# The Rise of Intelligent and Active Packaging: Transforming the Future of Food Protection

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**ABSTRACT**

Food loss and spoilage are major global challenges that affect food security, economic sustainability, and consumer health. Intelligent and active packaging technologies offer innovative solutions beyond the traditional protective role of packaging. Active packaging helps extend shelf life by controlling factors such as oxygen, moisture, ethylene, and microbial growth, while intelligent packaging monitors food quality and storage conditions using indicators, sensors, RFID tags, and QR codes. Together, these systems enhance food safety, freshness, traceability, and consumer confidence. Their applications span fruits, vegetables, meat, seafood, dairy, and bakery products. By reducing spoilage and food waste and supporting sustainable packaging materials, intelligent and active packaging contribute to more efficient and environmentally friendly food systems. This article highlights their principles, applications, benefits, challenges, and future prospects.

## INTRODUCTION

Food loss and spoilage remain major challenges worldwide, resulting in economic losses and threats to food security. The concept of food insecurity relates not only to hungry people, but also to the insecurity with respect to macro- and micro-nutrients: unbalanced diets may contribute to food insecurity(Santeramo & Lamonaca, 2021). Traditional packaging primarily acts as a barrier between food and the external environment but often fails to actively prevent deterioration or provide information about product quality. To address these limitations, Intelligent and active packaging technologies have emerged as innovative solutions that not only protect food but also help monitor and maintain its freshness, safety, and quality throughout storage and distribution (Bailen *et al*., 2006).

## 1. What Is Food Packaging and Quality Loss?

Food packaging is an essential component of the modern food industry, serving functions such as protection, containment, transportation, communication, and convenience. For decades, packaging materials have been designed mainly to shield food from physical, chemical, and biological damage (Kadirvel *et al*., 2025). However, advances in material science and sensor technology have transformed packaging from a passive protective barrier into an intelligent system capable of interacting with food and providing real-time information about its condition (M. Sheyan *et al*., 2022).

Oxidation, microbial spoilage, and metabolism are the primary factors responsible for the deterioration of many perishable foods, including apples, bananas, kiwifruit, pears, tomatoes, fish, meat, etc. These processes occur throughout various stages of the food supply chain, such as production, transportation, processing, storage, and marketing. These processes are directly related to the loss of food quality (including safety), influence consumer buying decisions, and impact consumer health, and thus affect the overall economics of the food industry (Santeramo & Lamonaca, 2021).

## 2. Understanding Active Packaging

Active packaging refers to packaging systems that actively interact with food or the surrounding environment to improve product quality and extend shelf life. Unlike conventional packaging, active packaging can absorb or release specific substances to control factors that contribute to food spoilage (Granda-Restrepo *et al*., 2009). Common examples include oxygen scavengers that reduce oxidation, moisture absorbers that prevent microbial growth, ethylene scavengers that delay fruit ripening, carbon dioxide regulators, antimicrobial agents that inhibit pathogens, and antioxidant compounds that preserve food quality.

**Table 1**. Examples of active packaging applications used in the food industry.

| Category | Active Packaging Application |
|---|---|
| **Absorbing/ Scavenging Properties** | Oxygen absorbers/scavengers, Carbon dioxide absorbers/ scavengers, Moisture absorbers/ scavengers, Ethylene absorbers/ scavengers, Flavour absorbers/ scavengers, Taint absorbers/ scavengers, UV light absorbers/ scavengers |
| **Releasing/ Emitting Properties** | Ethanol emitters, Carbon dioxide emitters, Antioxidant releasers, Preservative releasers, Sulphur dioxide emitters, Flavour releasers |
| **Removing Properties** | Catalytic removal of lactose, Catalytic removal of cholesterol |
| **Temperature Control** | Insulating materials, Self-heating packaging, Self-cooling packaging, Temperature-sensitive packaging |
| **Microbial and Quality Control** | UV-treated packaging materials, Surface-treated antimicrobial packaging materials |

## 3. Understanding Intelligent/ smart Packaging

Intelligent packaging is designed to monitor and communicate information about food quality, safety, and storage conditions. These systems incorporate indicators, sensors, and digital technologies that provide real-time feedback to manufacturers, retailers, and consumers. Examples include time-temperature indicators that track storage conditions, freshness indicators that detect spoilage, gas sensors that monitor package atmosphere, biosensors that identify contaminants, RFID tags for traceability, and QR codes that offer product information and supply chain transparency (Kadirvel *et al*., 2025).

