



Intelligent Packaging Applications in the Fruit and Vegetable Manufacturing Industry: Recent Advancements, Limitations and Future Outlook

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Received:10 June 2025; Revised:15 June 2025; Accepted: 25 June 225; Available online: 10 July 2025

Abstract— Intelligent packaging materials have emerged as a significant innovation in the fruit and vegetable manufacturing industry, offering the potential to improve product quality, enhance food safety, and extend shelf life. The technology, including components like sensors, indicators, and Radio Frequency Identification (RFID) tags, provides real-time insights into the condition of packaged produce by monitoring parameters such as freshness, ripeness, and microbial contamination. This is particularly crucial for fruit and vegetables, which are highly perishable owing to the rapid physiological and microbial changes. Research studies evidenced the functionality of intelligent packaging. For instance, pH-sensitive dye-based indicators have remarked strong correlations with the freshness levels of produce, including bananas and strawberries, with significant color changes indicating the onset of spoilage. Additionally, RFID-enabled smart labels integrated with ethylene gas sensors have been effectively applied in tomato packaging to detect elevated hormone levels that promote ripening by providing timely intervention to prevent overripening and post-harvest waste. Despite all of the apparent benefits, the industry confronts several types of challenges to the broad application of intelligent packaging, such as high production costs, limited scalability, and customer disapproval. Furthermore, incorporating new technologies into existing supply chains occasionally demands significant financial and capital expenditures. Future advances in intelligent packaging depend on the development of accessible, ecologically sound, and user-friendly solutions. Enhancing sensor responsiveness and selectivity, extending applicability to a larger variety of items, and investigating edible or biodegradable materials should be the key objectives of future research. Artificial intelligence could also make it possible for packaging systems to become more customized and adaptable, which would increase their utility and commercial viability.

Index Terms— Applications, Fruits and vegetables, Future outlook, Intelligent packaging, Limitations

1 INTRODUCTION

The global food industry has encountered different changes over recent years, driven by the increasing consumer demand for fresh and high-quality food products undergoing a transformative shift toward sustainability, efficiency, and safety. It has been investigated that at present 1.3 billion tons of food waste worth about 1 trillion USD has been generated. Based on the reports of the World Health Organization (WHO) approximately 10% of the global population of 60 billion people suffer from foodborne illnesses annually, resulting in 4.2 million deaths [1]. In order to minimize the waste generated during the production process, various procedures are followed. Packaging materials play a crucial role in securing the safety and quality of the fruits and vegetables in storing and transporting stages of the supply chain from farm to folk [2]. One of the most concerning developments in this area is the influence of intelligent packaging materials, which are typically designed to extend the shelf life, safety, and quality of fruits and vegetables [1]. Intelligent packaging refers to innovative packaging solutions driven by advanced innovative technologies including nanomaterials, sensors, and Internet of Things (IoT)-based tracking systems to regulate and enhance the storage conditions of perishable food categories such as fruits and vegetables [3]. Intelligent packaging materials provide an interactive and dynamic approach to food preservation, integrating technology to control and maintain the conditions of the food inside, communicating relevant information about the product to the consumers, and maintain or improve the product quality inside. Recent advancements in intelligent packaging materials related to the food and beverage industry have investigated and introduced active and smart packaging systems, including antimicrobial films, moisture and gas regulators, time-temperature indicators (TTIs), and biosensors which can detect spoilage indicators such as ethylene gas, microbial contamination, and humidity fluctuations [4,5]. The efficacy of such materials has been further improved through the rapid integration of nanotechnology, offering up the possibility of the creation of lightweight, economically beneficial, and biodegradable solutions that fulfill the increasing demand for environmentally friendly packaging options [6]. However, there are many barriers that prevent intelligent packaging materials from being widely applied in industry, even if their potential advantages in the production of fruits and vegetables are considerably high. To enable widespread utilization, specific barriers such as high production costs, regulatory issues, technological complexity, and customer distrust must be overcome throughout the life cycle of the packaging materials [7]. The applications of innovative technologies like radio frequency identification (RFID) sensors, bio-based polymers, and nanocomposites increase the economic and environmental risks of recycling and disposal [8]. Further, ensuring the compatibility of intelligent packaging materials with different types of fresh produce, optimizing sensor accuracy, and establishing standardized testing protocols are critical hurdles that must be overcome (Fig.1) [9]. Since the industry develops further, future perspectives include cost-effective methods, the development of environmentally friendly materials, and improved IoT integration to increase supply chain efficiency and transparency. By automating inventory management, reducing post-harvest losses, and offering real-time insights into food quality, the development of biodegradable intelligent packaging in conjunction with AI-driven predictive analytics is anticipated to completely transform the business [10]. In order to shape the future of intelligent packaging and spare innovation toward more environmentally friendly, consumer-friendly, and economically feasible solutions, cooperation between researchers, producers, and legislators will be crucial. Intelligent packaging materials will become more and more important in guaranteeing food safety, cutting waste, and assisting the worldwide shift to a more robust and effective agricultural supply chain by overcoming current constraints and utilizing technology breakthroughs [11]. With its significant potential, the implementation of intelligent packaging in the fruits and vegetables manufacturing industry witnessed certain challenges and limitations as identified

