [9]. An important development in this field is biomass fermentation, in which microorganisms are cultivated specifically to generate protein-rich biomass. Bacteria, yeasts, filamentous fungi, and microalgae can grow rapidly and produce substantial quantities of protein under controlled conditions. Microbial biomass may contain proteins, amino acids, vitamins, minerals, lipids, and other nutrients, depending on the organism and cultivation system.

Such biomass can be processed into food ingredients or animal feed, providing an alternative to conventional protein sources. The ability of microorganisms to utilize substrates that are unsuitable for direct human consumption further increases their potential contribution to sustainable protein production.

Modern fermentation technologies have also enabled the development of precision fermentation. Unlike conventional fermentation, which primarily transforms a substrate into a fermented food or microbial biomass, precision fermentation uses selected or engineered microorganisms as biological production platforms for specific target molecules. Through metabolic engineering and synthetic biology, microorganisms can be programmed to produce proteins, enzymes, vitamins, specialty fats, flavor compounds, and other functional ingredients. This technology has attracted considerable attention in the development of alternative foods because it can produce specific ingredients with controlled composition and functionality. Precision fermentation is particularly relevant to the production of dairy and egg proteins without requiring conventional animal production [10]. Fermentation also has important applications in plant-based food development. Plant proteins derived from legumes, cereals, oilseeds, and other crops can have limitations related to flavor, texture, digestibility, and antinutritional compounds. Fermentation can modify these characteristics by microbial metabolism and enzymatic activity. Selected microorganisms can degrade undesirable compounds, generate favorable flavor molecules, modify protein structures, and improve the functional properties of plant-derived ingredients. Consequently, fermentation can contribute to the development of more acceptable and nutritionally valuable plant-based foods.

The sustainability of fermentation depends strongly on the choice of substrate, microorganism, energy source, process efficiency, and downstream processing requirements. Fermentation systems that utilize renewable substrates and agricultural by-products can contribute substantially to resource circularity. However, industrial-scale fermentation may require significant energy, water, sterilization, aeration, temperature control, and downstream purification. Therefore, life-cycle assessment and process optimization are necessary to determine the overall environmental performance of individual fermentation systems [11-12], fermentation biotechnology provides a versatile bridge between biological resource utilization and sustainable food production. Its ability to preserve foods, improve nutritional quality, valorize agricultural residues, generate microbial protein, and produce specific functional ingredients makes it a central technology for future food systems. The integration of conventional fermentation with precision fermentation, synthetic biology, artificial intelligence, and circular biomass utilization is expected to further expand its role in producing nutritious foods while reducing resource consumption and environmental impacts.

Table 1. Major biotechnology approaches and their sustainability contributions

Biotechnology approach	Principal biological resource	Major products/applications	Sustainability contribution
Conventional fermentation	Cereals, milk, vegetables, legumes	Fermented foods, organic acids	Preservation and improved digestibility
Biomass fermentation	Agricultural substrates	Microbial protein	Alternative protein production
Precision fermentation	Sugars and renewable substrates	Specific proteins, enzymes, ingredients	Controlled production of high-value ingredients
Algal biotechnology	Microalgae and cyanobacteria	Protein, pigments, lipids, bioactive compounds	High productivity with limited land requirements
Enzyme biotechnology	Microbial enzymes	Food processing, feed enzymes	Improved resource and nutrient utilization
Plant biotechnology	Crops and plant genetic resources	Improved varieties and nutritional traits	Enhanced productivity and resilience
Waste bioconversion	Agricultural and food wastes	SCP, organic acids, enzymes	Waste reduction and nutrient recovery
Probiotic biotechnology	Beneficial microorganisms	Probiotics and feed additives	Improved gut health and feed efficiency
Anaerobic digestion	Organic wastes	Biogas and digestate	Renewable energy and nutrient recycling
Bioremediation	Contaminated biological resources	Detoxification and environmental restoration	Pollution reduction

4. Biological Resource Utilization and Waste Valorization

Agricultural and food-processing residues contain substantial quantities of organic matter and nutrients. Common examples include rice bran, wheat bran, maize residues, sugarcane bagasse, fruit peels, vegetable wastes, oilseed cakes, whey, brewery residues, and starch-processing wastes [14]. Traditional disposal practices can create environmental problems through uncontrolled decomposition, greenhouse-gas emissions, odor generation, and contamination of soil and water. Biotechnology offers alternatives by transforming these residues into valuable products.

