International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 10s, 2025
https://theaspd.com/index.php

Food Preservation Technologies, Biotechnology In Agriculture And Environmental Sustainability: An Integrated Approach To Agrifood Systems

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Summary
Food security, environmental sustainability and technological innovation in agriculture have become fundamental axes to face the global challenges derived from climate change, urbanization and population growth. This article explores the intersection between food preservation technologies, advances in agricultural biotechnology, and sustainable approaches that seek to transform agrifood systems. Through a theoretical review and comparative analysis of recent studies, integrated practices that improve supply chain efficiency, reduce food waste, and promote ecological resilience are examined. The results show that the synergistic implementation of these strategies favours the transition towards more sustainable and resilient agri-food models.
Keywords: *food preservation, agricultural biotechnology, environmental sustainability, agri-food systems, technological innovation.*

INTRODUCTION

The global agri-food system is at a critical stage of transformation. Population growth projected to exceed 9,700 million people by 2050 poses serious challenges in terms of food production, distribution and preservation (FAO, 2021). At the same time, climate change, biodiversity loss, and the depletion of natural resources are putting unprecedented pressure on traditional agriculture, demanding more resilient, efficient, and sustainable systems (González-Muñoz et al., 2022).In this scenario, the implementation of **emerging technologies** has become a priority strategy. Advanced **food preservation**, including methods such as ionizing irradiation, active packaging, high-pressure treatments, and nanotechnology, represents an effective solution for reducing post-harvest losses, extending the shelf life of food, and maintaining its nutritional and microbiological quality (Zhao, Wang, & Tang, 2023; Zhou, Zhang, & Sun, 2021). These losses represent up to 30% of global food production, generating not only economic impacts, but also environmental consequences due to the waste of resources used in its production (Singh, Rani, & Thakur, 2022).On the other hand, **agricultural biotechnology** has revolutionized production processes by creating crops that are more resistant to abiotic stress, developing biofertilizers, gene editing with CRISPR, and improving microorganisms that strengthen soil health (Kwon, Lee, & Kim, 2021). These innovations not only increase yield and food safety, but also decrease the use of agrochemicals, contributing to environmental and human health (Ramírez-

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Gómez, Ortega, & Villegas, 2023).Environmental **sustainability**, as the third axis of analysis, is today a guiding principle for the redesign of agri-food systems. Comprehensive approaches are required that consider ecological cycles, energy efficiency, water management, carbon footprint, and the well-being of rural communities. Models such as regenerative agriculture, the circular economy, and digital agroecology have begun to integrate with cutting-edge technologies to create more balanced agroproductive ecosystems (Liu & Huang, 2020; Adeleke, Adedokun, & Ajiboye, 2022).

Therefore, this article proposes a comprehensive analysis of the intersection between **preservationtechnologies**, **agricultural biotechnology**, and **environmental sustainability**, exploring how their synergy can drive the transition to **smart, resilient, and sustainable** agrifood systems. Through a critical review of recent literature, it seeks to identify the main strategies and advances that reduce losses, improve agricultural productivity and minimize environmental impact, thus contributing to the fulfillment of the Sustainable Development Goals (SDGs), especially those related to zero hunger (SDG 2), responsible production and consumption (SDG 12). and climate action (SDG 13).

Theoretical Framework

The development of sustainable agrifood systems requires a solid conceptual foundation that articulates three fundamental pillars: **food preservation technologies**, **biotechnology in agriculture**, and **environmental sustainability**. These components, approached from a systemic and integrative perspective, make it possible to identify opportunities to reduce losses, improve production efficiency and reduce the ecological impact of the agricultural sector.

1. Food Preservation Technologies

Preservation technologies have evolved towards increasingly sophisticated methods, capable of maintaining the organoleptic and nutritional quality of food while ensuring its microbiological safety. Traditional methods such as refrigeration or drying have been complemented by innovations such as:

- **High Hydrostatic Pressure (HPP):** Destroys microorganisms without altering sensory properties (Zhou et al., 2021).
- **Food Irradiation**: Uses gamma rays or accelerated electrons to extend shelf life without chemical residues (Singh et al., 2022).
- **Smart and Active Packaging**: Includes sensors to monitor the condition of the food, as well as controlled release of antimicrobials (Zhao et al., 2023).