over time [12]. This review discusses the recent advancements in intelligent packaging materials, explores their limitations, and considers the future perspectives of this technology [13].



Fig. 1. Contribution of intelligent packaging materials in food industry

Recent advancements in intelligent packaging

Sensor-embedded packaging

One of the most prominent applications in intelligent packaging is the integration of sensors that can monitor and report on the condition of the food product packed by the intelligent packaging. Those sensors can detect the different various parameters including temperature, humidity, gas composition (CO_2 , C_2H_2 , O_2), and microbial activity [14, 15].

- Humidity sensors:** These sensors can monitor the storage conditions of fruits and vegetables, with high water activities (a_w). Such food products lose the moisture within the food commodity and dry out when the humidity inside the packaging becomes too low. Conversely food commodities with low a_w including dried fruits vegetables, and powdered products tend to absorb the moisture inside the packaging resulting in the degradation of the food [16]. Therefore, to overcome the food loss due to the adverse conditions mentioned, it is important to apply a real-time monitoring system that indicates the humidity conditions inside the food packaging. Currently, there are multiple techniques for monitoring humidity, like measuring fluctuations in crystal capacitance, resonant frequency, and dielectric properties (Table 1). As dielectric properties of proteins are sensitive to humidity, they are frequently exploited in the development of intelligent food packaging materials. For example, nanocomposite films with a ZnO layer acting as a semiconductor and a gelatin-based layer whose dielectric properties depend on the moisture content have been utilized to monitor changes in the relative humidity of the packed food commodities [17]. Comparably by monitoring changes in its dielectric properties with humidity, wheat gluten has also been

utilized to identify changes in relative humidity in packing materials. Sensors integrated into food packaging materials can also be used to detect changes in humidity. Intelligent food packaging has employed interdigitated electrode (IDE) humidity sensors imprinted on multiple biodegradable materials. Biodegradable materials serve as an induction layer in these IDE capacitive devices. In addition, while the material acquires moisture from the atmosphere, its dielectric constant increases, indicating that the capacitance between the electrodes depends on the relative humidity of the environment [18]. The induction layer collected water vapor as the food humidity of the packaging rose, altering the capacitance of the capacitor and the resonant frequency of the sensor. As sensing layers, materials that include glossy photo paper, polylactic acid (PLA), polyethylene terephthalate (PET) that has been chemically planarized, starch, polypropylene (PP) composite, and polyvinyl alcohol can be employed. In general, since the quality characteristics of dry packaged products such as powders, cereals, and snacks made out of fruits and vegetables are heavily reliant on their water activity, humidity-sensitive intelligent packaging materials could prove very helpful in these applications [19]. Further, strawberries are found to be highly sensitive to temperature fluctuations. Intelligent packaging with temperature sensors can alert when the product is exposed to potentially damaging conditions, ensuring to prevention of spoilage [13].

