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Smart packaging adoption in fresh fruits and vegetables supply chains

Oana Butuc and Renzo Akkerman
Wageningen University and Research, Wageningen, Netherlands, and
Sander de Leeuw
Wageningen University and Research, Wageningen, Netherlands and
Department of Strategy, Analytics and Operations,
Nottingham Business School, Nottingham Trent University, Nottingham, UK

Abstract

Purpose – The purpose of this paper is to identify the influencing aspects behind the decision of smart packaging (SP) adoption for fresh fruits and vegetables and what improvement directions facilitate such adoption.
Design/methodology/approach – Empirical data are collected from interviewees who are active in the supply chain of fruits and vegetables and have expertise about their packaging. The data are analysed using the Motivation–Opportunity–Ability framework coupled with relational diagrams.
Findings – The paper provides empirical insights about the influencing aspects (categorized into motivations, opportunities and abilities) and improvement directions of SP adoption for fresh fruits and vegetables. Key motivations to adopt SP are reduced food loss and waste, increased supply chain efficiency and increased employment in developing countries. Important opportunities relate to the possibility of exploiting longer supply chains and contextual barriers that reduce SP necessity, unclear consumer purchasing preferences for SP and legislative barriers. The supply chain actors' abilities identified are collaboration and stakeholders' awareness. The improvement directions identified relate to actions for increasing the ease of using SP and reducing the associated costs.
Originality/value – Despite the extensive knowledge available in the literature, SP adoption in practice is still quite limited, especially on fruits and vegetables. This research's empirical findings contribute to closing this gap and suggest improvement directions for SP adoption on fruits and vegetables, thus minimizing loss and waste along the supply chain.

Keywords Smart packaging adoption, Fruits and vegetables, Food loss and waste

Paper type Research article

1. Introduction

In 2021, approximately 13% of produced food was lost before reaching retail (UNEP, 2021) and 19% was wasted at retailers, food services and households (UNEP, 2024). Fruits and vegetables are the food groups that are lost and wasted the most (22% and 24%, respectively), representing around 46% of the total food loss and waste (FLW) (Caldeira *et al.*, 2019). Fruits and vegetables are often not packed or poorly packed, making it more vulnerable to damage and deterioration (FAO, 2019). Packaging protects food for transport, storage, retail and consumer use (Saha *et al.*, 2022) and has an essential role in preserving its quality and extending its shelf life (FAO, 2019). To improve monitoring infrastructures, ensure product quality and reduce FLW, smart packaging (SP) is often proposed (Alam *et al.*, 2021; Onwude *et al.*, 2020).

SP has great potential to reduce FLW throughout the supply chain but has not been implemented widely (Drago *et al.*, 2020). Previous research has argued that there is a significant gap between scientific research and the market (Drago *et al.*, 2020; Wang *et al.*, 2019). Literature describes more SP solutions (such as freshness indicators) for food products than are actually applied in practice (Barska and Wyrwa, 2017). Recently, Sarma *et al.* (2023)

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concluded that the commercialization of SP is still quite limited. This is potentially connected to the lack of stakeholders' awareness about the SP potential on food products (Gigauri *et al.*, 2024). Moreover, although there have been studies on the drivers and barriers of SP (e.g. (Ganeson *et al.*, 2023, Sarma *et al.*, 2023)), these do not sufficiently provide a deeper understanding of the decision process behind SP adoption. According to Gigauri *et al.* (2024), there is limited research on the stakeholder's perspective about SP. In addition, although fruits and vegetables represent a high percentage of FLW in the supply chain (UNEP, 2024), this food category has not received much attention in previous research on SP (compared to, e.g. meat or fish products) (Alam *et al.*, 2021; Beshai *et al.*, 2020; Poyatos-Racionero *et al.*, 2018). Therefore, exploratory research is needed to understand the reasons behind the lack of SP adoption on fruits and vegetables and how this can be increased, from an empirical perspective, identifying the influencing aspects behind the drivers and barriers.

The aim of this study is to understand the influencing aspects behind the decision of SP adoption for fresh fruits and vegetables. Influencing aspects are defined as the main reasons that inhibit or enable the decision to implement SP on fresh fruits and vegetables. Additionally, these aspects are addressed with a higher level of detail by connecting them with causality links (relational diagram), allowing a deeper understanding than merely focusing on drivers and barriers. As a consequence of understanding these aspects, improvement directions that move towards enabling a wider adoption of SP were also derived. We retrieved these aspects and directions from an exploratory approach, by conducting semi-structured interviews with stakeholders from different stages in the supply chain, such as fruits and vegetables distribution companies, packaging companies and retailers. The data analysis consisted of categorizing the results by using the Motivation–Opportunity–Ability (MOA) framework coupled with relational diagrams. The MOA framework is helpful in analysing the decision process of supply chain actors since it has been a well-established information processing tool in management research (Macinnis *et al.*, 1991). The relational diagrams aim to further increase the understanding of how the many influencing aspects are connected in terms of cause and effect.

The remainder of this paper is structured as follows: Section 2 presents an overview of the literature on SP; followed by Section 3, where it is described how we approached and analysed the interviews; then Section 4, the empirical results are presented; in Section 5, the results are discussed and compared to previous literature; finally, Section 6 presents the conclusions.

2. Literature review

In this section, we briefly discuss the different types of SP that exist and outline what previous literature has discussed in terms of aspects influencing SP adoption in the fruits and vegetables supply chain.

2.1 Smart packaging

SP is a type of packaging that incorporates technology that provides an additional and more specific functionality to conventional packaging. As depicted in Figure 1, SP can be classified into two categories: intelligent packaging and active packaging (Beshai *et al.*, 2020; Siracusa, 2016).

(1) *Intelligent packaging* does not have a direct impact on the product (Biji *et al.*, 2015) but can be considered an extension of the communication function of conventional packaging (Salgado *et al.*, 2021). Intelligent packaging can be classified into indicators (time-temperature, gas and freshness), sensors (chemical and biosensors) and data carriers [radio frequency identification (RFID)] (Müller and Schmid, 2019). Indicators and sensors typically provide information regarding product quality (qualitative and quantitative, respectively), while data carriers enable the information flow along the supply chain (Beshai *et al.*, 2020; Drago *et al.*, 2020).

