



Smart Packaging Adoption in Fresh Fruit and Vegetable Supply Chains: Influencing Factors, Barriers, and Pathways Forward

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Fresh fruits and vegetables account for a disproportionate share of global food loss and waste, largely because they are perishable and often inadequately protected during handling, transport, and storage. Smart packaging (SP) packaging that senses, communicates, or actively regulates the condition of the product it contains has long been promoted as a way to close this gap, yet real-world adoption in the fruit and vegetable sector remains limited. This paper reviews and synthesizes the evidence on why SP has not been adopted more widely and what could change that trajectory. Drawing on a Motivation–Opportunity–Ability (MOA) framework, it organizes the discussion around the incentives that push supply chain actors toward SP, the environmental and market conditions that enable or constrain adoption, and the knowledge and collaborative capacity needed to implement it successfully. The paper concludes with practical recommendations for industry stakeholders and directions for future research.

Introduction

Food loss and waste (FLW) is one of the most persistent inefficiencies in the global food system. A substantial proportion of food produced worldwide never reaches a plate: some is lost between farm and retail due to spoilage, damage, or logistical breakdowns, and additional volumes are wasted later, at the retail, food service, and household stages. Fruits and vegetables are consistently identified as the food categories most affected by this problem, in part because they are fragile, perishable, and frequently packed poorly or not at all. Packaging plays a protective role throughout the supply chain, shielding produce from physical damage and environmental exposure during transport, storage, and retail display. Over the past two decades, researchers and technology developers have proposed a category of packaging known as smart packaging (SP) as a way to go beyond this basic protective function. SP incorporates sensing, communication, or active regulation capabilities that allow it to monitor product condition, extend shelf life, or communicate quality information to different actors along the supply chain. Despite a large and growing body of scientific literature describing SP technologies and their theoretical benefits, uptake in commercial practice especially for fruits and vegetables has lagged behind expectations. Prior research has pointed to a persistent gap between what is technically possible in the laboratory and what is actually deployed on supermarket shelves. Much of the existing literature catalogs the general drivers and barriers behind this gap, but comparatively little work has examined, in a detailed and empirical way, how supply chain actors themselves reason through the decision to adopt or reject SP, or how the various influencing factors interact with one another.

What Is Smart Packaging

Smart packaging is generally divided into two broad categories: intelligent packaging and active packaging. The distinction rests on whether the packaging interacts directly with the product it contains or simply communicates information about it.

Intelligent Packaging: Intelligent packaging does not alter the product directly. Instead, it extends the communication function of ordinary packaging by monitoring and reporting on conditions inside or around the package. This category includes indicators that reveal temperature history, gas composition, or freshness levels; sensors capable of detecting chemical or biological markers of spoilage; and data carriers such as radio-frequency identification (RFID) tags, which allow real-time information to travel with the product through the supply chain. Indicators and sensors are primarily used to communicate product quality, while data carriers support traceability and information flow between supply chain partners.

Active Packaging: Active packaging, in contrast, interacts directly with the packaged product by altering the internal atmosphere of the package. Typical mechanisms include scavengers or absorbers that remove oxygen, carbon dioxide, moisture, or ethylene from the package environment, and emitters that release carbon dioxide or antimicrobial compounds to inhibit microbial growth. The functional difference between a scavenger and an absorber is chemical: scavengers neutralize a substance through a chemical reaction, while absorbers simply capture it physically. Because these technologies act on the product's immediate environment, they are especially relevant to fruits and vegetables, where processes such as ripening and respiration continue after harvest and directly affect shelf life.

Drivers and Barriers Identified in Prior Literature

Before turning to the empirical findings, it is useful to summarize what previous research has already established about the forces that encourage or discourage SP adoption.

Drivers: The most frequently cited driver is shelf-life extension, since it directly reduces FLW by helping preserve product quality and safety for longer periods. A longer shelf life also opens the door to longer transport and storage windows, which can support more complex, geographically extended supply chains. Beyond product preservation, intelligent packaging improves the flow of information along the supply chain, which can help identify inefficiencies early, streamline logistics operations, and reduce associated costs. Improved information systems have also been linked to more efficient freight transportation and to a reduced risk of counterfeiting. Finally, combining SP technologies with other packaging solutions — for example, pairing oxygen scavengers with modified-atmosphere packaging — can improve the overall performance of both.

Barriers: Set against these benefits are several well-documented barriers. Package cost is often higher, particularly for sensors, time-temperature indicators, antimicrobial packaging, and RFID tags. There are also lingering questions about material safety, since some active packaging components could migrate into the food itself. Regulatory environments tend to be strict and cautious about anything that interacts directly with food contact surfaces, which slows approval processes. Additional packaging material, especially where it is not biodegradable, recyclable, or reusable, raises environmental concerns that can offset the FLW benefits SP is meant to deliver. SP performance itself can be inconsistent, undermining confidence in its reliability. Implementation, particularly for RFID-based systems, is often complex, requiring new information infrastructure and cross-organizational collaboration. Consumers frequently show limited awareness of or interest in SP, and even where intelligent packaging succeeds in building consumer trust, it can inadvertently shift purchasing behavior toward the freshest-looking products, increasing waste elsewhere in the retail environment.

