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Sustainable food systems: The role of food technology in reducing waste and improving food security

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Abstract
Food systems are under tremendous strain due to resource shortages, climate change and population increase worldwide. At the same time, about one-third of the food produced globally is lost or wasted each year, making food waste one of the most urgent issues. By creating creative solutions for sustainable food systems, food technology has become a key force in tackling these issues. The report outlines recent developments, obstacles and opportunities for using technology into global food systems to guarantee resilience, equality and sustainability.

In addition to reviewing the scope and causes of food loss and waste (FLW), this study looks at how food technology-including digital platforms, processing and preservation, post-harvest cold chains, smart and active packaging and up cycling-reduces waste and improves food security. We present an integrated framework for technology deployment, combine current data, case studies and technology effect evaluations and offer practical and policy suggestions for low-, middle-and high-income contexts. The study comes to the conclusion that in order to achieve equitable food systems, systemic action, inclusive governance and capacity building are needed; technology alone is not enough.

Keywords: Alternative proteins, food security, food technology, food waste, packaging, sustainable food systems, supply chain

1. Introduction

The difficulties facing the global food system are unprecedented. Nearly 828 million people go hungry every year and over 1.3 billion tons of food are wasted, according to the Food and Agriculture Organization (FAO). Inefficiencies in systems of production, distribution and consumption are highlighted by this paradox. The goals of sustainable food systems are to guarantee economic and social justice, reduce environmental effects and supply enough nourishment. A key component of creating sustainability is food technology, which is the application of scientific and technical concepts to the production, processing, distribution and preservation of food. It may improve nutritional quality, decrease waste and build robust food supply networks through creative methods.

Food waste happens on several levels: (i) Production stage: Post-harvest losses brought on by inadequate infrastructure, incorrect handling and storage. (ii) Processing and distribution: Poor packaging, spoiling and ineffective logistics. Furthermore, 8-10% of greenhouse gas emissions worldwide are caused by food waste, which exacerbates climate change. Resolving this issue is essential to attaining environmental sustainability and food security.

2. Materials and Methods

2.1 Research Design

This study combines the collecting and synthesis of secondary data in a descriptive and analytical research approach. Peer-reviewed journal results, government papers (FAO, UNEP, World Bank, IFPRI) and case studies describing technology interventions in food systems are all incorporated into the article. To evaluate the contribution of enhancing food security, both qualitative and quantitative evaluations were used.

2.2 Data Sources
Several trustworthy sources of information were used, including the FAO's Global Food Loss Index (2019-2023). Reports on the UNEP Food Waste Index (2021, 2024). Post-harvest loss data sets at the national level (India, Kenya, Brazil, USA). Peer-reviewed journals (Elsevier, Springer, Taylor & Francis) have published a variety of works. Government reports and industry white papers about packaging and cold chain technology. Using keywords like "food technology," "food waste reduction," "cold storage innovation," "smart packaging," "food technologies reduce loss and waste," and "technology in reducing waste and and food security," literature searches were carried out using Google Scholar and Science Direct.
The inclusion criteria were research that reported quantifiable effects or statistics on FLW reduction and were published between 2011 and 2025. 65 of the more than 100 assessed sources satisfied the requirements for inclusion in the in-depth study.

2.3 Data Analysis
Data for various technologies were tallied and contrasted. Using percentage computations and comparison summaries, quantitative data (percent decrease in food loss, increase in shelf life and cost-benefit ratios) were descriptively examined. To determine the main categories of technologies, enabling factors and adoption hurdles, qualitative data were subjected to thematic analysis.

3. Results and Discussion
3.1 Processing and Preservation Technologies for food waste reduction
UV therapy, pulsed electric fields and high-pressure processing (HPP) increase shelf life without sacrificing nutritional value. One of the most effective no thermal technologies to hit the food processing market in recent years is high-pressure processing (HPP). To accomplish pasteurization effects, high pressure is used, often between 450 and 600 MPa in the food business. HPP is frequently used to extend the shelf life of foods that are primarily reduced or additive-free. Compared to other pasteurization methods, such as thermal pasteurization, it can inactivate the pathogenic vegetative bacteria and enzymes that cause spoiling in food items at and below room temperature with greater preservation of micronutrients and less changes in sensory qualities. Effect of HPP for food waste reduction are shown in table 1

