

## **A review of life-cycle benefits of emerging food technologies: gauging global potentials.**

Emerging food technologies are frequently proposed as solutions for reducing the environmental impacts of food systems, yet their sustainability benefits depend strongly on how they are implemented and evaluated. This presentation reviews the life-cycle greenhouse gas (GHG) implications of several emerging food technologies and synthesizes quantitative findings from recent life-cycle assessment (LCA) studies. The analysis focuses on technologies that are increasingly discussed in the context of sustainable food systems, including precision-fermentation proteins, food by-product upcycling, shelf-life extension technologies, shelf-stable food systems, and advanced thermal processing.

The review first establishes a quantitative baseline by comparing the life-cycle GHG emissions of conventional protein sources. Published estimates suggest that ruminant meat proteins typically emit approximately 300 – 600 kg CO<sub>2</sub>-equivalent per kg protein, whereas plant proteins such as soy or pea typically emit about 4 – 20 kg CO<sub>2</sub>-equivalent per kg protein. Emerging fermentation-based proteins exhibit emissions ranging from roughly 5 – 60 kg CO<sub>2</sub>-equivalent per kg protein depending largely on electricity carbon intensity, fermentation yield, and downstream processing requirements. These comparisons illustrate both the potential for significant reductions and the large variability observed across studies.

Across emerging technologies, several recurring mechanisms explain observed environmental benefits. These include the avoidance of agricultural emissions through alternative protein production, reductions in food loss and waste through shelf-life extension technologies, the elimination or reduction of cold-chain energy demand through shelf-stable products, and improvements in processing efficiency through advanced thermal technologies. At the same time, the review highlights several dominant drivers that frequently determine environmental outcomes, including electricity consumption, processing energy demand, packaging materials, ingredient substitution assumptions, and real-world food waste reduction rates.

A key finding across the literature is that environmental performance varies widely depending on system context and methodological assumptions. Life-cycle results are particularly sensitive to functional unit definitions, system boundaries, allocation choices, and the treatment of avoided burdens. In many cases, avoided production—such as reduced food waste or displaced high-impact ingredients—accounts for a larger share of environmental benefits than the efficiency of the new technology itself.

Overall, the synthesis suggests that emerging food technologies are often conditionally beneficial rather than inherently sustainable. Their environmental performance depends strongly on electricity carbon intensity, supply-chain configuration, and the extent to which they replace higher-impact products or practices. Life-cycle assessment therefore remains essential for identifying where technological innovation can deliver genuine environmental improvements across the food system.