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Innovative post-harvest technologies to reduce food loss and waste

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Abstract
Food loss and waste (FLW) is a pressing global issue, with approximately one-third of all food produced for human consumption lost or wasted annually. Post-harvest losses, occurring between harvest and consumption, are particularly significant in developing countries due to inadequate infrastructure and limited access to advanced technologies. This paper reviews recent advancements in innovative post-harvest technologies, including cold chain innovations, modified atmosphere packaging, edible coatings, nanotechnology, and digital solutions. These technologies have shown great potential in reducing FLW, enhancing food quality, and extending shelf life. The paper also discusses the economic, environmental, and social impacts of these technologies, highlighting their role in achieving the United Nations Sustainable Development Goals (SDGs). Finally, the paper identifies challenges and future directions for the widespread adoption of these technologies.

Keywords: Food loss and waste, post-harvest technologies, cold chain, nanotechnology, digital solutions and food quality

1. Introduction
Food loss and waste (FLW) is a critical global issue, with an estimated 1.3 billion tons of food lost or wasted annually, representing approximately one-third of all food produced for human consumption. Post-harvest losses, which occur between harvest and consumption, are particularly significant in developing countries due to inadequate infrastructure, lack of access to advanced technologies, and poor handling practices. These losses not only exacerbate food insecurity but also contribute to economic losses and environmental degradation.

Innovative post-harvest technologies have emerged as essential tools to address these challenges. By improving storage, transportation, and processing methods, these technologies can significantly reduce FLW, enhance food quality, and extend shelf life. This paper reviews recent advancements in post-harvest technologies, including cold chain innovations, modified atmosphere packaging, edible coatings, nanotechnology, and digital solutions (fig. 1). It also discusses the economic, environmental, and social impacts of these technologies, highlighting their potential to transform food systems and contribute to the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 2 (Zero Hunger).

2. Cold Chain Innovations
The cold chain is a temperature-controlled supply chain that is critical for preserving perishable foods such as fruits, vegetables, dairy, and meat. Recent advancements in cold chain technologies have focused on improving efficiency, sustainability, and accessibility:

2.1 Solar-Powered Cold Storage
In regions with limited access to electricity, solar-powered refrigeration systems have been developed to provide affordable and sustainable cooling solutions. These systems use photovoltaic panels to generate electricity, which powers refrigeration units, ensuring that perishable foods remain fresh during storage (Al-Amin *et al*., 2021) [1].

Solar-powered cold storage is particularly beneficial in rural and off-grid areas, where traditional cold storage infrastructure is often unavailable.

