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Smart Packaging for Fresh Produce: From Passive Protection to Intelligent Quality Monitoring

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Fresh fruits and vegetables continue to remain biologically active even after harvest. They respire, lose moisture, produce or respond to ethylene, undergo ripening and senescence, and eventually become susceptible to physiological disorders and microbial spoilage. Conventional packaging provides essential protection during storage, transportation and marketing, but it generally cannot detect or communicate changes occurring in the produce. Smart packaging is changing this concept by transforming the package from a passive protective material into a system capable of protecting, monitoring and communicating product quality. It broadly includes active packaging, which interacts with the produce or its surrounding environment to maintain quality, and intelligent packaging, which detects and communicates changes in product condition. Technologies such as ethylene scavengers, moisture regulators, antimicrobial packaging, time–temperature indicators, freshness indicators, gas sensors, biosensors, RFID and QR-based traceability are creating new possibilities for postharvest management. Recent advances in biodegradable polymers, natural colour-changing pigments, printed sensors and digital technologies are making these systems increasingly sustainable and practical. Smart packaging has considerable potential to reduce postharvest losses and improve quality management, although challenges related to cost, accuracy, food safety, scalability and consumer acceptance need to be addressed before widespread commercial adoption.

Keywords: Smart packaging, fresh produce, active packaging, intelligent packaging, sensors, postharvest management

Introduction

Fresh fruits and vegetables may appear inactive after harvest, but several biological processes continue within their tissues. Respiration continues, moisture is lost through transpiration, climacteric fruits produce ethylene, stored food reserves are consumed, tissues gradually soften and the produce ultimately undergoes senescence. The rate of these changes depends strongly on temperature, relative humidity, atmospheric composition, maturity and handling conditions. This living nature of horticultural produce makes maintaining freshness from harvest to consumption particularly challenging. Packaging is therefore an important component of postharvest management. Conventional packages such as corrugated fibreboard boxes, plastic films, trays, punnets and bags protect produce from mechanical injury, contamination and excessive moisture loss and make transportation and marketing easier. However, most conventional packages perform these functions passively. A normal package cannot tell the retailer whether the cold chain was interrupted during transportation, whether excessive moisture has accumulated inside it, whether a fruit is rapidly ripening or whether the remaining marketable life of the commodity has been shortened.

This limitation has created interest in smart packaging, in which packaging performs functions beyond simple containment and protection. Smart packaging can interact with the packaged produce, monitor changes occurring within the package and, in some systems, communicate this information to producers, distributors, retailers or consumers. The development of low-cost sensors, biodegradable materials, natural indicators and digital technologies has accelerated research in this area. Recent advances in ethylene-detection systems, for example, are creating possibilities for real-time monitoring of the ripening and freshness of climacteric fruits such as banana, mango and kiwifruit (Kumar et al., 2026).

From Passive Protection to Active Packaging

Smart packaging can broadly be understood through two closely related concepts: active packaging and intelligent packaging. Active packaging interacts with the commodity or the atmosphere surrounding it to maintain quality or extend shelf life. Intelligent packaging, in contrast, senses or records changes and provides information about the condition of the packaged product. The two technologies can also be combined, creating a package that not only detects an undesirable change but may also help control it. Ethylene management is an excellent example of active packaging for horticultural produce. Ethylene is a naturally occurring plant hormone involved in fruit ripening and senescence. Climacteric commodities such as banana, mango, papaya, avocado, tomato and kiwifruit show increased ethylene production during ripening. When s uch produce is enclosed within a package, ethylene can accumulate in the surrounding atmosphere and accelerate ripening, softening and senescence. Ethylene-scavenging systems are therefore designed to absorb, adsorb or degrade the gas. Scavenging materials can be incorporated into sachets, pads, labels or packaging films. Recent smart-packaging research is also moving beyond simply removing ethylene toward detecting ethylene as an indicator of fruit ripening, allowing packages to provide information about the physiological condition of the produce (Kumar et al., 2026). Moisture is another important factor. Fresh produce continuously loses water through transpiration, and this moisture may accumulate inside closed packages. Low relative humidity results in excessive water loss, shrivelling and loss of freshness, while excessive humidity and condensation favour microbial development. Moisture-absorbing pads and humidity-regulating materials can help maintain a more suitable microenvironment. This is particularly useful for commodities such as leafy vegetables, berries and fresh-cut produce, where free moisture can rapidly contribute to quality deterioration.