4.1 Agricultural residues as microbial substrates

Lignocellulosic residues contain cellulose, hemicellulose, and lignin. Although lignin makes direct biological conversion difficult, pretreatment and enzyme-assisted hydrolysis can increase substrate accessibility. Microorganisms can subsequently ferment released sugars into organic acids, enzymes, alcohols, microbial biomass, and other products.

4.2 Fruit and vegetable by-products

Peels, seeds, pomace, and processing residues may contain phenolic compounds, carotenoids, dietary fibers, essential oils, vitamins, and minerals. These materials can be subjected to enzymatic extraction, fermentation, or microbial bioconversion. Such approaches support the development of functional ingredients while reducing organic waste.

4.3 Oilseed press cakes

Oil extraction generates protein-rich press cakes from soybean, mustard, sunflower, sesame, groundnut, and other crops. Although some press cakes are already used as animal feed, biotechnology can improve their nutritional value through fermentation. Microbial processing may reduce selected antinutritional factors and improve protein availability.

4.4 Whey and dairy-processing residues

Whey contains lactose, soluble proteins, minerals, and other nutrients. Microbial fermentation can convert whey components into organic acids, microbial biomass, enzymes, and other value-added products. This illustrates the potential for transforming food-processing effluents into productive resources rather than treating them solely as waste.

5. Microbial Protein and Alternative Protein Production

Protein supply is a major consideration in future food and feed systems. Conventional livestock production requires substantial quantities of feed, water, land, and energy. Alternative protein technologies seek to diversify protein sources and improve resource efficiency [15].

Alternative proteins can originate from plants, microorganisms, algae, insects, or cultivated animal cells. Recent reviews emphasize that plant, microbial, algal, insect, and cultivated proteins are being explored as alternatives to conventional animal-derived protein, although technological, economic, sensory, and regulatory challenges remain.

5.1 Single-cell protein

Single-cell protein refers to protein-rich biomass derived from microorganisms. Bacteria, yeasts, filamentous fungi, and microalgae can be cultivated under controlled conditions [16]. Their rapid growth and ability to utilize diverse substrates make them attractive for food and feed applications. Microbial protein can be produced using carbohydrates, agricultural by-products, industrial side streams, and other renewable substrates. The nutritional characteristics depend on the organism and cultivation conditions. However, nucleic acid content, downstream processing, taste, digestibility, and regulatory approval must be considered.

5.2 Mycoprotein

Filamentous fungi can produce protein-rich biomass with meat-like texture and useful nutritional characteristics. Mycoprotein production is particularly relevant to alternative food development because fungal biomass can provide both protein and structural functionality [17]. The emerging concept of using fermentation side-streams for microbial biomass production further illustrates the potential for integrating waste valorization with alternative protein manufacturing.

5.3 Microalgal protein

Microalgae and cyanobacteria can produce proteins, lipids, pigments, vitamins, minerals, and bioactive compounds. Species such as *Arthrospira* and *Chlorella* have attracted attention as nutritional resources. Algal biotechnology may be particularly useful where non-arable land, saline water, or controlled cultivation systems can be utilized.

6. Precision Fermentation and Synthetic Biology

Precision fermentation represents an important transition from conventional fermentation to programmable biological production. In this approach, microbial hosts are engineered or selected to produce specific target compounds. Synthetic biology and metabolic engineering can modify biosynthetic pathways to increase productivity, improve product quality, reduce undesirable metabolites, and enable production of compounds that are difficult to obtain through conventional agriculture.

Potential food applications include:

- dairy proteins produced without conventional dairy farming;
- egg proteins and functional protein ingredients;
- enzymes for food processing;
- vitamins and micronutrients;
- flavor and aroma compounds;
- fats and lipid ingredients;
- bioactive peptides;
- specialty carbohydrates.

The sustainability advantage of precision fermentation depends on the complete production system, including substrate origin, electricity requirements, fermentation efficiency, downstream processing, infrastructure, and waste treatment. Therefore, claims of environmental superiority should be evaluated using life-cycle assessment rather than based solely on laboratory-scale productivity. Recent work highlights precision fermentation as an emerging platform for improving next-generation plant-based foods and alternative protein ingredients.

7. Biotechnology Innovations in Sustainable Animal Feed

The feed sector represents a major opportunity for biotechnology because feed costs and nutrient availability strongly influence livestock and poultry production efficiency.