Table 1: High-pressure processing (HPP) of foods for commercial usage by businesses to improve microbiological food safety

Food category	Food type and the relative significance of HPP-containing food compared to other food kinds that employ HPP	Reasons	HPP conditions	References
Meat and meat products	Hot dogs, deli meat, ready-to-eat sliced meatsand other prepared, comminuted meat items	Extension of shelf life; decrease of pathogens (*Salmonella*, *E. coli* O157:H7, *Listeria monocytogenes*, *Staphylococcus aureus* and *Campylobacter*);	400-600 MPa/2-4 min/4-8 °C	Koutsoumanis *et al*., 2022 [8]; Iqbal *et al*., 2022 [1]
Juices, fruits, vegetables and other goods	High acid fruit/veg juices	Pathogen reduction; shelf-life extension	600 MPa/3 min/5 °C	Koutsoumanis *et al*., 2022 [8]; Iqbal *et al*., 2022 [1]

The meat business has a long history of using HPP. HHP is a novel non-thermal post-packaging decontamination technique that has mostly been applied in the RTE meat products market (Meloni, 2019) [10]. The effectiveness of HPP in enhancing the safety of raw meat and meat products has been shown in several research. Jofre and Serra (2016) [7] summarized the inactivation levels of *L. monocytogenes* in various meat products treated to HPP as well as the effective uses of HPP in meat and meat products.
Vacuum packaging and freeze-drying both lessen microbial spoiling. In order to meet industry demands and consumer expectations, the five papers that were published in this special issue of highlighted the primary obstacles in the ongoing research on freeze-drying and identified ways to improve the method's convenience and preserve product quality (Sagar Bhattan *et al*., 2020; Maril *et al*., 2020; Pablo Munzenmayer *et al*., 2020) [15, 9, 12].
As substitutes for chemical additives, new natural preservatives are being created, such as plant extracts and essential oils (Teshome *et al*., 2022) [16]. Natural food preservatives having a broad spectrum of antibacterial activity are sought after by researchers and food processors. Natural antioxidants, natural edible coating agents and antimicrobial compounds are all vital tools for shielding foods and associated products from the damaging effects of bacteria and other deterioration processes. The most often used plants by the food industry as natural antimicrobials to reduce food-borne viruses and extend food shelf life include fruits, vegetables, herbs and spices. The most prevalent antimicrobial substances in mammals are peptides, also known as polypeptides.
Numerous compounds produced by microorganisms may be useful in combating harmful and decaying germs. The majority of microbially derived antibacterial chemicals are produced as byproduct metabolites during the fermentation of food. Food shelf life can be increased by applying edible coating and antibacterial compounds made from bacterial cells are shown in table 2.
Spoilage is postponed by active packaging that has oxygen-scavenging or antibacterial qualities. Biopolymers (chitosan, starch and alginate) are used to make edible films and coatings that prolong freshness and cut down on plastic usage. By providing real-time information on food safety and quality, smart labels and sensors help to prevent the premature disposal of edible goods. By guaranteeing traceability, block chain technology lowers losses due to contamination or recalls. sensors from the Internet of Things and artificial intelligence (AI). maximize logistics and storage conditions. In distant locations, cold chain improvements like solar-powered refrigeration reduce spoiling. The creation of alternate proteins and carbohydrates is another way that food technology contributes to increased food security. Sustainable substitutes for traditional cattle include lab-grown meat, insect proteins and plant-based meat substitutes. Nutrient-dense food sources with less of an impact on the environment are provided by algae biotechnology.

Table 2: Food shelf life can be increased by applying edible coating and antibacterial compounds made from bacterial cells.