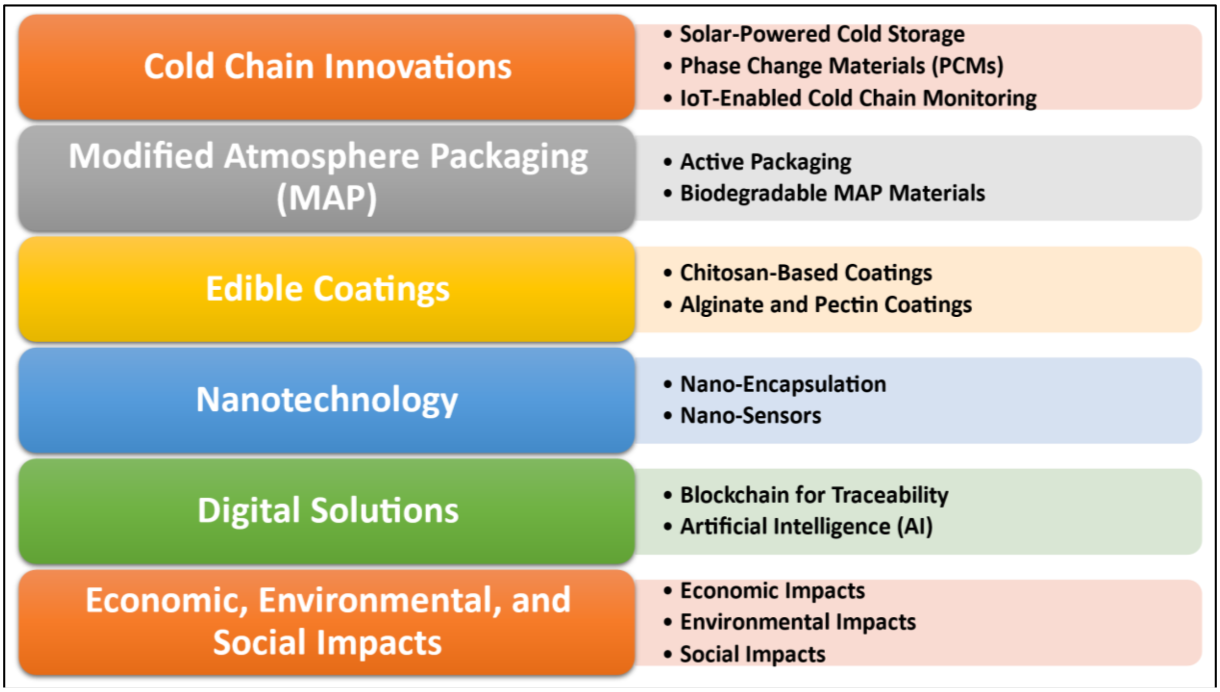

Fig. 1: Innovative Post-Harvest Technologies to Reduce Food Loss and Waste

2.2 Phase Change Materials (PCMs)
Phase Change Materials (PCMs) are substances that absorb and release thermal energy during phase transitions, such as melting and solidification. They are used in cold chain systems to maintain stable temperatures during transportation, reducing energy consumption and improving efficiency. For example, PCMs can be incorporated into insulated containers to keep food products cool without the need for continuous refrigeration (Zhang *et al*., 2022) [2].

2.3 IoT-Enabled Cold Chain Monitoring
The Internet of Things (IoT) has revolutionized cold chain management by enabling real-time monitoring of temperature and humidity. IoT devices, such as sensors and data loggers, are placed in storage facilities and transportation vehicles to collect and transmit data to a central system. This allows stakeholders to monitor conditions remotely and take corrective actions if deviations occur, ensuring optimal storage conditions and reducing the risk of spoilage (Huang *et al*., 2023) [3].

3. Modified Atmosphere Packaging (MAP)
Modified Atmosphere Packaging (MAP) involves altering the composition of gases surrounding food products to extend shelf life. Recent developments in MAP have focused on improving effectiveness and sustainability:

3.1 Active Packaging
Active packaging incorporates components that interact with the food or its environment to maintain freshness. For example, oxygen scavengers can be added to packaging to reduce oxygen levels, slowing down oxidation and microbial growth. Similarly, carbon dioxide emitters and ethylene absorbers can be used to control the atmosphere inside the package, extending the shelf life of fruits and vegetables (Yildirim *et al*., 2021) [4].

3.2 Biodegradable MAP Materials
Traditional MAP materials are often made from non-biodegradable plastics, which contribute to environmental pollution. Recent research has focused on developing sustainable packaging materials derived from plant-based polymers, such as polylactic acid (PLA) and starch-based films. These materials are biodegradable and compostable, reducing the environmental impact of MAP (Hosseini *et al*., 2022) [5].

4. Edible Coatings
Edible coatings are thin layers applied to food surfaces to prevent moisture loss, microbial growth, and oxidation. Recent innovations in edible coatings have focused on improving functionality and sustainability:

4.1 Chitosan-Based Coatings
Chitosan, a natural polysaccharide derived from crustacean shells, has antimicrobial properties and is widely used in edible coatings. Chitosan-based coatings can extend the shelf life of fruits and vegetables by inhibiting the growth of spoilage microorganisms and reducing moisture loss (Sridhar *et al*., 2021; Chaudhari *et al*., 2021) [15, 6].