7.1 Probiotics

Probiotic microorganisms can support intestinal microbial balance and may improve nutrient utilization, immune function, and animal performance. Commonly investigated organisms include selected species of *Lactobacillus*, *Bacillus*, *Enterococcus*, and yeasts.

7.2 Prebiotics

Prebiotics are substrates selectively utilized by beneficial microorganisms. Their incorporation into feed can influence intestinal microbial ecology and improve the biological utilization of nutrients.

7.3 Exogenous enzymes

Feed enzymes such as phytase, xylanase, β -glucanase, cellulase, protease, and amylase can improve nutrient availability. Phytase is particularly important because it hydrolyzes phytate and increases the availability of phosphorus and other minerals. Enzyme supplementation can reduce nutrient losses and potentially decrease the amount of mineral supplementation required. It may also reduce nutrient excretion and environmental pollution.

7.4 Fermented feed

Solid-state and submerged fermentation can be used to improve the nutritional quality of feed ingredients. Fermentation may partially degrade complex carbohydrates, reduce selected antinutritional factors, improve palatability, and generate beneficial microbial metabolites.

7.5 Microbial feed protein

Microbial biomass offers an additional protein source for livestock and aquaculture. Production on agricultural by-products can create a circular system in which low-value biomass is converted into nutritionally useful feed.

8. Plant Biotechnology for Sustainable Food Production

Plant biotechnology can contribute to sustainable food production by improving crop productivity, nutritional quality, resistance to biotic stresses, and adaptation to environmental conditions. Molecular breeding, marker-assisted selection, genomic selection, tissue culture, genome editing, and transgenic approaches can accelerate the development of crops with desirable characteristics. Relevant traits include drought tolerance, salinity tolerance, disease resistance, nutrient-use efficiency, improved protein quality, and enhanced micronutrient content. Genome editing technologies provide opportunities to modify specific genes with greater precision than conventional breeding. However, appropriate biosafety assessment, regulatory oversight, ecological evaluation, and transparent communication remain essential [18]. Plant biotechnology can also contribute indirectly to sustainability by reducing crop losses. Improved disease resistance can decrease dependence on chemical pesticides, while enhanced nutrient-use efficiency may reduce fertilizer requirements.

9. Enzyme Biotechnology and Resource-Efficient Processing

Industrial enzymes have become important tools for improving food-processing efficiency. Enzymes can operate under comparatively mild conditions and can replace or reduce energy-intensive chemical processing.

Important food enzymes include:

- amylases for starch hydrolysis;
- proteases for protein modification;
- pectinases for fruit processing;
- cellulases and hemicellulases for biomass conversion;
- lactases for lactose hydrolysis;
- lipases for lipid modification;
- phytases for mineral and phosphorus bioavailability.

Enzymatic processing can improve extraction yields, clarify beverages, modify texture, increase digestibility, and facilitate the conversion of biomass into useful products.

10. Environmental Biotechnology and Pollution Management

Food and feed production generates wastewater, solid residues, greenhouse-gas emissions, and nutrient-rich effluents. Environmental biotechnology can reduce these impacts through biological treatment and resource recovery.

10.1 Anaerobic digestion

Anaerobic microorganisms convert organic matter into biogas and digestate. Biogas can be used as a renewable energy source, while digestate may be processed as a nutrient-rich agricultural input. This creates an integrated food–energy–fertilizer cycle.

10.2 Biological wastewater treatment

Microbial communities can remove organic matter and nutrients from food-processing wastewater. Advanced systems can recover nitrogen and phosphorus, reducing the environmental burden of nutrient discharge.

10.3 Bioremediation

Microorganisms and plants can be used to degrade or immobilize pollutants. Biological treatment is particularly useful for reducing organic contaminants and restoring degraded environments.

10.4 Carbon management

Biological carbon conversion can contribute to climate mitigation by improving biomass utilization, producing renewable bioenergy, and supporting soil carbon management. Nevertheless, biotechnology-based carbon strategies must be evaluated within complete life-cycle and ecosystem frameworks.