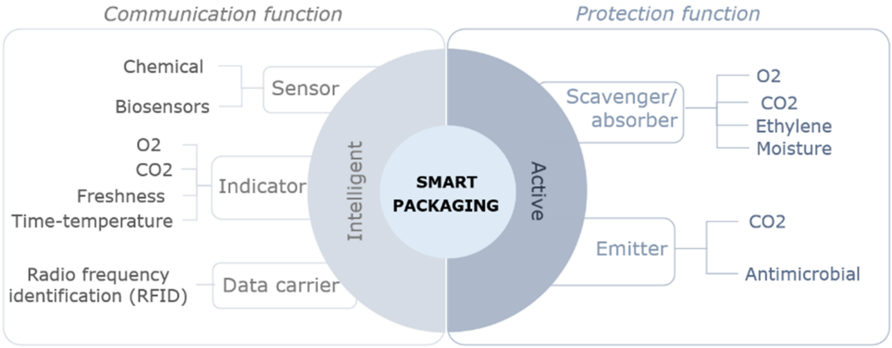

Figure 1. SP categories according to their functionalities. Source: Authors' own work, using information from Beshai *et al*. (2020), Lydekaityte and Tambo (2020)

(2) *Active packaging* interacts directly with the packed products, being an extension of the protection function of conventional packaging (Salgado *et al.*, 2021). With active packaging, the packaging environment is maintained favourable to avoid quality decrease, mainly by removing/adding certain substances from the atmosphere inside the package. Six active packaging categories are typically distinguished: oxygen scavenger, carbon dioxide scavenger and emitter, ethylene scavenger/absorber, moisture absorber and antimicrobial emitter (Salgado *et al.*, 2021; Siracusa, 2016; Vigneshwaran *et al.*, 2019). The difference between scavengers and absorbers is that scavengers eliminate the substance by chemically reacting with it, while absorbers merely physically absorb it (Drago *et al.*, 2020).

In Table 1, a more detailed description of each intelligent and active packaging category is presented to elaborate on their main functionality and in which form they are used. For the interested reader, in the Supplementary Material, we include an overview of commercially available SP solutions for different categories.

2.2 Drivers and barriers of smart packaging adoption

Previous literature has already identified various drivers and barriers with respect to the adoption of SP (summarized in Table 2). Among key drivers, the ability to extend shelf life stands out as one of the most important, as it helps to reduce FLW by better ensuring and communicating food safety and quality (Vigil *et al.*, 2020; Chen *et al.*, 2020). The extended shelf life also enables longer transportation and storage (Wyrwa and Barska, 2017). Additionally, intelligent packaging increases the efficiency of the information flow along the supply chain, which can be useful for early detection of supply chain inefficiencies and improving logistics operations, leading to the reduction of associated costs (Müller and Schmid, 2019). A good information system has positive effects on the efficiency of freight transportation (Kye *et al.*, 2013) but also helps prevent counterfeiting (Wang *et al.*, 2019). Finally, combining different packaging solutions optimize their efficiency, e.g. oxygen scavengers with modified atmosphere packaging or RFID with other intelligent packaging, e.g. sensors (Wang *et al.*, 2019; Biji *et al.*, 2015).

Although SP clearly has promising opportunities, there are also barriers related to its adoption. Firstly, the package cost may increase (mainly for sensors, TTI, antimicrobial and RFID) (Drago *et al.*, 2020; Sobhan *et al.*, 2021; Jung and Zhao, 2016; Wang *et al.*, 2019). Secondly, the safety of using certain materials is questioned due to the possible migration of components into food (mainly in ethylene scavengers, biosensors, freshness indicators and O_2 indicators and sensors) (Sharma and Ghoshal, 2018; Beshai *et al.*, 2020; Drago *et al.*, 2020).

Table 1. Form and function of each category of intelligent and active packaging

SP	Category	Form	Function	References
Intelligent packaging	Time-temperature indicator (TTI)	Tag, label	Detect temperature fluctuations in a certain time frame	Biji *et al.* (2015), Fuertes *et al.* (2016), Kuswandi and Jumina (2020), Müller and Schmid (2019), Pavelková (2013), Poyatos-Racionero *et al.* (2018), Sani *et al.* (2021), Taoukis and Tsironi (2016), Wang *et al.* (2019), Ahari and Soufiani (2021)
	Gas indicator	Label, film, printing ink	Detect changes in the gas (O_2/CO_2) composition inside the packaging. Useful to detect packaging integrity and gas release from spoilage	Drago *et al.* (2020), Fuertes *et al.* (2016), Müller and Schmid (2019), Salgado *et al.* (2021), Wang *et al.* (2019), Ahari and Soufiani (2021)
	Freshness indicator	Label, tag	Detect metabolites released by food resulting from ripening (fruits and vegetables) or microbial growth	Drago *et al.* (2020), Mustafa and Andreescu (2018), Poyatos-Racionero *et al.* (2018), Taoukis and Tsironi (2016)
	Chemical sensor	Film	Detect the presence, concentration and composition of compounds resulting from chemical reactions of food spoilage (e.g. O_2, CO_2)	Biji *et al.* (2015), Drago *et al.* (2020), Müller and Schmid (2019)
	Biosensor	Film	Detect the presence, concentration and composition of compounds resulting from biological reactions of food spoilage (e.g. pathogens, toxins)	Barska and Wyrwa (2017), Beshai *et al.* (2020), Biji *et al.* (2015), Drago *et al.* (2020), Salgado *et al.* (2021), Sharma and Ghoshal (2018)
	Radio frequency identification (RFID)	Label	Store and communicate real-time product information, over long distances. Useful for traceability	Drago *et al.* (2020), Müller and Schmid (2019), Biji *et al.* (2015), Fuertes *et al.* (2016), Poyatos-Racionero *et al.* (2018), Salgado *et al.* (2021), Sharma and Ghoshal (2018), Soon and Manning (2019), Wang *et al.* (2019), Yousefi *et al.* (2019), Barska and Wyrwa (2017)
Active packaging	O_2 scavenger	Sachet, label, film, tray	Reduce the amount of O_2 inside the packaging to avoid oxidative food deterioration	Beshai *et al.* (2020), Biji *et al.* (2015), Drago *et al.* (2020), Janjarasskul and Suppakul (2018), Kuswandi and Jumina (2020), Salgado *et al.* (2021), Vigneshwaran *et al.* (2019), Wyrwa and Barska (2017), Barone *et al.* (2021)
	CO_2 scavenger	Sachet, pad, film	Reduce the amount of CO_2 inside the packaging to avoid undesirable flavour, texture and colour	Mustafa and Andreescu (2018), Wyrwa and Barska (2017), Beshai *et al.* (2020), Biji *et al.* (2015), Drago *et al.* (2020), Kuswandi and Jumina (2020), Barone *et al.* (2021)