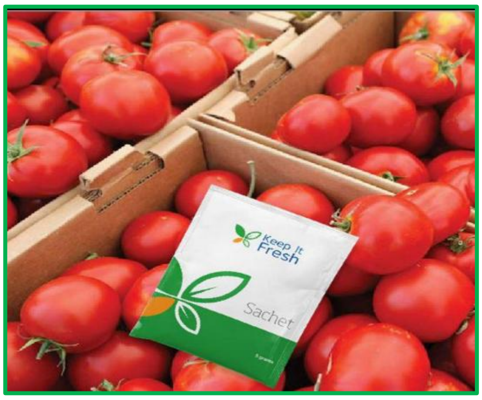

Fig. 1. Active packaging using a freshness-preserving sachet for maintaining the postharvest quality of tomatoes.

Active packaging can also provide antimicrobial protection. Fruits and vegetables are susceptible to fungal and bacterial spoilage during storage and marketing, particularly when tissues have been mechanically injured. Instead of simply acting as a physical barrier, antimicrobial packaging incorporates functional compounds into films, coatings or pads. Natural essential oils, plant extracts, organic acids and other antimicrobial substances are increasingly being investigated because of growing interest in safer and more environmentally friendly preservation technologies. Such systems can provide antimicrobial action close to the surface of the commodity, where infection and decay commonly begin. Management of oxygen and carbon dioxide is another important application. Fresh produce requires oxygen for respiration, but excessively low oxygen or high carbon dioxide concentrations may result in anaerobic respiration, off-flavours and physiological injury. Functional packaging materials can be designed with appropriate gas permeability or combined with oxygen scavengers and carbon dioxide regulators. These approaches can complement modified atmosphere packaging by creating a more favourable gaseous environment around the produce.

Intelligent Packaging: A Package That Communicates

While active packaging primarily helps preserve quality, intelligent packaging provides information about what is happening to the commodity. This represents one of the most exciting changes in packaging science because the package becomes a tool for quality monitoring. two boxes of strawberries harvested and packed on the same day. One is continuously maintained under recommended refrigeration, while the other is accidentally left at a high temperature for several hours during transportation. Both boxes may carry exactly the same packing or expiry date, yet their actual remaining shelf lives may be very different. Conventional labels cannot communicate this difference.

Time–temperature indicators (TTIs) are designed to address this problem. These indicators respond to the temperature history experienced by the packaged product. Depending on their design, physical, chemical, enzymatic or biological reactions produce a gradual visible change. Rather than indicating only how many days have passed since packing, a TTI can provide information about whether the product has experienced undesirable temperature conditions. This is particularly valuable for fresh produce because deterioration is strongly influenced by both the magnitude and duration of temperature exposure. Freshness indicators take the concept a step further by responding to changes associated with product deterioration. As fruits and vegetables respire, ripen and senesce, the atmosphere surrounding them changes. Gases, volatile organic compounds, metabolites and other chemical changes may therefore provide indirect information about freshness. A small indicator incorporated into the package can respond to these changes, often through an easily observable colour shift.