These technologies are essential to reduce post-harvest losses, which account for 14% of food produced globally, especially in regions with limited infrastructure (FAO, 2021).

Table 1. Food preservation technologies and their impact

TECHNOLOGY	MAIN FUNCTION	KEY BENEFITS	FOUNTAIN
HIGH HYDROSTATIC PRESSURE (HPP)	Heat-free microbial inactivation	Preserves flavor, texture and nutrients	Zhou et al. (2021)
IRRADIATION	Elimination of pathogens and pests	Increases shelf life, leaves no chemical residue	Singh et al. (2022)

ACTIVE & SMART PACKAGING	Monitoring and conservation	Reduce waste, improve traceability	Zhao et al. (2023)
BIOCONSERVATION	Use of beneficial microorganisms	Natural technique, good consumer acceptance	González-Muñoz et al. (2022)

2. Biotechnology in Agriculture

Biotechnology applied to modern agriculture offers effective solutions to meet the challenges of productivity, climate resilience and soil health. The most representative techniques include:

- **Gene editing with CRISPR-Cas9**: Allows precise modifications in the DNA of crops to improve characteristics such as resistance to drought or diseases (Kwon et al., 2021).
- **Biofertilizers and biostimulants**: They replace synthetic fertilizers and promote a healthy soil microbiota (Ramírez-Gómez et al., 2023).
- **New generation GM crops**: Designed for high yields and water use efficiency (Adeleke et al., 2022).

These applications reduce the environmental impact of intensive agriculture and contribute to sustainable management of the agricultural ecosystem.

Table 2. Biotechnological applications in agriculture

BIOTECHNOLOGICAL TECHNIQUE	MAIN APPLICATION	ENVIRONMENTAL BENEFIT	FOUNTAIN
CRISPR-CAS9	Gene editing in crops	Reduction of agrochemicals and greater genetic efficiency	Kwon et al. (2021)
BIOFERTILIZERS	Chemical fertilizer substitution	Soil improvement, less pollution	Ramírez-Gómez et al. (2023)
RESILIENT GM CROPS	Adaptation to water and saline stress	Lower water consumption and marginal land use	Adeleke et al. (2022)
FIXING MICROORGANISMS	Inoculation in roots	Natural atmospheric nitrogen capture	González-Muñoz et al. (2022)

3. Environmental Sustainability in Agri-Food Systems

Environmental sustainability implies the rational use of natural resources within a framework of intergenerational justice. In modern agri-food systems, this concept includes:

- **Reducing the carbon and water footprint**: Through precision agriculture, remote sensing, and drones (Liu & Huang, 2020).
- **Circular economy**: Use of agricultural waste to produce bioenergy or organic inputs (FAO, 2021).
- **Digital agroecology**: Using big data and artificial intelligence to optimize agricultural decision-making (Adeleke et al., 2022).

These strategies strengthen the system's resilience to climate change, while protecting biodiversity and encouraging regenerative practices.

METHODOLOGY

This study was developed under a **qualitative approach with an exploratory-descriptive design**, supported by a **systematic review of scientific literature** and complemented with a thematic content analysis technique. The methodology used made it possible to identify the main emerging technologies in food preservation and agricultural biotechnology, as well as their interrelation with the principles of environmental sustainability applicable to agri-food systems.

1. Methodological design

The guidelines of the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) were followed to ensure the transparency and rigor of the review process (Page et al., 2021). The strategy consisted of collecting, filtering, classifying and analysing relevant studies published between 2019 and 2024.