**Table 2. Characteristics of Different Data Carrier Types Used in Intelligent Packaging Systems**

| Data Carrier Type | Description |
|---|---|
| Linear Barcodes | • Parallel spaces and bars • Symbology (1-D) |
| QR Codes | • Dark and light square-coded modules • Each module encodes a single bit, using black for "1" and white for "0" • Modules are structured in a grid layout, creating square or rectangular shapes • Symbology (2-D) |
| Data Matrix Codes | • Evolution of the barcode • Dark and light square-coded modules • Each module encodes a single bit, using black for "1" and white for "0" • Modules are structured in a grid layout, creating square or rectangular shapes • Symbology (2-D) |
| RFID Tags | • Evolution of the barcode • Acquiring and issuing electromagnetic waves • A conductive pattern that regulates the emission frequency • An optimised antenna achieves impedance matching for maximum power transmission to the chip • Chip stores the EPC • EPC contains the product data • EPC is exclusive to each RFID tag • EPC registers the manufacturing time |

## 4. How Intelligent and Active Packaging Work Together

While active packaging helps maintain food quality by controlling the internal package environment, Intelligent packaging monitors and communicates information about product status. Together, these technologies create a comprehensive food protection system that both preserves and tracks food quality. This combination helps reduce spoilage, improve supply chain efficiency, and enhance consumer confidence by providing greater assurance of food safety and freshness (Nopwinyuwong *et al*., 2010).

The adoption of Intelligent and active packaging offers numerous advantages to the food industry and consumers. These technologies can significantly extend shelf life, improve food safety, reduce spoilage and waste, and optimise inventory management. They also contribute to better product quality by maintaining ideal storage conditions and provide consumers with valuable information about product freshness and origin, increasing transparency and trust in food products.

Intelligent and active packaging technologies are widely used across various food categories. Fresh fruits and vegetables benefit from ethylene scavengers and moisture regulators that slow ripening and spoilage (Bailen *et al*., 2006). Meat, poultry, fish, and seafood products utilise antimicrobial packaging and freshness indicators to maintain safety and quality. Dairy products benefit from oxygen control systems, while bakery and ready-to-eat foods use active packaging to preserve texture, flavour, and freshness during storage and distribution.

## 5. Role in Sustainability and Circular Economy

One of the most significant advantages of Intelligent and active packaging is its contribution to sustainability. By extending shelf life and reducing food spoilage, these technologies help decrease food waste throughout the supply chain. Many modern packaging systems also incorporate biodegradable and bio-based materials, reducing reliance on petroleum-derived plastics. As a result, Intelligent and active packaging supports the principles of the circular economy by promoting resource efficiency and environmental protection (M. Sheyan *et al*., 2022).

## 6. Recent Innovations and Emerging Trends

Rapid technological advancements continue to expand the capabilities of smart and active packaging. Nanotechnology-based packaging materials offer enhanced barrier and antimicrobial properties, while nanoemulsions and essential oil-incorporated films provide natural preservation solutions. Emerging innovations include Internet of Things (IoT)-enabled packaging, artificial intelligence-driven monitoring systems, and edible packaging materials that further improve food safety, traceability, and sustainability (W. Hu *et al*., 2022).

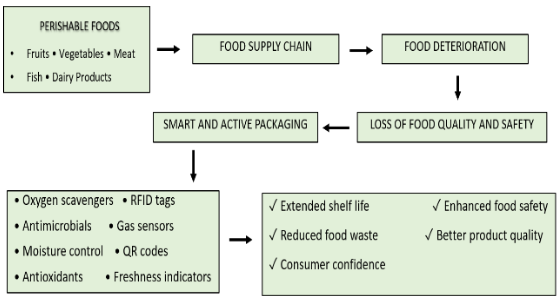


**Fig. 1** Types and Benefits of smart and active packaging

## 7. Challenges and Future Perspectives

Despite their many advantages, smart and active packaging technologies face several challenges. High production costs and the complexity of manufacturing can limit large-scale adoption, particularly in developing countries. Regulatory approval processes, concerns about consumer acceptance, and issues related to recycling and disposal also present obstacles. Furthermore, integrating advanced technologies into existing food supply chains requires significant investment and technical expertise.

The future of food packaging is expected to be increasingly intelligent, connected, and sustainable. Integration with digital technologies such as artificial intelligence, cloud computing, and IoT platforms will enable more precise monitoring of food quality. Personalised packaging systems may provide customised information based on consumer needs, while smart packaging will play a growing role in e-commerce and food delivery services. These advancements have the potential to strengthen global food security by minimising losses and ensuring safer food distribution.

## CONCLUSION

Intelligent and active packaging technologies are revolutionising food protection by moving beyond the traditional role of packaging as a passive barrier. Through their ability to preserve food quality, monitor freshness, enhance safety, and reduce waste, these innovations offer practical solutions to many challenges facing modern food systems. Continued research, technological development, and wider commercial adoption will be essential for realising their full potential and building a more sustainable and secure food future.

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