Framing the Decision: The Motivation–Opportunity–Ability Approach

To make sense of how supply chain actors actually weigh these competing factors, the underlying study organized its findings using the Motivation–Opportunity–Ability (MOA) framework. Originally developed to explain how consumers process advertising information, the MOA framework has since been applied to a range of supply chain and organizational questions, including servitization relationships, environmental cooperation between firms, and consumer behavior change campaigns. Its core proposition is that behavioral intentions arise from motivation, but whether those intentions translate into actual behavior depends on the opportunities present in the environment and the skills or knowledge available to the actor.

Applied to SP adoption, motivation refers to the reasons supply chain actors want to implement SP in the first place; opportunity refers to the contextual conditions — market structure, regulation, consumer behavior — that make adoption easier or harder; and ability refers to the knowledge, collaborative capacity, and technical competence needed to put SP into practice. The underlying study supplemented this framework with relational diagrams that map how these factors causally influence one another, an approach not commonly used in MOA-based research but one that adds useful nuance by showing, for example, how a single barrier such as high cost can simultaneously discourage adoption while also motivating innovation toward cheaper alternatives.

Motivations for Smart Packaging Adoption

Reduced Food Loss and Waste: The clearest and most frequently cited motivation for adopting SP is its potential to reduce FLW. Shelf-life extension was described as having tangible, sometimes dramatic effects: one interviewee described a British retailer's use of a gas-scavenging pad that extended strawberry shelf life by two to two-and-a-half days, preventing the disposal of tens of thousands of packs. However, translating shelf-life gains into precise FLW reduction estimates proved difficult in practice, partly because SP has not been widely implemented and partly because rigorous before-and-after assessment requires sustained commitment across the supply chain. Where estimates were available, savings appeared to vary substantially depending on the technology and product involved, with some organic-sector applications reporting reductions in the range of 30 to 50 percent. Reduced waste was also tied to direct financial benefits: products that are not discarded can instead be sold, and improved quality and safety perception can independently support higher sales.

Increased Supply Chain Efficiency: Intelligent packaging was also credited with improving overall supply chain efficiency by enabling real-time information sharing, which supports better communication, traceability, and inventory management for retailers. Active packaging can additionally improve the efficiency of other packaging systems already in use, such as modified-atmosphere packaging, by removing ethylene that would otherwise accumulate and shorten shelf life. At the same time, some interviewees cautioned that adding new functionality to packaging lines can slow production, illustrating a trade-off between product-level and process-level efficiency.

Increased Employment in Developing Countries: A less commonly discussed motivation, but one raised independently by an SP producer, was the potential for SP-enabled longer supply chains to support economic development in exporting countries. By allowing produce to travel further without spoiling, SP can help sustain trade relationships that support rural livelihoods in exporting regions, even where this involves additional transport-related environmental costs.

Opportunities: Contextual Enablers and Barriers

Facilitator: The Possibility of Longer Supply Chains: Where supply chains are already short — as is often the case in smaller, geographically compact markets — the case for SP weakens, since products reach their destination while still fresh without additional intervention. In larger markets with greater distances between producers and consumers, shelf-life extension becomes correspondingly more valuable, and SP faces less resistance.

Barrier: Reduced Necessity for Smart Packaging: Several interviewees questioned whether SP is genuinely needed for many products. Fast-selling items such as avocados may move through the retail chain quickly enough that shelf-life extension offers little added value. Consumer awareness of SP also remains low in many markets, meaning that demand for the technology is not being actively pulled through the supply chain. Where existing logistics are already efficient, produce may arrive sufficiently fresh without any additional technological intervention. Raising the visibility of SP through clear communication of measurable benefits was suggested as a way to build both consumer and business demand.

Barrier: Unclear Consumer Purchasing Preferences: Consumer behavior toward SP is inconsistent. Price-sensitive shoppers may be unwilling to pay a premium for smart-packed produce, and more frequent shoppers, who store food for shorter periods, may see less benefit

from shelf-life extension. Even where consumers express a stated willingness to pay for SP benefits, their actual purchasing behavior does not always follow through, creating uncertainty for businesses considering investment. Interactive and easily accessible SP features, such as QR-code-based shelf-life information, were proposed as a way to increase consumer engagement and narrow this gap between stated preference and actual behavior.

Barrier: Legislative Constraints: Regulation, particularly around food contact materials, was widely viewed as a barrier. Concerns about the migration of active packaging components into food create friction with existing food safety rules, and legislative attention increasingly focused on plastic reduction can work against SP formats that rely on plastic substrates. Approval processes for new packaging materials were also described as slow and costly. Interestingly, some interviewees suggested that legislation could become an enabler rather than a barrier if updated to address data protection, transparent trade practices, or binding food waste reduction targets, rather than regulating SP technologies directly.