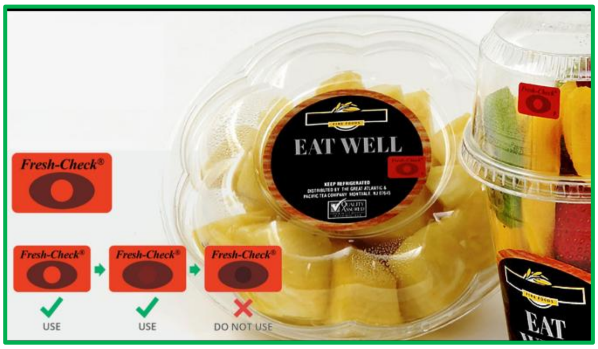

Fig. 2. Intelligent packaging with a colour-changing indicator for real-time monitoring of freshness and quality of fresh produce.

Natural pigments have attracted considerable attention for this purpose. Anthocyanins, the pigments responsible for red, purple and blue colours in many fruits and vegetables, are particularly promising because their colour changes under different chemical environments. Researchers are incorporating anthocyanins into biodegradable polymer films to create colour-responsive freshness indicators. Recent studies show that anthocyanin-based smart packaging is developing toward multifunctional systems capable of providing visual freshness information while potentially contributing antioxidant or antimicrobial properties. However, improving pigment stability under light, oxygen and changing temperatures remains an important challenge for commercialization (Yang et al., 2025).

Gas sensors provide another opportunity for intelligent packaging. Sensors capable of detecting oxygen, carbon dioxide, ethylene or specific volatile compounds could monitor the atmosphere inside a package without requiring it to be opened. Ethylene sensors are especially relevant for climacteric fruits because increasing ethylene production can indicate progression of ripening. Recent research has explored optical and colour-based sensor films that produce a visible response in the presence of ethylene, potentially allowing consumers or handlers to assess ripening more easily (Kumar et al., 2026).

Biosensors represent a more advanced approach. These systems combine a biological recognition component with a signal-generating mechanism and may eventually allow packages to detect specific microorganisms or metabolites associated with deterioration. Their ability to provide rapid and non-destructive information is attractive, but the major challenge is producing sensors that are accurate, inexpensive, stable and practical enough for disposable fruit and vegetable packages.

Connecting the Package to the Supply Chain

Smart packaging is also becoming increasingly digital. QR codes, radio-frequency identification (RFID) and near-field communication (NFC) can give packaged produce a digital identity. Information related to origin, harvest, packing, storage, transportation and distribution can be linked with a particular package or consignment. The value of such systems becomes greater when digital identification is combined with sensors. A package could potentially record temperature or other environmental conditions throughout the journey from the farm to the packhouse, cold store, transport vehicle, distribution centre, retailer and finally the consumer. If deterioration occurs unexpectedly, the recorded information could help identify where the cold chain failed or where unfavourable conditions were encountered. In the future, this information could also improve inventory management. Rather than selling produce only according to the order in which it arrived, retailers could prioritise packages according to their actual remaining shelf life. Produce predicted to deteriorate sooner could be sold first, discounted or diverted to processing, while produce with longer remaining life could continue through normal marketing channels. In this way, smart packaging could help shift postharvest management from fixed expiry dates toward dynamic quality-based decision making.

Smart Packaging Must Also Be Sustainable

The benefits of smart packaging raise an important environmental question. If sensors, electronic components and functional materials are added to every package, could solving food waste inadvertently create more packaging waste? For this reason, sustainability has become an important direction in smart-packaging research. Scientists are developing biodegradable and bio-based packaging using starch, cellulose, chitosan, proteins and other renewable polymers. Natural pigments and plant-derived compounds can provide sensing, antioxidant or antimicrobial functions while reducing dependence on synthetic additives. Another particularly promising approach is to obtain packaging materials from agricultural and food-processing by-products. Fruit peels, vegetable residues and other processing wastes contain cellulose, pectin, starch, pigments and bioactive compounds that can potentially be recovered and converted into functional packaging materials. Such approaches support a circular concept in which food-processing waste becomes a resource for producing packaging that, in turn, helps reduce further food loss (Xie et al., 2024). Colourimetric indicators are also attracting interest because they can provide easily visible freshness information without complicated electronic components. Recent research is therefore focusing not only on increasing sensor sensitivity but also on developing low-cost, biodegradable and consumer-friendly indicator systems. Nevertheless, the environmental performance of smart packaging needs to be considered throughout its complete life cycle. A biodegradable film containing difficult-to-recycle electronic components may not necessarily be more sustainable than a simpler recyclable package.