- **Gas sensors (Oxygen sensors):** When exposed to high oxygen concentrations for extended periods of time, many foods including unsaturated oils or pigments extracted from fruits and vegetables degrade chemically in ways that are undesirable. By flushing out and substituting the oxygen with an inert gas, such as nitrogen, or by generating a vacuum to remove the oxygen (O₂), food processing techniques and packaging materials are therefore frequently designed to regulate the level of oxygen in packaged food [20]. However, if the material used for packing becomes damaged or not entirely impermeable, oxygen may penetrate the food, thereby lowering its quality. The creation of intelligent packaging materials that can identify the oxygen content of food has therefore attracted attention. The oxygen content of food packaging is currently monitored using two main methods namely phosphorescence-based sensors and colorimetric redox-based sensors [21]. On the other hand, the ripening process of fruits is most probably associated with the release of ethylene (C₂H₂) gas. Gas sensors in the packaging can identify the concentration of ethylene, providing real-time information on the ripeness and shelf life of the product. This technology is commonly useful for fruits like bananas and avocados, which have a narrow timeline between optimal ripeness and spoilage [13].
- **Microbial sensors:** These sensors can detect the presence of pathogens or spoilage microorganisms in the food. For instance, packaging with biosensors that detect *Escherichia coli* or *Salmonella* can alert early warning to consumers and retailers, potentially preventing foodborne illnesses [13]. The food-borne microorganisms can be beneficial or detrimental to the quality and safety of the food commodity. The presence of some microorganisms is considered to be essential for the production of certain foods, such as the use of yeasts in bread or *Lactobacillus* used in yogurt manufacturing [22]. In contrast, the presence of pathogenic or spoilage organisms, such as *Salmonella typhimurium*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Escherichia coli*, degrades the food quality, resulting in food waste, and raising the risk of food poisoning. Bacterial contamination is, in fact, one of the primary causes of food-related sickness and death. As a result, maintaining food safety and quality requires the capacity to monitor the variety and number of microorganisms present in food. Traditionally, advanced laboratory techniques including bacterial culture, colony counting, polymerase chain reactions (PCR), isothermal amplification, and enzyme-linked immunosorbent assays (ELISA) have been employed for microbial detection methods. While these methods are extremely precise and sensitive, they are typically expensive, time-consuming, and/or labor-intensive to execute. In order to assist consumers in rapidly determining

whether they have been contaminated, researchers have been developing fast microbial detection techniques that may be included in food packaging materials [23]. Currently, lateral-flow test strip (LFTS) technology and DNAzyme probe technology are the two primary techniques utilized for bacterial detection in intelligent food packaging materials. The LFTS technique works on the basis of loading antibodies (Abs) tagged with gold (AuNPs) or palladium (PdNPs) nanoparticles onto a test strip. Bacteria in a food suspension attach themselves to the Abs tagged with AuNP or PdNPs to create a complex. Capillary pressures lead the complex to move across the strip, where it gets captured by an additional antibody bound to a different section of the strip. The aggregated metal colloids that detect bacteria then generate colorful lines or spots. This test requires no special equipment and only takes approximately 15 minutes; however, it is far less sensitive than PCR- or culture-based techniques [24]. Still, there is a lot of potential for the flow test strip assay to be used in intelligent packaging materials for bacterial detection. To detect the bacteria in milk and other liquid meals, for instance, it has been utilized.

Time-Temperature Indicators (TTIs):

