frontiers | Frontiers in Science

TYPE Frontiers in Science Editorial
PUBLISHED 23 October 2025
DOI 10.3389/fsci.2025.1706475

OPEN ACCESS

EDITED BY
Frontiers Editorial Office,
Frontiers Media SA, Switzerland

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RECEIVED 16 September 2025
ACCEPTED 29 September 2025
PUBLISHED 23 October 2025

CITATION
Schloter M and Schulz S.
Microbiomes at the heart of sustainable agri-food systems and global health.
Front Sci (2025) 3:1706475.
doi: 10.3389/fsci.2025.1706475

Microbiomes at the heart of sustainable agri-food systems and global health

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KEYWORDS

microbial communities, agriculture, crop production, food processing, One Health

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

Key points

- Healthy food requires healthy microbiomes: from soil to the human gut, microbial communities shape nutrient quality, food safety, and resilience.
- Food systems and health are inseparable: managing microbiomes supports both sustainable agriculture and disease prevention, aligning with the One Health framework.
- Microbes offer natural solutions to improving food systems: biocontrol, probiotics, and fermentation can reduce waste, replace antimicrobials, and enrich diets.
- Future priorities should be emphasized: research must shift from taxonomy to function, regulatory issues must be considered, and equitable global availability must be ensured for microbiome innovations.

The accelerating convergence of climate change, biodiversity loss, and food insecurity represents one of the defining challenges of this century. Agri-food systems are under increasing pressure to deliver safe, nutritious, and sufficient food while limiting environmental harm, prompting the search for new scientific approaches to guide innovation. Among these, microbiome research has emerged as both transformative and integrative. In their lead article in Frontiers in Science, "Harnessing agri-food system microbiomes for sustainability and human health," Fernández-Gómez et al. (1) highlight the pivotal role of microbial networks across soils, aquatic environments, crops, livestock, food processing, and human health. Their review provides a timely anchor for this special editorial project, positioning microbiomes at the intersection of sustainability, resilience, and the One Health framework.

From meta-omics to modulation

Rapid advances in meta-omic tools—including metagenomics, metatranscriptomics, metaproteomics, and metabolomics—have enabled the past decade of microbiome research. These approaches allow researchers to move beyond cataloguing microbial communities to uncovering functional roles and ecological interactions. Applications range from outbreak detection and food safety monitoring to mapping microbial transmission between mothers and infants and exploring phage–host interactions that underpin ecosystem resilience.

Yet the true promise lies in the ability to intervene. Strategies such as probiotics, prebiotics, biocontrol agents, and synthetic consortia open possibilities for designing more resilient agri-food systems (2). The main challenge remains in scaling these laboratory successes to real-world contexts, where ecological complexity, socio-economic factors, and regulatory uncertainty complicate translation.

Microbiomes in the One Health concept: a connective infrastructure

Advances in methodology have made it increasingly clear that microbiomes should not be viewed as isolated units but instead as dynamic, interconnected systems that span soil, water, plants, animals, and humans. They regulate nutrient cycling, contribute to disease resistance, shape food quality, and ultimately influence health outcomes (3). This ecological continuity makes it useful to think of microbiomes as infrastructure: the largely invisible scaffolding that supports agri-food systems. Fernández-Gómez et al. (1) describe how microbial communities intersect in multiple ways—from rhizosphere interactions that drive crop productivity to rumen microbes influencing greenhouse gas emissions and from spoilage organisms in distribution chains to fermentation processes that enrich dietary diversity.

By embedding microbiomes within a One Health perspective, this work broadens the concept of food system sustainability beyond efficiency metrics to encompass planetary and public health. Sustainability, in this framing, becomes a matter of microbial stewardship.

From soil to sea: microbiomes as drivers for sustainability

Nowhere is the potential of microbiome science more apparent than in primary production. Microorganisms in soil and on plants influence nutrient cycling, protect crops from stress, and shape food quality. By improving nitrogen fixation, mobilizing phosphorus, or producing metabolites that enhance plant resilience, soil microbes contribute directly to crop nutrition (4). For example, microbial inoculants can boost mineral uptake and improve yields under drought or salinity stress (5). These microbiomes also affect food safety: the phyllosphere can carry beneficial or harmful microbes that are transferred to edible products. Understanding and managing these communities are critical for delivering fruits and vegetables that are not only abundant but are also safe for consumption.

Animal-associated microbiomes shape feed conversion, growth, and disease resistance. In ruminants, the rumen microbiome influences productivity and methane emissions; targeted dietary interventions can both enhance feed efficiency and reduce greenhouse gas emissions. In aquatic systems, microbial communities sustain oxygen production and nutrient cycles while underpinning aquaculture productivity (6). Healthy animal microbiomes therefore contribute to both high-quality food production and public health, exemplifying the One Health perspective.