Challenges Before Commercial Adoption

Despite rapid research progress, widespread application of smart packaging to fresh fruits and vegetables still faces several challenges. Cost is perhaps the most immediate barrier. Adding a sophisticated sensor may be economically reasonable for high-value produce exported over long distances but difficult to justify for inexpensive vegetables sold locally. The development of inexpensive printed sensors and simple colour-changing indicators could therefore play an important role in future adoption. Accuracy is equally important. Fresh produce is naturally variable. Fruits harvested from the same plant may differ in maturity, respiration rate and physiological behaviour. A sensor must therefore provide meaningful information despite this biological variability. False indications could reduce consumer confidence rather than improve it. Food-contact safety and regulatory approval are also critical, particularly when nanoparticles, antimicrobial substances or chemical indicators are incorporated into packaging. Materials must perform their intended function without undesirable migration into the food. Consumer understanding presents another challenge. A freshness indicator has little value if consumers cannot interpret its colour correctly. Future packages therefore need simple and universally understandable signals rather than complicated scientific information. Recent reviews of colourimetric freshness indicators identify stability, accuracy, large-scale manufacturing and practical commercialization as major areas that still require development (Cheng et al., 2025).

Future Prospects

The future of smart packaging is likely to be shaped by the convergence of sensors, sustainable materials and digital technologies. Printed sensors could make intelligent labels cheaper and easier to manufacture, while multi-sensor systems may allow a single package to monitor several factors such as temperature, humidity, oxygen, carbon dioxide and ethylene simultaneously. Integration with the Internet of Things (IoT) could allow information collected from packages to be transmitted throughout the supply chain. Instead of discovering quality deterioration only when a shipment reaches the market, abnormal temperature or atmospheric conditions could potentially be identified during transportation itself. Artificial intelligence and machine-learning tools could further analyse sensor data together with commodity type, storage history and environmental conditions to predict remaining shelf life. Another important development will be commodity-specific packaging. Strawberries, mangoes, bananas, leafy vegetables and tomatoes have different physiological characteristics and deterioration mechanisms. Future smart packages could therefore be designed according to the specific requirements of individual commodities rather than applying a single packaging system to all fresh produce. Perhaps the most promising direction is the development of responsive packaging that can both sense and act. A future package could detect increasing ethylene and activate an ethylene-removal mechanism, sense excessive moisture and regulate humidity, or recognise early microbial activity and release an antimicrobial agent. Such a system would represent a major transition from passive packaging to a miniature postharvest management system surrounding the commodity.

Conclusion

Smart packaging represents an important change in the way fresh fruits and vegetables may be protected and managed after harvest. Instead of functioning only as a container, the package can increasingly interact with the produce, monitor its environment and communicate information about its quality. Active technologies such as ethylene scavengers, moisture regulators, antimicrobial materials and gas-management systems can help maintain favourable storage conditions, while intelligent systems such as time–temperature indicators, freshness indicators, gas sensors and biosensors can provide information about the actual condition of the commodity. The combination of these technologies with biodegradable materials, natural colour indicators, digital traceability, IoT and data-based shelf-life prediction offers considerable potential for reducing postharvest losses. However, the most successful smart package will not necessarily be the one containing the most sophisticated technology. It will be the one that is accurate, affordable, safe, sustainable, simple to interpret and suitable for large-scale use. As these challenges are addressed, packaging may evolve from a passive covering into an intelligent partner that protects fresh produce throughout its journey from farm to consumer.

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