Temperature and time possess a major impact on the quality of most meals. Almost every product has a shelf-life limit, but it is occasionally difficult to determine if contact to other environmental conditions has decreased the expiration date of the particular product [25]. Additionally, one of the primary factors influencing the quality of the majority of meals is temperature. Implementing real-time temperature and time monitoring in the food supply chain is therefore very important. Therefore, time-temperature indicators (TTIs) are another important advancement in intelligent packaging. TTIs can be defined as small devices that can change colour based on the cumulative exposure of a product to temperature over time [26]. They are useful in tracking the cold chain for perishable products like fruits and vegetables, ensuring that the produce has been stored and transported under appropriate and optimal conditions. Further TTIs can be used to monitor the temperature history of apples during transportation for example and if the apples are exposed to temperatures above a certain threshold for too long, the TTI changes its colour, indicating that the product may have deteriorated [14]. TTIs are currently classified based on various working principles, including chemical, physical, enzymatic, microbial, and other TTIs. Indicators based on polymerization, photochromism, and redox reactions are included in chemical TTI. The polymer-based chemical TTI generates polydiacetylene (PDA) compounds by stimulating the 1,4-addition polymerization process of polymer monomers with high temperatures. The speed of this irreversible polymerization process will accelerate as the temperature increases. At the visible light absorption peak, the absorption spectrum changes hue by transitioning from the high wave band to the low wave band. The chemical based on photoluminescence TTI is made by utilizing the reverse reaction of photoluminescence chemicals and the principle of thermally induced fading. Time and temperature will result in changes in response speed and fading degree, which can be a direct indicator of changes in food shelf life. Redox reactions, or light-induced redox reactions, between the molecule in the indicator and oxygen in the air are how TTI based on redox reactions achieve color change. Food shelf life can be determined from the reaction rate, which is also strongly correlated with temperature and time accumulation [27].

Intelligent labels and QR codes

The integration of intelligent labels and QR codes into packaging can allow consumers to access detailed information about the origin, processing, and condition of a particular food product at the same time. By scanning a QR code, consumers can obtain information on the harvest date, transportation conditions, and recommended storage practices of the product. This technology can not only enhance transparency but also help consumers make informed decisions about the freshness and safety of the produce when they purchase [1]. A QR is a graphical identification symbol of a specific width and thickness which stores data and

information in a special device, based on the basic principle of optical recognition. Those can be categorized into 1D and 2D codes according to their shape. Those are low-cost, easy to use, and widely used to monitor stock control, inventory recording, and checkout. Based on the type, they have different storage capacities. One-dimensional barcodes are with black and white stripes of different widths, linearly arranged according to certain rules meantime two-dimensional barcodes, are arranged in a two-dimensional geometry. Information can be read quickly and without requiring additional employees or equipment due to QR code technology. Currently, the most popular QR code is the Universal Product Code (UPC). Since each product has a unique UPC, barcodes are used to trace its whereabouts along the supply chain. By deleting or changing the barcode to render it unreadable, this kind of data carrier may also be used with sensors and indicators to verify the freshness of vegetables that are packed [1].

Active packaging

Active packaging is being monitored by actively interacting with the food product to extend its shelf life and this includes materials that can absorb ethylene gas, release antioxidants, or regulate humidity levels within the packaging itself [14].

Ethylene absorbers: These are most commonly useful for fruits that are sensitive to ethylene, including tomatoes and kiwis. By absorbing excess amounts of ethylene, the packaging can slow down the ripening process, extending the shelf life of the product [28].

Antimicrobial packaging: This acts by the incorporation of antimicrobial agents into the packaging material, which can inhibit the growth of bacteria, molds, and yeasts. This technology is very beneficial for leafy greens and berries, which are highly susceptible to microbial spoilage [29].

Table 1. Types of intelligent packaging materials used in fruit and vegetable manufacturing

Type of intelligent packaging material	Purpose	Fruit/ vegetable	Reference
Gas indicator	Detecting the carbon dioxide gas without harming the packaging material	Kimchi	[15]
RFID and WSN	Tracking and tracing food product location along with temperature and humidity data	Kimchi	[30]
RFID, CO ₂ and O ₂ sensor	Determining the freshness of the product	Broccoli	[15]
Sensor	Measuring head space CO ₂ in MAP storage	Salad leaves	[31]
Time-temperature indicator	Monitoring the quality of food during storage or distribution	Any food item	[32]

Limitations of intelligent packaging

Despite the promising advancements, the widespread adoption of intelligent packaging in the fruits and vegetables manufacturing industry witnessed several limitations including the cost, scalability, regulatory challenges, and environmental impact (Fig. 2).