(*continued*)

Table 1. Continued

SP	Category	Form	Function	References
	CO_2 emitter	Pad	Increase the amount of CO_2 inside the packaging to inhibit microbial growth and reduce respiration rate	Mustafa and Andreescu (2018), Wyrwa and Barska (2017), Beshai *et al.* (2020), Biji *et al.* (2015), Janjarasskul and Suppakul (2018), Kuswandi and Jumina (2020), Vigneshwaran *et al.* (2019), Barone *et al.* (2021)
	Moisture absorber	Sachet, pad, sheet, tray	Reduce moisture inside the packaging to inhibit microbial growth	Alam *et al.* (2021), Drago *et al.* (2020), Kuswandi and Jumina (2020), Vigneshwaran *et al.* (2019), Wyrwa and Barska (2017), Beshai *et al.* (2020), Biji *et al.* (2015), Janjarasskul and Suppakul (2018), Barone *et al.* (2021)
	Ethylene scavenger/ absorber	Sachet, film	Reduce the amount of ethylene inside the packaging to delay ripening	Biji *et al.* (2015), Drago *et al.* (2020), Janjarasskul and Suppakul (2018), Mustafa and Andreescu (2018), Salgado *et al.* (2021), Sharma and Ghoshal (2018), Wei *et al.* (2021), Vigneshwaran *et al.* (2019), Wyrwa and Barska (2017), Barone *et al.* (2021)
	Antimicrobial emitter	Sachet, pad, sheet, tray, label, film	Increase the antimicrobial components inside the packaging to inhibit microbial growth	Vigneshwaran *et al.* (2019), Beshai *et al.* (2020), Biji *et al.* (2015), Drago *et al.* (2020), Janjarasskul and Suppakul (2018), Kuswandi and Jumina (2020), Wyrwa and Barska (2017), Ahari and Soufiani (2021), Barone *et al.* (2021)

Source(s): Authors' own work, using information from literature.

Table 2. Summarizing table of drivers and barriers for SP adoption

Drivers	Barriers
Food loss and waste reduction	High packaging cost
Shelf life extension	Questionable packaging safety
Food quality and safety assurance	Strict legislation
Information flow enhancement	High packaging waste
Longer transportation and storage	Packaging performance
Reduction of logistics costs	Complex implementation
Prevention of counterfeiting	Consumer awareness
Other technologies efficiency optimization	Consumer picking behaviour

Source(s): Authors' own work, using information from literature.

Thirdly, regulations can be very strict and conservative about food contact materials to guarantee food safety (Mohammadian and Jafari, 2020; Drago *et al.*, 2020). Fourthly, packaging waste is generated because most of the material used is neither biodegradable, easily recyclable nor reusable (Alam *et al.*, 2021). This is related to the perceived negative impact on the environment that such packaging may have (Russell, 2014). Fifthly, SP might not be 100% reliable nor fully accurate, posing performance barriers (Sani *et al.*, 2021). Sixthly, the implementation of SP can be complex (mainly RFID) because more information is shared, which requires an updated network to handle and protect such information, but also multidisciplinary collaboration (Chen *et al.*, 2020; Alam *et al.*, 2021). Seventhly, consumers are reluctant to new technologies, which can be justified by the lack of awareness about the purpose and function of such innovations (Janjarasskul and Suppakul, 2018). Finally, intelligent packaging informs consumers, which increases their trust, but it can also negatively influence their purchasing behaviour in the sense of making them choose fresher products and consequently increasing food waste in supermarkets (Müller and Schmid, 2019).

There is extensive knowledge in the literature about the influencing aspects of SP adoption; however, in practice, SP is not widely applied on fruits and vegetables, making it necessary to merge the existent theoretical knowledge with empirical data (Lydekaityte and Tambo, 2020). Therefore, the purpose of this paper is to understand, from an empirical perspective, why SP is not adopted as widely as expected and what improvement directions facilitate such adoption.

3. Methodology

3.1 Research approach

This research has an exploratory nature in which interviews were conducted. Semi-structured interviews, built around a series of open questions, were chosen because (1) we wanted to get the independent perspective of each individual stakeholder; (2) to be able to further explore, with follow-up questions, interesting points of view that would emerge around a pre-defined question; and (3) to provide the safe environment for the interviewees to express themselves and avoid potentially biased responses, for example, due to the presence of another individual if a focus group was conducted (Adams, 2015). The interview consisted of two main topics: SP adoption and SP improvement directions. The main interview guide is presented in Appendix 1, in which the formulated questions aim at gathering information on the reasoning behind SP adoption and possible improvement directions. These two topics were addressed in the interview because, according to Beshai *et al.* (2020), there is a reduced number of studies about SP adoption of fruits and vegetables and there is a need to investigate how the current SP can be improved.

The transcription of the interviews was done with *Amberscript* and by using the text recording facility of *Microsoft Teams*. The interviews were conducted remotely via *Microsoft Teams* or *Zoom* video calls and lasted about 45 min. The meetings were recorded, with the interviewee's permission, to facilitate correct transcription, ensuring accuracy and providing a strong foundation for evidence documentation (Voss *et al.*, 2002).

The selection of interviewees was based on two criteria: interviewees should (1) be active in the supply chain of fruits and vegetables and (2) have expertise about fruits and vegetables packaging. The focus was on approaching representatives from different stages in the fruits and vegetables supply chain, as depicted in Figure 2, including distribution companies of fruits and vegetables, packaging companies, packaging consultant companies, packaging researchers, SP associations and retailers.