S. No	Food additives	Application & results	Reference
1.	Chitosan (antimicrobial agent)	On star fruits (*Averrhoa carambola* L.), chitosan-stearin edible coatings can preserve their firmness and attractiveness while extending their shelf life at low temperatures.	Teshome *et al*., 2022 [6]
2.	Chitosan (antimicrobial agent)	An efficient technique for delaying the "berangan" banana ripening process in ambient air is the chitosan-glycerol coating.	Jafarizadeh *et al*., 2011 [6]
3.	Alginate and sunflower oil (antioxidation agent)	impacts of applying various edible coatings on fresh-cut apples in order to prolong their shelf life. Whey from milk protein and soy from plant protein are used for coatingand sunflower oil is added to enhance the fruit's quality.	Ghavidel *et al*. 2013 [4]
3.	Garlic, cinnamon (antimicrobial agent and anti-oxidation agent	As a natural meat and fish preservation, gum acacia edible coating combined with garlic and cinnamon demonstrates the antibacterial and antioxidant properties of these spices. The microbial presence decreases week by week and the shelf life is prolonged to three weeks.	Rakshit and Ramalingam 2003 [14]
5.	Organic acids	create a selective barrier against nonacidophiles by lowering the pH of the surrounding environment. By interfering with membrane potential and rupturing the cytoplasmic membrane, lactic acid has an antibacterial impact.	Teshome *et al*., 2022 [6]
6.	Bacteriocins (Nisin)	Bacteriocins can prevent food-borne pathogens such *Listeria monocytogenes*, *Enterococcus faecalis* and *Clostridium botulinum*.	Agriopoulou *et al*., 2020 [2]
7.	Lactic acid bacteria (LAB)	The primary biocontrol agents are lactic acid bacteria (LAB), which are considered to create hydrogen peroxide, which prolongs the shelf life of perishable goods. It has probiotic and antibacterial properties.	Teshome *et al*., 2022 [6]

The technique of fortifying food items with vital elements (such vitamins and minerals) to increase their nutritional value and stop population deficits is known as fortification.

The process of boosting a crop's nutritional value using biological methods, such as plant breeding, genetic engineering, or agronomic techniques, is known as biofortification. Malnutrition is addressed with food fortification with micronutrients (iron, vitamin D and iodine). At the production stage, nutritional value is improved through genetic engineering and biofortification techniques (such as iron-rich beans and Golden Rice). AI, dronesand remote sensing assist farmers in managing pests, fertilizing cropsand optimizing irrigation to raise yields in a sustainable manner. By ensuring year-round output in urban settings, vertical farming and hydroponics lessen reliance on conventional farmlands.

4. Scale and Impact of Food Loss and Waste

Roughly one-third of the food produced for human consumption is lost or wasted each year, or more than a billion tons, according to estimates from significant international surveys. FLW has serious negative effects on the environment and society. It wastes freshwater and land resources, considerably increases greenhouse gas emissions and impedes attempts to eradicate hunger. Consumer-level waste is higher in higher-income countries but also plays a significant role in urbanizing middle-income contexts. The spatial distribution of losses varies by region and commodity. In low-and middle-income countries, post-harvest losses are particularly high for perishable fruits, vegetables, fish and roots/tubers because of inadequate cold chains and storage.

Beyond quantity, FLW increases price volatility and decreases the amount of effective food accessible to disadvantaged groups. Therefore, lowering supply chain losses helps stabilize supplies and boost actual food availability—two steps toward greater food security.

5. Challenges and Future Directions

Food technology has encouraging prospects, yet there are still obstacles to overcome: Access in low-income areas is restricted by the high cost of sophisticated technology. Different cultures have different levels of consumer acceptability for new meals (such as cultured meat and insect proteins). Certain technology' energy use raises environmental issues that need to be properly addressed. Gaps in policies and regulations prevent new techniques from being widely adopted. Future studies should concentrate on: Applying the concepts of the circular economy to food systems (e.g., turning food waste into animal feed or biofuel). promoting low-cost, energy-saving solutions for poor nations. extending the use of data to inform decisions in food supply chains. strengthening international cooperation to provide fair access to food technology.

6. Conclusion

A comprehensive strategy that tackles waste reduction and food security at the same time is needed for sustainable food systems. Food production, processing, packaging and distribution might all be revolutionized by food technology. Societies can drastically cut losses while maintaining nutritional security for expanding populations by utilizing advancements in alternative food production, packaging, supply chain management and preservation. However, success depends on consumer acceptability, legislative backing and fair execution. Food technology must thus be seen as a crucial facilitator within a larger framework of sustainability rather than as a stand-alone solution.

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