- **Cost**

One of the basic challenges is the cost associated with developing and implementing intelligent packaging systems. The integration of sensors, indicators, and active components into packaging materials increases production costs, which can be a challenge for both manufacturers and consumers. This is particularly challenging in the price-sensitive fruit and vegetables sector, where the margins are normally low [15].

- **Scalability**

The scalability of intelligent packaging technology is another obstacle, and some applications have proven successful on a small scale or in niche markets, scaling these technologies for widespread use with diverse supply chains could be complex. Issues such as sensor calibration, data management, and ensuring the reliability of the technology across different environmental conditions can impede large-scale implementation.

- **Regulatory challenges**

The utilization of intelligent packaging materials imparts new regulatory challenges. Ensuring that these materials are safe for food contact, comply with existing regulations, and are environmentally sustainable requires rigorous testing and certification processes. The regulatory platform varies by region, adding to the complexity of introducing these products to the global market.

- **Environmental impact**

While intelligent packaging can reduce food waste by extending shelf life and improving product quality, it can also contribute to environmental concerns. The production and disposal of high-tech packaging materials often involve the use of non-renewable resources and generate waste that is not easily recyclable. The challenge arises in balancing the benefits of intelligent packaging with the requirement for sustainable practices in the food industry [33].

Future perspectives

Looking forward, the future of intelligent packaging in the fruits and vegetables manufacturing industry has significant promise, but it will require concerted efforts to overcome the current limitations [34].

- **Cost reduction through technological innovation**

In order to make intelligent packaging used in the food industry more accessible, research and development have to focus on reducing the cost of sensors and other components. Advances in nanotechnology, printed electronics, and bioplastics can offer potential solutions to develop more affordable and sustainable intelligent packaging solutions [35].

- **Integration with IoT and Blockchain**

The integration of intelligent packaging with the Internet of Things (IoT) and blockchain technology represents a major opportunity for diverse applications and implementation. IoT-enabled packaging can facilitate real-time monitoring and data collection across the supply chain, while blockchain can ensure transparency and traceability, enhancing consumer trust and regulatory compliance [15].

- **Sustainability**

Since the environmental impacts on the applications become more concerning, the development of sustainable intelligent packaging materials has been crucial. This involves the application of biodegradable or compostable materials, as well as innovations in recycling technology to manage the disposal of packaging waste derived from high technology [35].

- **Consumer education and consumer acceptance**

The success of intelligent packaging will further depend on consumer acceptance. Educating consumers about the advantages of these technologies and the way to use them effectively is essential. This includes clear labeling, user-friendly interfaces, and demonstrating the value of the added cost through enhanced product quality and safety [15].