We aimed at finding a spread of supply chain actors to interview by contacting them through the relevant companies' websites, LinkedIn pages and contacts of people who were interviewed. A total of 50 people were contacted, resulting in 19 interviews. We conducted 19 interviews because we reached theoretical saturation, as we observed minimal incremental learning (Eisenhardt, 1989). In Appendix 2, a detailed description of the interviewees can be found (their role, company type and if they use/produce SP). All participants provided informed consent before participation and no sensitive personal data was collected. For privacy and confidentiality reasons, the personal information and company names are kept anonymous.

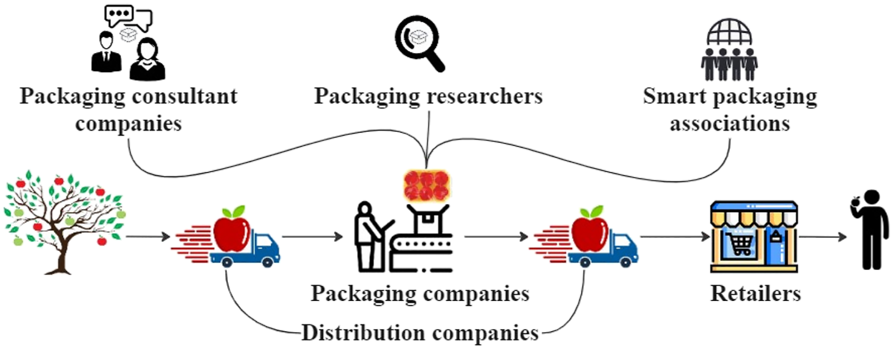

Figure 2. Scope – supply chain actors selected for the interviews. Source: Authors' own work

The data analysis was done within case data and by searching for cross-case patterns (Voss *et al.*, 2002). Firstly, we looked into each interview results to identify specific key words that were mentioned as aspects. Secondly, we compared between different interviews the key words obtained to search for differences and similarities to increase the findings validity (Voss *et al.*, 2002). Thirdly, considering the definition of each category of the MOA framework and the key words derived from the interviews, we were able to place them in the respective category. The relational diagram was built based on the variables that have a positive or negative impact on these aspects, mentioned by the interviewees. The improvement directions were also identified by key words and included in the relational diagram, as having a positive influence towards facilitating SP adoption.

3.2 Motivation–opportunity–ability (MOA) framework

The MOA framework is a management research tool that has not been often used in supply chain management despite its great potential (Kim *et al.*, 2015). Nevertheless, the MOA framework was used in several studies, for example, to explore the managerial challenges in servitization relationships in the supply chain (Raja and Frandsen, 2021), to assess the efficacy of consumer food waste awareness campaigns (Soma *et al.*, 2021), to assess how the effectiveness of buyer-driven knowledge transfer impacts the supplier's operational performance (Kim *et al.*, 2015), to understand the impact of environmental cooperation with customers on financial performance (Chen *et al.*, 2022). This framework states that motivations are translated into behavioural intentions and that actual behaviour is dependent on the knowledge/skills and opportunities present in the environment (Macinnis *et al.*, 1991).

In this paper, this relates to (1) the motivation of the supply chain actors' to implement SP; (2) the environmental or contextual enablers and inhibitors of SP adoption (opportunity); and (3) the supply chain actor's knowledge, skills and competencies to implement such technology (ability). We categorized the aspects according to the MOA framework and supplemented this with relational diagrams to include interdependencies between aspects. The latter is not commonly used in studies based on the MOA framework, but we use the relational diagrams to include the cause-and-effect relationships that were identified by the interviewees. This allows us to make the interactions between aspects more explicit and increase the overall understanding behind each influencing aspect. The relational diagrams are based on the causal loop diagrams used in System Dynamics methodology (see, e.g. Sterman (2000)).

The results section is structured based on the categories of the MOA framework. Firstly, for a general overview of the results, a figure is presented. In this figure, all the obtained influencing aspects are placed in the respective category (motivations, opportunities and abilities) with the relational diagram, in which the improvement directions are highlighted as well. Next, in each subsection, the results (influencing aspects and improvement directions) are addressed considering their category (Section 4.1 – Motivations, Section 4.2 – Opportunities and Section 4.3 – Abilities). In these subsections, the interviewees insights are presented in more detail, allowing the reader to further understand how the relational diagram was built.

4. Results

In this section, we present our results with regard to the influencing aspects and the improvement directions that need to be tackled, which were identified by the interviewees. When referring to or quoting specific interviewees, we use the labels IN1–IN19, which correspond to the interviewee numbers listed in Appendix 2.

Figure 3 depicts a summary of the results. With this figure, it is possible to visualize the motivations, opportunities and abilities that are behind the adoption of SP. The aspects mentioned by the interviewees are placed within each category of the MOA framework, represented by the coloured boxes. These motivations, opportunities and abilities have an influence on achieving the goal, which is represented by the arrow pointing to the green circle. In addition, a relational diagram is presented around the three main boxes to give more understanding of the causality of aspects (in grey text) but also to understand how the improvement directions identified (green text) impact these aspects. The links are represented by the arrows that show the positive (+) or negative (−) relationships. All the information used to create this figure was retrieved from the interviews.

4.1 Motivation

The supply chain actors' motivations to implement SP, identified during the interviews, are reduced food loss and waste, increased supply chain efficiency and increased employment in developing countries.

4.1.1 Reduced food loss and waste. There was no doubt about the benefits of using SP in actual practice. Using SP leads to shelf life extension, which is beneficial, impacting FLW positively. IN14 indicates this clearly, based on a successful case of one British retailer: *"Strawberries have a very short shelf life but by putting this (gas scavenging) pad in the bottom, they extended shelf life of these by 2 or 2.5 days. That in terms of strawberries is immense, and it meant that they saved disposing of probably 20 or 30 thousand packs of strawberries"*. It can, however, be challenging to translate shelf life extension into estimates of how much FLW could actually be reduced when using SP. The interviews showed that this may depend on the type of product but also on the conditions under which the product is used and the type of technology applied. According to IN19, it is quite hard to quantify the reduction of loss and waste of fruits and vegetables using SP for two main reasons. Firstly, it has not been widely implemented. Secondly, even in those implemented cases, it is still a very detailed assessment that takes a lot of commitment and needs the support of the entire supply chain. Nevertheless, IN5 has experienced in the organic food sector that savings depend on the technology used: *"When we used long life bags, we reduce it (FLW) about 30–35%. We could save more, I know from my colleagues, from non-organics, they put pads on grapes, and save a lot more. I think waste saving would be around 45–50%"*.