4.2 Alginate and Pectin Coatings
Alginate and pectin are natural polysaccharides derived from seaweed and citrus peels, respectively. They are used to create biodegradable and edible films that can be applied to food surfaces. These coatings provide a barrier to oxygen and moisture, helping to preserve the quality and freshness of food products (Pires *et al*., 2024) [7].

5. Nanotechnology
Nanotechnology has shown great promise in enhancing food preservation and safety. Key applications include:

5.1 Nano-Encapsulation
Nano-encapsulation involves encapsulating bioactive compounds, such as antioxidants and antimicrobial agents, in nanocarriers. This improves their stability and allows for controlled release, enhancing their effectiveness in preserving food products. For example, nano-encapsulated essential oils can be used to inhibit microbial growth and extend the shelf life of perishable foods (Zabot *et al*., 2022) [8].

5.2 Nano-Sensors
Nano-sensors are used to detect pathogens and spoilage indicators in real-time, ensuring food safety. These sensors can be incorporated into packaging materials to monitor the condition of food products during storage and transportation. If spoilage or contamination is detected, the sensors can alert stakeholders, allowing for timely intervention (Awlqadr *et al*., 2024) [9].

6. Digital Solutions
Digital technologies are revolutionizing post-harvest management through data-driven approaches:

6.1 Blockchain for Traceability
Blockchain technology enhances transparency and traceability in supply chains by creating a decentralized and immutable record of transactions. This allows stakeholders to track the movement of food products from farm to fork, reducing losses due to inefficiencies and improving accountability (Kamilaris *et al*., 2021) [10].

6.2 Artificial Intelligence (AI)
AI algorithms can analyze large datasets to predict optimal harvest times and storage conditions, minimizing losses. For example, AI-powered systems can use weather data, crop conditions, and market demand to recommend the best time to harvest and store crops, ensuring maximum quality and shelf life (Fadiji *et al*., 2023) [11].

7. Economic, Environmental, and Social Impacts
Innovative post-harvest technologies offer numerous benefits across economic, environmental, and social dimensions:

7.1 Economic Impacts
Reducing FLW increases farmers' incomes by minimizing losses and improving marketability. It also reduces costs for consumers by ensuring a steady supply of affordable, high-quality food (Kaur *et al*., 2024) [12].

7.2 Environmental Impacts
Minimizing FLW reduces greenhouse gas emissions associated with food production and waste disposal. It also conserves natural resources, such as water and land, by optimizing the use of agricultural outputs (Gatto and Chepeliev, 2024) [13].

7.3 Social Impacts
Improved food availability and quality contribute to better nutrition and food security, particularly in vulnerable populations. By reducing FLW, innovative technologies can help address hunger and malnutrition, contributing to the achievement of SDG 2 (Zero Hunger) (WHO, 2023) [14].

8. Challenges and Future Directions
Despite their potential, the adoption of innovative post-harvest technologies faces several challenges:

Fig 2: Challenges in Innovative Post-Harvest Technologies to Reduce Food Loss and Waste

8.1 High Initial Costs
Many advanced technologies require significant upfront investment, which may be prohibitive for small-scale farmers and developing countries.

8.2 Lack of Awareness
Limited knowledge and awareness of these technologies among stakeholders can hinder adoption.

8.3 Infrastructure Limitations
Inadequate infrastructure, such as poor road networks and unreliable electricity supply, can limit the effectiveness of these technologies.

8.4 Future Directions
- Develop cost-effective and scalable solutions to make technologies accessible to all stakeholders.
- Promote awareness and capacity-building through training programs and extension services.
- Integrate traditional knowledge with modern technologies to create context-specific solutions.

9. Conclusion
Innovative post-harvest technologies hold immense potential to reduce food loss and waste, enhance food security, and promote sustainability. By leveraging advancements in cold chain systems, packaging, coatings, nanotechnology, and digital solutions, we can transform food systems and contribute to the achievement of the SDGs. Collaborative efforts among governments, researchers, and the private sector are essential to overcome challenges and ensure widespread adoption of these technologies.

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