Table 1. General design of the methodological process

Stage	Activities carried out	Tools used
Data collection	Search scientific databases (Scopus, Web of Science, ScienceDirect) with combined keywords	Mendeley, Zotero, Google Scholar
Selection	Application of inclusion and exclusion criteria	Automatic filters and manual review
Analysis	Thematic coding and synthesis of results	Analysis matrix in Excel
Validation	Cross-review of academic peer studies	Comparison with grey literature

2. Inclusion and exclusion criteria

Rigorous criteria were established for the selection of sources:

- **Inclusion criteria**:
  - Studies published between 2019 and 2024.
  - Peer-reviewed scientific papers.
  - Publications in English or Spanish.
  - Research focused on: food preservation technologies, agricultural biotechnology or applied environmental sustainability.
- **Exclusion criteria**:
  - Duplicate studies.
  - Publications without empirical evidence or systematic theoretical review.
  - Technical reports without explicit methodological support.

Table 2. Inclusion and exclusion criteria applied

Category	Inclusion	Exclusion
Publication period	2019 – 2024	Before 2019
Font Type	Scientific articles, reviews, specialized books	Press releases, blogs, informal websites
Language	English and Spanish	Other languages without translation available

Thematic focus	Technologies in agriculture and agri-food sustainability	Areas not related to agri-food

3. Search procedure

Combinations of terms in English and Spanish were used, such as: "food preservation technologies", "agricultural biotechnology", "sustainable agri-food systems", "postharvest losses", "packaging and shelf life", "precision agriculture" and "agri-food sustainability". The search yielded a total of 132 articles, of which 52 met the established criteria and were selected for analysis.

4. Data analysis

The selected articles were organized in a **thematic synthesis matrix**, which allowed the identification of trends, gaps and convergences between the three axes of the study. Open coding was applied to extract key categories, such as: types of technology, environmental impacts, competitive advantages, implementation challenges, and cross-sectoral synergies.

This analytical process was guided by qualitative analysis methodologies proposed by Flick (2022), which allow establishing relationships between emerging categories and generating an integrative interpretation of the investigated phenomenon.

5. Limitations of the study

The main limitations are related to access to certain paid items and the scarcity of integrative studies that simultaneously analyze the three pillars addressed. However, this limitation was compensated for by including systematic reviews and multisectoral case studies.

RESULTS

The results obtained from the systematic review allow us to identify a clear trend towards convergence between food preservation technologies, biotechnology in agriculture and environmental sustainability as synergistic elements for the transformation of agrifood systems. The findings were organized into three main analytical categories:

1. Effectiveness of Food Preservation Technologies

Emerging technologies for food preservation have proven effective in reducing post-harvest losses, improving safety and extending shelf life without compromising nutritional quality.

Key findings:

- The application of **high hydrostatic pressure (HPP) reduces** the microbial load by an average of 45% **without affecting the texture or flavor of fruits and natural juices (Zhou et al., 2021).**
- The use of **active packaging** with antimicrobial release managed to extend the shelf life of fresh foods by an **additional 5 to 10 days**, especially in meats and vegetables (Zhao, Wang & Tang, 2023).
- Ionizing irradiation **technology** applied to cereals and dried fruits reduced **the proliferation of molds and bacteria** in tropical conditions by 80% (Singh et al., 2022).

Table 1. Impact of preservation technologies according to type of food

Technology	Type of food	Loss reduction (%)	Increased service life (days)	Fountain
High hydrostatic pressure	Juices, fruits	40–50%	+7	Zhou et al. (2021)
Active Packaging	Vegetables, fresh meats	30–45%	+10	Zhao et al. (2023)
Ionizing irradiation	Cereals, dried fruits	50–60%	+15	Singh et al. (2022)

2. Advances of Agricultural Biotechnology in Sustainability

Studies indicate that agricultural biotechnology has been instrumental in increasing production efficiency without compromising environmental integrity. Positive impacts are observed in the reduction of the use of agrochemicals, water optimization and resistance to environmental stress.

Key facts:

- The use of **microbial biofertilizers** made it possible to reduce **the use of synthetic fertilizers by 35%** and increase productivity by up to **20% in corn and soybean crops** (Ramírez-Gómez et al., 2023).
- Crops edited with **CRISPR-Cas9** have shown a **25% increase in drought resistance** in arid areas, mainly in rice and wheat (Kwon et al., 2021).
- A 32% improvement in soil health **has been documented** following three continuous agricultural cycles with sustainable biotechnology applications (Adeleke, Adedokun & Ajiboye, 2022).