Another important aspect related to FLW reduction that was mentioned frequently (IN4, IN10, IN12 and IN18) is saved costs. It was argued that if products are not wasted, these can be sold, thus increasing the revenue and profit (IN11, IN14 and IN16). Additionally, since quality and safety are typically improved by SP, the use of SP also independently increases sales (IN19). An SP expert we interviewed puts it as follows: "*It gives them (retailers) more sales, less discounting and they don't need to throw food away. The consumers can keep the product for longer and therefore it's less waste to them and more money in their pocket. [. . .] It's not necessarily a step too far in terms of cost against value because what you can save is probably quite often more than what you're wasting"*.

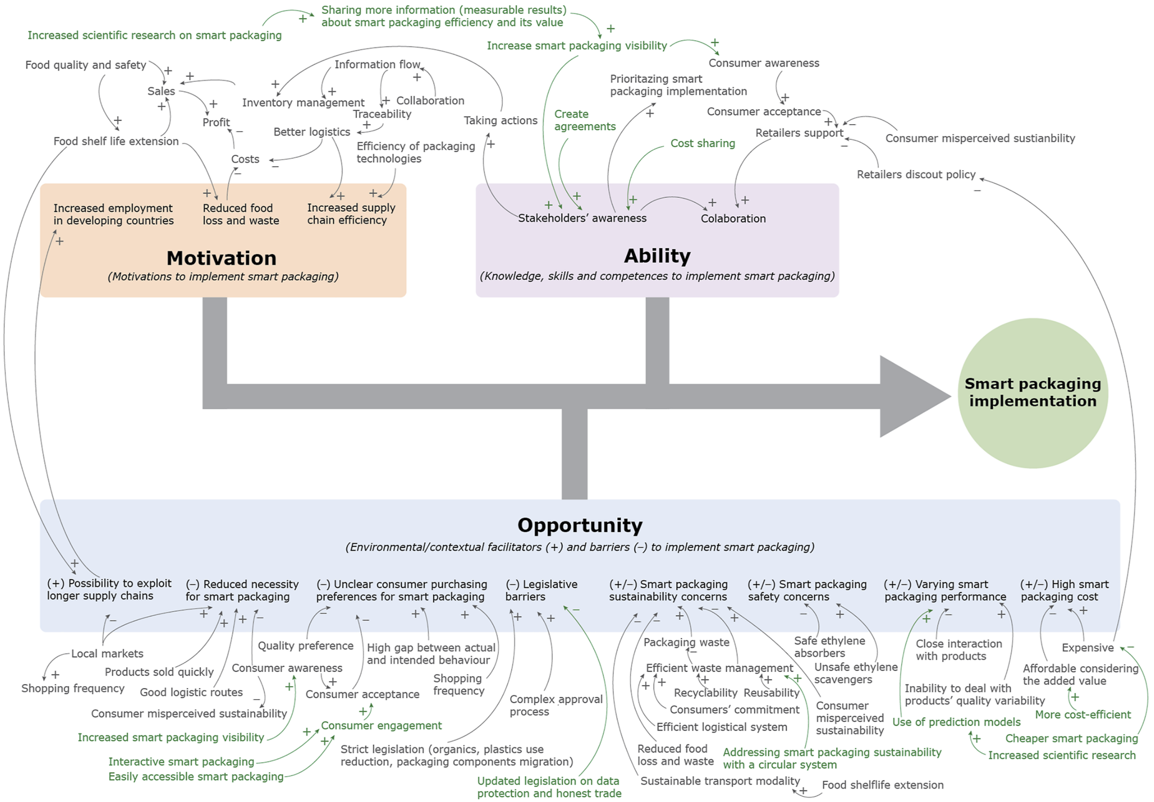

Figure 3. Results overview, retrieved from the interviews, using the MOA framework with a relational diagram. Influencing aspects are placed within each coloured box; the grey text represents causality behind the aspects, the green text represents the improvement directions and the arrows with + and – are the positive and negative relationships, respectively. Source: Authors' own work

4.1.2 Increased supply chain efficiency. With intelligent packaging, the efficiency of the supply chain can be increased. Since more real-time information is shared about the product, intelligent packaging connects the different actors, allowing better communication and traceability along the entire supply chain (IN7, IN10, IN15 and IN18). Connected to the increase in information flow, retailers can better manage their stock (IN14 and IN15). Since they have more information about the product, they are able to control their inventory and thus apply discounting strategies, as stated by a food supply chain analyst. Another relevant point about the efficiency of the supply chain is that using active packaging can increase the efficiency of other packaging technologies (IN19), for example, modified atmosphere packaging: *"The detrimental part of modified atmosphere packaging is it traps the ethylene within that pack. If you absorb the ethylene within that pack, you extend the product shelf life by another 2–3 days. So, it increases the technologies' efficiency"*. Nevertheless, despite the potential of SP increasing the overall efficiency of the supply chain, it can also compromise it with regards to an efficiency decrease in packaging processes, for instance, by adding another functionality (e.g. processor) to a high speed production line, it will slow down the packaging line (IN14).

4.1.3 Increased employment in developing countries. With SP, food can be transported through longer supply chains. This can contribute to the growth of developing countries that export fruits and vegetables, as explained by a SP producer: *"Globalization is here and it's a great way of helping poorer countries develop. I think food has a great way to maintain those rural communities in far off countries even if there is the assumed carbon penalty. In my opinion, those countries are part of the global food solution that we have, and there is a price to pay. But if we're sensible about it, it's a price that is worth paying"*.

4.2 Opportunity

In the MOA framework, opportunities are the environmental/contextual facilitators (identified with "+") and barriers (identified with "–") to implement SP. Therefore, the facilitator (+) mentioned during the interviews is the possibility to exploit longer supply chains and the barriers (−) mentioned are the reduced necessity for SP, unclear consumer purchasing preferences for SP and legislative barriers. Nevertheless, there were aspects identified as both facilitators and barriers (+/−) such as the SP sustainability concerns, packaging safety concerns, varying packaging performance and high packaging cost.