Mixed Factor: Sustainability Concerns: SP sustainability provoked divided opinions. Additional packaging waste and limited recyclability were widely cited concerns, particularly for plastic- and electronics-based solutions. However, some interviewees pointed out that SP can sometimes be added to packaging that already exists, without generating additional material, and that some newer solutions are designed to be recyclable or reusable. A recurring theme was the mismatch between public perception — which tends to equate less packaging with more sustainability — and the more nuanced scientific view that food waste often carries a larger environmental cost than the packaging used to prevent it.

Mixed Factor: Packaging Safety Concerns: Safety concerns were less frequently discussed but not absent. Some active packaging chemistries, such as those relying on potassium permanganate for ethylene control, were flagged as potentially unsafe by one interviewee even though a competing interviewee's company markets a similar solution, illustrating a lack of industry consensus on which materials are genuinely safe.

Mixed Factor: Varying Performance: Perceptions of SP performance also varied. Ethylene scavengers were praised by some for their proximity to the product, but others noted that performance can degrade sharply when many products with different ripeness levels are packed together, reducing the likelihood that emitted ethylene will actually be absorbed rather than triggering ripening in neighboring produce. Suggested improvements included better handling of product variability and the use of predictive models to estimate remaining shelf life more accurately.

Mixed Factor: High Cost: Cost remains one of the most persistent obstacles, especially given the thin margins typical of the fresh produce industry. Retailers, in particular, were identified as reluctant investors, partly because low-cost retail models leave little room to pass added packaging costs on to consumers. At the same time, cost varies considerably across SP categories and even within a single category such as sensors, suggesting that more affordable options do exist and that further technical development could narrow the cost gap further.

Abilities: Collaboration and Awareness

Collaboration: Collaboration across the supply chain was identified as essential but difficult to achieve. Actors are often protective of their data, which limits the information-sharing needed to make intelligent packaging effective. Retailers were repeatedly described as the pivotal decision-makers: without their buy-in, upstream investment in SP by distributors or packers is unlikely to succeed. Retailer decisions, in turn, are shaped by perceptions of what their own customers will accept, adding another layer of dependency. Creating formal agreements and sharing costs across supply chain partners were both suggested as ways to overcome this collaboration barrier.

Stakeholders' Awareness: A lack of awareness about SP's potential benefits was described as a significant obstacle, driven largely by limited promotion and uneven levels of knowledge across different supply chain actors. Even where some retailers were exploring SP for specific products, others saw no compelling reason to prioritize it given more pressing operational concerns. Interviewees emphasized that awareness alone is not sufficient: actors also need to

know how to act on the information SP provides, whether that means adjusting logistics decisions based on shelf-life data or aligning pricing strategies with inventory freshness. Independent, trustworthy scientific research was suggested as a way to build confidence in SP claims, particularly given that much current messaging about SP benefits comes directly from vendors with a commercial interest in promoting it.

Discussion

Taken together, these findings suggest that the gap between SP's technical potential and its limited real-world adoption in the fruit and vegetable sector cannot be explained by any single barrier. Rather, it reflects the interaction of multiple, sometimes offsetting, forces. Cost, regulation, and inconsistent performance all constrain adoption, but they interact with genuine motivations — waste reduction, efficiency gains, and even developmental benefits for exporting countries — that continue to make SP an attractive proposition in principle. Several points of tension deserve particular attention. First, the sustainability trade-off between packaging waste and food waste is not easily resolved and depends heavily on the specific product and technology involved; blanket assumptions that less packaging is always more sustainable can work directly against FLW reduction goals. Second, retailers occupy an outsized role as gatekeepers of SP adoption, meaning that efforts to expand SP use should arguably focus disproportionately on retailer incentives and constraints rather than on upstream producers or technology developers alone. Third, legislative attention may be more usefully directed toward transparency, data protection, and binding waste-reduction targets than toward SP-specific regulation, since the latter risks reinforcing existing barriers around approval complexity rather than easing them. It is also worth noting that consumer behavior surrounding SP is more complex than a simple awareness deficit. Even informed and willing consumers do not always translate stated preferences into purchasing behavior, suggesting that engagement strategies need to go beyond information provision toward more active, interactive forms of communication.

Conclusions

Smart packaging retains clear, evidence-backed potential to reduce food loss and waste, improve supply chain efficiency, and, in some cases, support economic development along extended supply chains. Yet its adoption in the fresh fruit and vegetable sector continues to lag behind its technical promise, held back by a combination of cost, regulatory friction, inconsistent performance, sustainability trade-offs, and gaps in collaboration and awareness across the supply chain. Future research would benefit from several directions in particular: more rigorous, case-based quantification of the FLW reductions SP actually delivers under real operating conditions; deeper investigation into the retailer perspective, given retailers' outsized influence over adoption decisions; and further study of the net environmental impact of SP once packaging waste, food waste, and transport-related trade-offs are considered together. Because many of the perishability and shelf-life challenges affecting fruits and vegetables are shared by other short-shelf-life products including meat, fish, eggs, and even certain healthcare products insights from this sector are also likely to be transferable, making continued research in this space valuable well beyond its immediate scope.

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