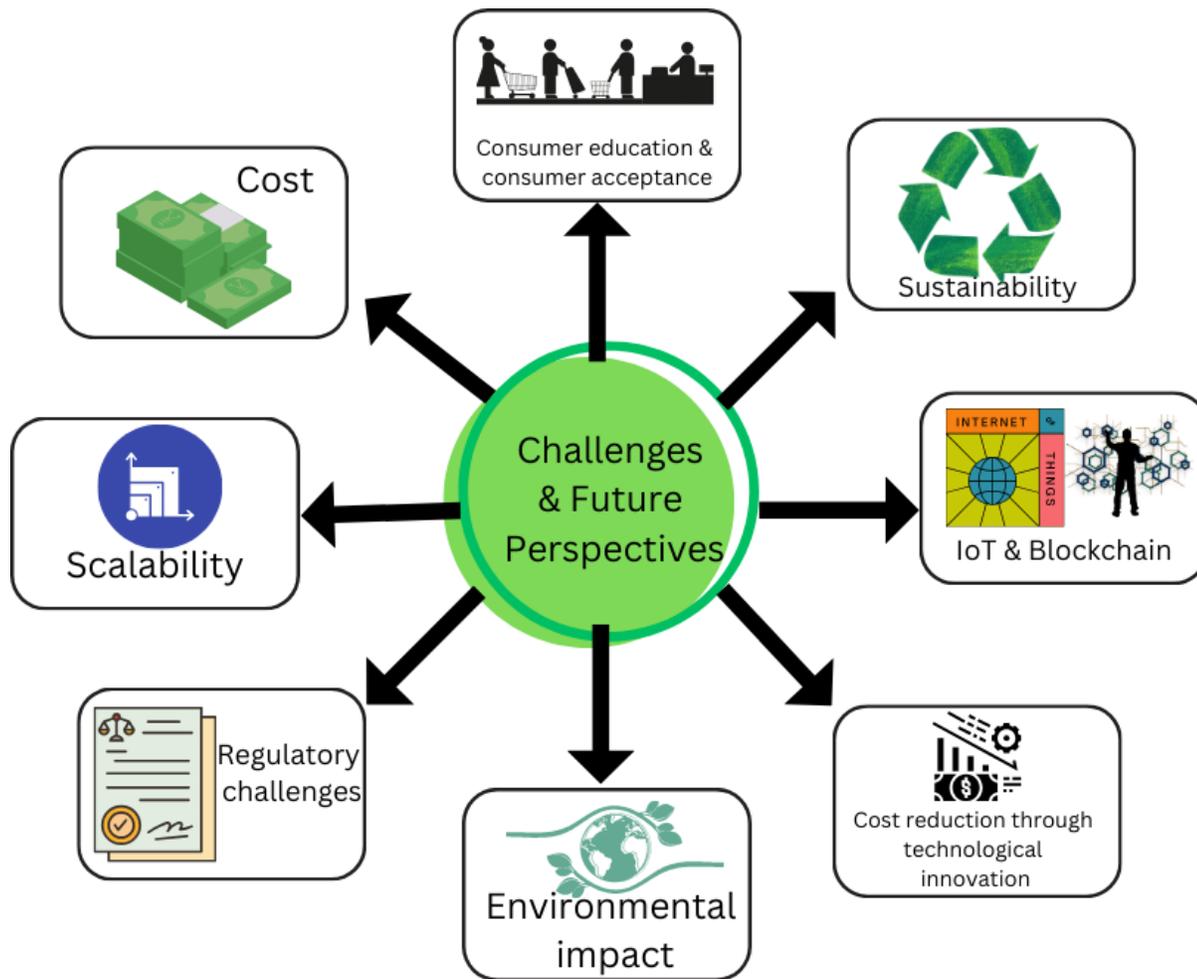


Fig. 2. Challenges and future perspectives of intelligent food packaging

CONCLUSION

Intelligent packaging materials have been representing a transformative advancement in the fruits and vegetables manufacturing industry, offering innovative solutions to enhance product quality, safety, and shelf life. Such packaging applications provides real time indicators about the packed food inside the insights on humidity, temperature, colour and other quality parameters are indicated by contributing to reduce the food waste simultaneously. Sensor focused packaging materials such as humidity sensors, biosensors and indicators inside the packaging including TTIs, gas indicators are common examples for them. Meantime the challenges such as cost, scalability, regulatory hurdles, and environmental impact must be addressed to fully realize the potential of this technology. With continued innovation and a focus on sustainability, intelligent packaging has the potential to play a crucial role in the future of food preservation and distribution, ensuring that consumers have access to fresh, safe, and high-quality produce.

ABBREVIATIONS

World Health Organization (WHO)
Internet of Things (IoT)
time-temperature indicators (TTIs)
radio frequency identification (RFID)
water activity (a_w)
interdigitated electrode (IDE)
polylactic acid (PLA)
polyethylene terephthalate (PET)
polypropylene (PP)
oxygen (O_2)
ethylene (C_2H_2)
polymerase chain reactions (PCR)
enzyme-linked immunosorbent assays (ELISA)
lateral-flow test strip (LFTS)
antibodies (Abs)
gold (AuNPs)
palladium (PdNPs)
Universal Product Code (UPC)

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ACKNOWLEDGMENT

The authors are grateful to the Department of Materials and Mechanical Technology, Faculty of Technology, University of Sri Jayewardenepura, Sri Lanka for facilitating the requirements to conduct the research work and the National Research Council (NRC), Sri Lanka for providing the financial aids under the grant number NRC IDG 22-047 to the research project.

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