4.2.1 Facilitators. 4.2.1.1 Possibility to exploit longer supply chains (+). With shelf life increase comes the possibility of having longer supply chains, which is an advantage of SP. If products last longer, they can be transported and stored for longer periods of time (IN17). This means that products can be supplied by producers from further exporting countries, and thus, this opportunity is connected to the motivation previously mentioned of increasing employment in developing countries. Nevertheless, when local markets are in place, supply chains are naturally shorter making SP unvaluable, as explained by a packaging manager (IN6): *"The Netherlands is a fairly small country where the consumers are close to the producers. In America, the distances are significantly larger, so they will allow smart packaging quicker"*.

4.2.2 Barriers. 4.2.2.1 Reduced necessity for SP (−). Some interviewees have questioned the business and consumer need for SP (IN10, 15). The low necessity for SP is a barrier due to three main reasons. Firstly, SP is not needed for all products, e.g. avocados, as they are sold quickly, as stated by IN9 (retail sector). Secondly, mainly in Europe, the consumers' awareness seems to be relatively low. In other countries, consumers are more open to new technologies and conscious about quality (IN6, IN16 and IN18). The potential of SP is unknown to consumers and consequently they do not ask for such technology (IN1). Thirdly and finally, according to IN5 and IN7, in the specific case of the Netherlands, the supply chain is already very efficient, thus, produce are sufficiently fresh when arriving to their desired destination: *"If you take it off the tree right into the box, send it to Holland where it is packed,* *you have less problems. You don't have to do much with smart packaging because they're pretty fresh. The need has not been there to use it wide scale"*.

Increasing the visibility of SP could help raise consumer awareness and potentially increase both the need and acceptance for such technology (IN1, IN5, IN6, IN10, IN12, IN13, IN14, IN16, IN18 and IN19). Sharing more information about SP efficiency, how it works and the value it brings to the different supply chain actors, including retailers and consumers, will increase their awareness (IN1). If people become more aware, they will more easily accept and implement SP. This should be done by presenting measurable results, as IN10 highlighted: *"Present good examples to show that if you have this packaging in the fridge, it reduces about 25% of food waste at the consumer level. So showing how strong they are and that there's enough added value to consider this option"*.

4.2.2.2 Unclear consumer purchasing preferences for SP (**–**). Consumers have different purchasing behaviours, which pose a barrier to SP adoption. There are different consumer segments which go to supermarkets that satisfy their needs according to their quality preference. For example, SP would not be a good solution for consumers who prefer low price products rather than choosing (potentially more expensive) products aimed at avoiding FLW (IN9). Additionally, the shopping frequency plays an important role since more frequent shopping leads to shorter storage periods, and SP becoming less valuable (IN16 and IN18). Moreover, even if SP would be beneficial to a certain consumer segment, it is not straightforward that this consumer will accept and purchase smart-packed produce. Although information is provided about the SP potential and there is a positive response, consumers' actions often differ from their intended behaviour, as emphasized by packaging manager IN5: *"I would say that consumer, if you tell them why, they are willing to pay for it. But again, are they going to do it? Is their behaviour going to follow what they say?"*.

Increasing consumer engagement could be advantageous in promoting greater consumer acceptance of purchasing SP. Making SP interactive and easily accessible can engage consumers (IN10, IN17 and IN18); however, this feature is more appropriate to intelligent packaging. As IN10, explains, it should display different types of information in various different ways: *"Have a QR code for shelf life, for promoting healthy eating, which is a big trend. Having these interactive techniques also for kids in schools. It should be interesting and attractive enough for consumers. [. . .] If you have 10 products in your fridge, then I know which one needs to go first because of its shelf-life. It can be used an app as well"*.

4.2.2.3 Legislative barriers (**–**). Legislation is mentioned as mostly being a barrier for SP adoption. Current EU regulations about food quality and safety are quite strict (IN6, IN7 and IN12). When talking about packaging legislation, the focus is on the migration of packaging components into food, which is the main drawback for active packaging adoption, as explained by packaging expert IN4: *"The regulations prevent the implementation of solutions because when you talk about interactions between the package and the food, if something comes out of the package and migrates to the food that can be a safety problem. But in active packaging, we actually want an interaction between the packaging and food but according to the regulations, this is not allowed because it's focused on the prevention of migration"*. Additionally, SP adoption might be inhibited because current legislation is switching the focus to plastic reduction (IN13). A manager from a packaging manufacturer (IN11) provided the example of France, which has in place a plastic ban on fruits and vegetables. Moreover, the approval process of a new packaging material is quite complex. The product must "*prove itself multiple times*" before the company can start using it (IN3). SP expert IN14 further developed this line of thought: *"If you're using stuff that's outside of the known world of ingredients to try and produce an inhibitor, it has to go through approval. Well, my experience with EFSA [European Food Safety Authority] is not good, not because they deny things, but because it takes them too long to deliver a judgment on it. If you developed a product and it's taking you half a million dollars and six months to do and you wait three years to get EFSA's approval for it, you are not over employing to get into that area"*. Despite all the mentioned points, a SP producer (IN19) explained that the limited adoption of their technology has no legal cause, since their solution is compliant with legislation.

Although legislation was mostly considered a barrier to implementing SP, it can become an incentive (IN7). This would be possible by updating and creating new regulations on, for instance, data protection (IN18) but also on another topics, as the packaging manager from a fruits and vegetables distributor (IN5) explained: "*Getting the law in place, and it's not about making a law that says you have to use smart packaging, but about the fact that you cannot have more than x% of food loss and with proofs you achieved it. Legislation about honest trade would be helpful for smart packaging: if it's honest that a supermarket makes roughly 30–35% profit on a product and the farmer gets maybe 1%, there's a discrepancy there*".