Table 2. Quantitative results of applied biotechnology

Biotechnological technique	Main result	% Improvement/Reduction	Crops studied	Fountain
Biofertilizers	Reduction of chemical fertilizers	-35%	Corn, soybeans	Ramírez-Gómez et al. (2023)
CRISPR-Cas9	Increased tolerance to water stress	+25%	Wheat, rice	Kwon et al. (2021)
Gene Editing + Management	Regenerative soil health	+32%	Potato, onion	Adeleke et al. (2022)

3. Synergies for the Sustainability of Agrifood Systems

One of the main emerging conclusions is that the integration of conservation technologies and agricultural biotechnology generates **multiplier effects** when implemented under an environmental sustainability strategy.

Featured trends:

- Integrated systems show an **average reduction of 28% in the carbon footprint**, especially in fruit and vegetable value chains (Liu & Huang, 2020).
- In pilot areas of Colombia and Mexico, the combination of these technologies increased **the net income of small producers by up to 40%,** due to the reduction of losses and access to differentiated markets (González-Muñoz et al., 2022).
- The use of artificial intelligence to monitor preservation and production conditions made it possible to optimize water resources by 20 % **less consumption per ton produced** (FAO, 2021).

Table 3. Effects of technological convergence on sustainability

Combination of technologies	**Environmental/Economic Indicator**	**Improvement (%)**	**Region / Case Study**	**Fountain**
Preservation + biofertilizers	Carbon footprint	-28%	Colombia, Spain	Liu & Huang (2020)
CRISPR + Smart Packaging	Producer profitability	+40%	Mexico, Brazil	González-Muñoz et al. (2022)
AI Sensors + Bioproduction	Water Saving	-20%	Morocco, Chile	FAO (2021)

General Summary

The data show that the strategic combination of agri-food technological innovations can generate a **multifactorial positive impact**: economic improvement, ecological efficiency and greater productive resilience to climate change. The **key** to success lies in the **coordination of public policies, financial incentives and technology transfer** appropriate to rural contexts.

CONCLUSIONS

The findings of this study allow us to affirm that the convergence between **food preservation technologies**, **agricultural biotechnology** and **environmental sustainability** represents a promising and necessary way to transform agrifood systems towards more resilient, inclusive and sustainable models.

Firstly, it is evident that **preservation technologies** have evolved from traditional methods to intelligent solutions that significantly reduce post-harvest losses, extend shelf life and ensure food safety without compromising the organoleptic properties of the products. These technologies not only generate economic benefits by avoiding shrinkage, but also contribute to reducing the ecological footprint of the global food system (Zhou et al., 2021; Zhao et al., 2023).On the other hand, **agricultural biotechnology** has shown a disruptive advance in genetic improvement, biological soil management and the optimization of the use of inputs. Gene editing using CRISPR-Cas9, together with the application of biofertilizers and nitrogen-fixing microorganisms, has improved crop efficiency in adverse environments and reduced dependence on agrochemicals with a high environmental impact (Kwon et al., 2021; Ramírez-Gómez et al., 2023).However, the greatest potential lies in the **synergy** between these technologies, when they are implemented under a sustainability framework. The results show that integrated systems that combine these innovations can reduce the carbon footprint, optimize water use and improve the economic performance of smallholders. This integration favours the creation of shorter, more transparent, circular agri-food chains that are adaptive to climate change (Liu & Huang, 2020; Adeleke et al., 2022).In addition, the study shows that technological availability is not enough to achieve systemic impact. It is necessary to articulate **public policies**, **accessible financing models** and **mechanisms for knowledge transfer**, especially to rural communities and areas of high food vulnerability. Agri-food sustainability should be understood as an inclusive, multidimensional and participatory process (FAO, 2021).Finally, the urgency of promoting interdisciplinary research and the training of technical capacities that promote the ethical, efficient and sustainable use of these technologies at various scales of production is highlighted. The future of global food security will depend on our collective ability to integrate **technological innovation with the principles of ecological justice and social equity** (González-Muñoz et al., 2022).

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