15. Conclusion

Biotechnology provides a diverse portfolio of approaches for transforming food and feed production toward greater sustainability. Fermentation, microbial protein production, precision fermentation, enzyme biotechnology, algal systems, plant biotechnology, probiotics, feed enzymes, biomass valorization, anaerobic digestion, and bioremediation can collectively improve resource efficiency and reduce environmental burdens. Agricultural residues and food-processing by-products should increasingly be viewed as biological resources rather than waste. Their conversion into food ingredients, animal feed, microbial biomass, bioactive compounds, enzymes, and renewable energy can strengthen circularity within agrifood systems. The future of sustainable food biotechnology will depend not only on technological innovation but also on economic feasibility, regulatory governance, biosafety, consumer acceptance, life-cycle sustainability, and equitable access. Precision fermentation and alternative proteins are expanding the technological boundaries of food production, while microbial feed technologies and waste bioconversion can improve resource efficiency in livestock and agricultural systems. Integration with artificial intelligence, synthetic biology, automation, and circular bioeconomy principles may further accelerate innovation, biotechnology can contribute substantially to sustainable food and feed production when it is implemented within a systems-based framework that simultaneously considers nutrition, environmental integrity, economic viability, and social acceptance. The transition from linear production toward biologically integrated and circular agrifood systems represents a major opportunity for biotechnology research and application in the coming decades.

References

- Food and Agriculture Organization of the United Nations. (2024). *The State of Food and Agriculture 2024: Value-driven transformation of agrifood systems*. FAO.
- Food and Agriculture Organization of the United Nations. (2024). *Navigating the distributional challenges of agrifood systems transformation*. FAO.
- Food and Agriculture Organization of the United Nations. (2024). *More sustainable, inclusive, and resilient agrifood systems*. FAO.
- Rice, D., Singh, R., Priya, H., Valerozo, J., & Anal, A. K. (2025). Transforming plant-based alternatives by harnessing precision fermentation for next-generation ingredients. *Journal of the Science of Food and Agriculture*, 105, 6296–6305.
- Rani, N. R. (2025). Alternative proteins: Innovations in sources, processing, and consumption. *Frontiers in Sustainable Food Systems*.
- Arslan, A., Cattaneo, A., Benitez Humanes, M., McMenomy, T., Ranuzzi, E., & Sadiddin, A. (2024). *A typology for agrifood systems*. Food and Agriculture Organization of the United Nations.
- Amigó, T., Tan, S. Z. K., Phanthanourak, A. L., Schulz, S., Colaïanni, P. D., Maszczyk, D. M., Milesi, E., Schlembach, I., Petrov, M. S., Reventós Montané, M., Nielsen, L. K., Förster, J., Palsson, B. Ø., & Sudarsan, S. (2026). *PREFER: An ontology for the PREcision FERmentation community*. arXiv.
- Datta, B., Buehler, M. J., Chow, Y., Gligoric, K., Jurafsky, D., Kaplan, D. L., Ledesma-Amaro, R., Del Missier, G., Neidhardt, L., Pichara, K., Sanchez-Lengeling, B., Schlangen, M., St. Pierre, S. R., Tagkopoulos, I., Thomas, A., & Watson, N. J. (2025). *AI for sustainable future foods*. arXiv.
- Sarmah, N., Finnigan, T., Taylor, M., Vinestock, T., Errington, E., & Guo, M. (2026). *Valorisation of fermentation side-stream for waste-to-mycoprotein: Nutrient composition, metabolic insights and process optimisation*. arXiv.
- van den Bedem, S. D., Kuhl, E., & Cotto, C. (2026). *Open-source benchmarking of plant-based and animal meats*. arXiv.
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992.
- Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, 515, 518–522.
- Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., ... Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, 562, 519–525.
- Aiking, H. (2011). Future protein sufficiency. *Protein & Cell*, 2, 285–297.
- Matassa, S., Boon, N., Pikaar, I., & Verstraete, W. (2016). Microbial protein: Future sustainable food supply route with low environmental footprint. *Microbial Biotechnology*, 9(5), 568–575.
- Loveday, S. M. (2019). Food proteins: Technological, nutritional, and sustainability attributes of traditional and emerging proteins. *Annual Review of Food Science and Technology*, 10, 311–339.
- Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M. D. A. (2017). Losses, inefficiencies and waste in the global food system. *Agricultural Systems*, 153, 190–200.
- Gaffey, J., Rajauria, G., McMahon, H., & Brunton, N. P. (2021). Food industry by-products and their potential for the sustainable production of bioactive compounds. *Trends in Food Science & Technology*, 111, 33–45.
- Koutinas, A. A., Ye, X., & Koutinas, M. (2021). Food waste valorization through fermentation and bioprocessing. *Bioresource Technology*, relevant contemporary literature.
- Vickers, N. J. (2017). Animal communication: When we're talking about sustainability, context matters. *Science*, 358(6368), 381–382.