4.2.3 Both facilitators and barriers. 4.2.3.1 Smart packaging sustainability concerns (+/−). The sustainability of SP arises many discussions as it is considered either a facilitator or a barrier for its adoption. Many interviewees mentioned the additional packaging waste generated and the complicated waste management (low reusability and recyclability). Such concern is mainly about the increase in plastic and electronic use in such packages (IN1, IN4, IN5, IN7, IN14 and IN18). However, a packaging manager from a fruits and vegetables supplying company (IN8) pointed out that SP can be implemented on produce that is already packed, which, in the end, does not add extra packaging but rather improves the existing one. Regarding the questionable existence of reusable and recyclable SP, examples of a reusable anti-microbial inhibitor and a recyclable sensor were mentioned by IN14 and IN15, respectively. Moreover, both SP producers interviewed emphasized the recyclability and/or reusability of their solution: "*This sachet is very close to paper that you can recycle at the end. The chemical that is inside is a natural clay mix with potassium permanganate, so when it has chemically reacted completely, you can use to fertilize the soil*" (IN16); "*It can be disposed in domestic waste and we can recycle it. In a circular economy way, it is even possible to recover the active part of it and reuse that. We used to apply it on plastic but we're now applying effectively on paper*" (IN19). For SP to be sustainable, it needs efficient waste management. The consumer usually throws away the packages, and if SP is used for all fruits and vegetables that are purchased, it is a considerable number of packages that need to be collected. This ultimately requires an efficient logistical system to cope with that but also, it needs a committed consumer (IN7). Nevertheless, for SP solutions that are merely used for transport, their waste management is less complex as the involvement of the consumer is not required (i.e. the case of IN16's sachet).

Unfortunately, the public perceives higher sustainability in avoiding packaging. As for the scientific community, food waste is considered more unsustainable than packaging waste because more resources are typically used for food production than for packaging production, as explained by a packaging expert. For this reason, IN2 considers that SP might be more interesting for researchers rather than for industries. However, packaging manager IN13, from a fruits and vegetables supply and distribution company, was concerned about consumers' misperceived sustainability conception, contrasting with the experts' line of thought: "*The opinion of the public at the moment is: don't use plastic. And that's a very hard discussion that worries me because I know for sure that if you don't use packaging materials, the waste of the food will increase*".

On a more positive note, active packaging has an influence on the transport modality (IN19). Since active packaging can increase shelf-life and increase the efficiency of other packaging systems (e.g. modified atmosphere packaging), it is possible to transport products by sea freight instead of air freight. This ultimately has an impact on the supply chain sustainability since the carbon footprint is reduced with the long-haul modality change, mainly for more delicate products (i.e. asparagus) that are usually transported through airplanes, as explained by a CSR manager from a packaging and distribution company.

SP Sustainability is a very important discussion that can be tackled in different ways. Nevertheless, interviewees suggest that having a circular system (recyclability and reusability) is essential to improve SP sustainability (IN1, IN9, IN14 and IN18). Establishing good logistics is key, but also getting the appropriate consumer mindset to commit to such a system, as stated by IN18: *"Reusable packaging, like the loop system, needs a big logistics system to be able to clean it and bring it back. But also the consumer mindset to do the effort to bring it back. But there is still a lot to be developed that can help bringing us to a more sustainable and circular world"*.

4.2.3.2 Packaging safety concerns (+/−). Packaging safety was not widely mentioned. One SP producer (IN19) highlighted the safeness of their solution due to the passive absorption of ethylene into the paper-like filter. Still, not all SP solutions available in the market can be deemed safe, due to, i.e. the use of potassium permanganate: *"There are other ethylene control technologies around, such as potassium permanganate, but they work by oxidizing potassium permanganate. (. . .) Potassium permanganate is toxic, it should not be behind a barrier"*. Interestingly, the use of potassium permanganate is the SP mechanism provided by the other SP producer interviewed. This interviewee said that this SP has been commercialized, to some extent, in Europe, which rises some discussion, since it is considered unsafe by IN19.

4.2.3.3 Varying smart packaging performance (+/−). For some interviewees, SP performs well (IN5, IN16, IN19), while for others, SP is assumed to have low performance (IN2, IN3, IN4 and IN7). On one hand, ethylene scavengers are efficient because they are always close to the fruit, as opposed to merely having cold chains that can be interrupted and more easily accelerating food's quality decay, as stated by one of the SP producers interviewed. On the other hand, when many products are inside one package, the quality can be quite different and thus it is harder for ethylene absorbers/scavengers to perform well, as IN2 further explains (IN2): *"If you have green bananas and one of these decides to ripe, sends up one molecule of ethylene which will disperse in the bag, the chance that it will hit the packaging wall and be absorbed is ∼40% and the chance it hits the next banana and starts its ripening is 60%. So in reality, the ethylene absorber doesn't work"*.

To deal with the drawbacks of SP performance, some improvements were suggested. Firstly, SP needs to be able to handle product variability (IN2 and IN4). Secondly, prediction models should be used to optimize SP performance (IN1). This can be helpful to predict the product's shelf-life using, e.g. information from TTIs, but this is only possible with the increase in scientific research. Thirdly and finally, SP should provide specific information about the remaining shelf life of fruits and vegetables (IN3).

4.2.3.4 High smart packaging cost (+/−). SP is still too expensive to implement, especially in the food industry since margins are quite low and technologies used must be as cheap as possible (IN2, IN10, IN14, IN15 and IN18). The main problem with increased costs is that some supply chain actors might not be willing to invest, more precisely retailers (IN1, IN5 and IN19). One of the reasons why retailers might not be collaborative, is that in case of discount retailers, they need to cope with their policy of low cost products, as an interviewee from the retail sector mentioned: *"Our customers are not going to pay a premium price for our fruits and vegetables, that means we are going to pay that price ourselves. We cannot ask them to pay +0.05€ for a smart packed cucumber, we're not allowed to do that"*.

Regardless, not all SP cost the same. There might be a more expensive or a more affordable solution, depending on what you wish to retrieve from such technology (IN4 and IN14). Even within the same SP category, e.g. sensors, it is possible to have different price ranges, as discussed by a packaging expert and an innovation consultant. Additionally, when applying SP, it will not be fit for all products (IN11). This line of thought is further explored by a packaging manager: *"It depends on the value of the product. An avocado would cost 0.60€ and if you have a smart label, it will be extra 0.02–0.04€. So it will increase the cost of a product by a few percentage. However, a kiwi is a cheaper product, so if you put an expensive label on it, that's a different question"*.

To deal with the high SP cost, the interviewees suggested that it should be cheaper (IN4, IN6, IN7, IN15, IN17 and IN18) but also cost-efficient, as explained by IN14: *"It's got to be about cost versus the effect. The price has to be realistic, but it has to have a very powerful, very* *clear effect on the product so that it can actually be demonstrated without any cause that there is value in adding this".*

4.3 Ability

The abilities are the supply chain actors' knowledge, skills and competences to implement SP. The interviewees identified two abilities: collaboration and stakeholders' awareness.