Microbiomes also provide a natural barrier for disease. Probiotic and prebiotic strategies in dairy, poultry, and aquaculture systems can lower pathogen loads, reducing the need for antimicrobials and supporting global efforts to combat antimicrobial resistance (2).

As Fernández-Gómez et al. (1) note, poor management, such as fertilizer runoff or heavy antimicrobial use, destabilizes these microbial networks, spreading antimicrobial resistance and driving ecosystem decline. Conversely, practices such as biofertilizers and integrated multi-trophic aquaculture exemplify how microbiome-informed approaches can balance productivity with ecological integrity. Microbiome science also offers concrete ways to mitigate agriculture's contribution to climate change, particularly through reducing nitrous oxide and methane emissions.

Microbiomes in the food chain: from spoilage to fermentation

Food loss and waste remain major inefficiencies, with nearly half of fresh food products spoiling post-harvest (7). Microbiome insights provide opportunities to extend shelf life and improve safety while also enhancing functionality. Examples include lactic acid bacteria that protect shrimp against pathogens (8) and yeast-based treatments that limit spoilage in strawberries (9).

At the same time, fermentation illustrates the long history of beneficial microbiome use in food systems. Fermented foods not only reduce waste but also deliver live microbes and bioactive compounds that contribute to gut health, counteracting the microbiome-depleting effects of ultra-processed foods. Future innovations will need to carefully balance safety considerations with efforts to restore microbial diversity in the human diet.

The human dimension: diet, gut microbiota, and health

The impact of food system microbiomes ultimately converges in the human gut. Dietary patterns, from fiber-rich plant-based diets to high-fat Western diets, profoundly influence microbial diversity and shape risks for non-communicable diseases. Loss of microbial diversity is becoming increasingly associated with obesity, cancer, and gut–brain disorders (10).

Interventions such as fermented foods, probiotics, and prebiotics offer avenues for restoring microbial functions. These strategies extend beyond individual nutrition, representing public health interventions with the potential to alter population-level disease burdens. Incorporating microbiome science into dietary policy could therefore benefit both healthcare and sustainability agendas.

Direct microbial transmission from food to the gut can enrich diversity. For instance, studies have documented how maternal microbes, including *Bifidobacterium*, are transferred through diet-related pathways to infants, shaping immune development. This highlights the promise of microbiome-aware dietary strategies—probiotics, prebiotics, and functional foods—as medical nutrition tools for preventing gastrointestinal and metabolic disorders (2).

Governance and education: the path forward

Scientific progress has outpaced governance frameworks. As Fernández-Gómez et al. (1) observe, there is no standardized approach for evaluating the safety, efficacy, and environmental implications of microbiome-based products. Regulators face the dual task of enabling innovation while protecting public interests.

Education is equally critical. Farmers, industry actors, consumers, and policymakers all need a clearer understanding of microbial stewardship to support adoption and prevent misuse. Embedding microbiome literacy into curricula and consulting services will be key to fostering cultural change. Addressing inequities in microbiome science is also essential: innovations should not remain the privilege of high-income regions but must instead be made accessible to the communities most vulnerable to food insecurity and biodiversity loss.

Conclusion: microbial stewardship for a resilient future

The call from the World Health Organization (WHO) for healthier diets cannot be met without transforming how we view and manage microbiomes. Microbes shape the safety, quality, and health-promoting properties of food at every step—from soil fertility to human digestion. They are not invisible passengers but active partners in food production and public health.

The review from Fernández-Gómez et al. underscores a central point: microbiomes are not peripheral but fundamental to food system resilience, sustainability, and health. As this "lead article and its hub" demonstrate, microbiome research offers a unifying framework through which agri-food challenges can be reimagined.

Moving forward will require integrative and transdisciplinary thinking: coupling cutting-edge technologies with ecological principles, aligning innovation with regulation, and ensuring equitable access to solutions. Above all, it will require a commitment to microbial stewardship. If guided wisely, microbiomes may become critical allies in navigating the converging crises of climate change, food insecurity, and human health—shaping resilient futures through largely invisible means.

Statements

Author contributions

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

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

Funding

The authors declared that no financial support was received for this work and/or its publication.

Conflict of interest

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

The author MS declared a past co-authorship with the lead article authors AS, EM, TCC, PDC, LL, IS, HS, GB, LSC, YS, and TK. The author SS declared a past co-authorship with the lead article authors TK and GB.

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

Generative AI statement

The authors declared that no generative AI was used in the creation of this manuscript.

Publisher's note

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