4.3.1 Collaboration. Collaboration along the entire supply chain is extremely crucial for SP adoption, which might not be entirely in place yet. Collaboration is only possible with increased information flow and the supply chain actors' willingness to share such information. Usually, stakeholders are very conservative and protective of their data to share it, which is a big barrier that is urgent to overcome (IN3). Additionally, if the distributor invests in SP, for it to succeed, the retailers need to support it as well. Retailers are identified as the main influencing actors because if they do not approve it, the remaining actors cannot implement it (IN5, IN7, IN11, IN13, IN14 and IN19). Nonetheless, even if retailers are interested in implementing SP, their decisions are still influenced by their customers, as explained by IN9: *"For retailers, also has to do with how sustainable certain packaging is perceived by the client. So a lot of our decisions are still based on consumer perceived sustainability".*

In order to overcome some challenges that might impede supply chain collaboration, IN4 and IN14 suggested creating agreements and sharing costs.

4.3.2 Stakeholders' awareness. Stakeholders are not aware of the SP potential mainly because there is not a lot of promotion. Consequently, people get sceptical of the unknown, which inhibits the adoption of such technology (IN8, IN12, IN14, IN17 and IN18). Moreover, supply chain actors have different levels of knowledge and awareness, which might be a barrier impeding collaboration that is needed to implement such innovations (IN14). As previously mentioned, packaging managers and consultants have the perception that retailers are not collaborative in implementing such technology; however, a retailer interviewed (IN9) showed increased awareness and interest in using SP. Although some retailers might not see the value of implementing SP, it does not mean all retailers discard this idea, as shown by IN9: *"We don't use smart packaging yet but we're looking into it specifically for cucumbers and avocados. And the company that we're researching this with is not that far with introducing smart packaging for cucumbers".* Establishing priorities can or not be related to the stakeholders' awareness. On one hand, if the potential of SP is not known, stakeholders might not even consider making its implementation a priority. On the other hand, even if they are aware of SP's value, it just might not be valuable to their company specifically, as IN13 states: *"Until this moment, that kind of problems are not serious enough to switch over to these techniques".*

Stakeholder awareness is extremely important because when using SP, the user has to be aware that taking actions is necessary to optimize its effect. If there is a label that gives information about temperatures, it should be used to predict the product's shelf-life (IN1), and this consequently should be coupled with logistical decisions. If the pricing system is adapted based on the inventory level and the food shelf life, the supply chain is optimized; otherwise, if such results are not used, SP is not valuable (IN4).

To deal with the lack of stakeholder awareness, further scientific research on SP is suggested. Conducting scientific research on specific SP and its effect is extremely important because companies need a trustworthy source to increase their confidence in taking the risk of implementing SP (IN3): *"I think there should be independent scientific research. Now most of the companies that sell these SP are communicating about advantages and it's sometimes difficult to see what is the real story. So now we're doing the tests ourselves".*

5. Discussion

Interview statements were in agreement with information from the literature, mainly on the beneficial performance outcomes of SP, but also on inhibiting aspects that make the business case difficult. Nevertheless, the results of this research also provide additional and contrasting points of discussion to the literature.

Interviewees and literature are in agreement about the advantages. This includes the positive influence on food quality and safety, which directly results in shelf life extension and FLW reduction, allowing for longer transportation and storage (Chen *et al.*, 2020; Alam *et al.*, 2021; Wyrwa and Barska, 2017). In addition, using SP allows for a better information flow and inventory management, facilitating logistics (Janjarasskul and Suppakul, 2018; Schaefer and Cheung, 2018; Chaudhuri *et al.*, 2018). According to Valashiya and Luke (2023), increasing the information flow is possible with increased collaboration, which positively impacts the efficiency of managing the supply chain. Nevertheless, building collaborative relationships among stakeholders can be challenging and time-consuming (Saha *et al.*, 2023). Besides the aforementioned advantages, SP also brings economic benefits (Schaefer and Cheung, 2018; Chaudhuri *et al.*, 2018). However, both authors and interviewees agree that SP is still expensive, although expensive packaging can be associated with decreasing other logistics costs and increasing sales (Kuswandi and Jumina, 2020; Chaudhuri *et al.*, 2018; Ganeson *et al.*, 2023). High-cost investment is a common challenge for the adoption of new technologies, especially for small and medium-sized enterprises (Saha *et al.*, 2023). Additionally, the trade-off between FLW and packaging waste's impact on the environment is highly discussed in both literature and interviews since people more commonly assume that packaging has a higher negative impact on the environment (Licciardello, 2017; Onwude *et al.*, 2020). In fact, some authors and interviewees highlight that the trade-off depends on which fruits and vegetables SP is applied to, since the environmental impacts of food waste vary significantly per product (Buisman and Rohmer, 2023). Nevertheless, an improvement suggested by the literature and the interviewees is implementing a circular economy by increasing SP recyclability and reusability, which would move this trade-off in favour of SP and also more easily convince consumers to use SP (Lydekaityte and Tambo, 2020; Dwibedi *et al.*, 2024). Moreover, current marketing strategies are also found to be ineffective in achieving consumer engagement (Chen *et al.*, 2020). Therefore, the development of apps to monitor specific features (e.g. food quality), while providing reminders on expiring dates (Fan *et al.*, 2024) and recommendations on storage strategies for consumer or retail use (Alam *et al.*, 2021) could be helpful to increase consumer engagement. Besides investing in better marketing, establishing partnerships to overcome adoption issues is essential (Alam *et al.*, 2021; Chen *et al.*, 2020). Another suggestion for improvement that will increase users' trust on SP is that independent entities should conduct more validation studies on larger scales that present measurable results and demonstrate how SP functions on realistic situations (Salgado *et al.*, 2021; Poyatos-Racionero *et al.*, 2018; Mustafa and Andreescu, 2018). Finally, legislation constraints are still considered a crucial barrier that is hard to overcome since regulations on food safety are strict and the approval process is long, complex and expensive (Beshai *et al.*, 2020, Mohammadian and Jafari, 2020).

Our empirical findings also complement the literature with new discussions. Firstly, the technologies behind SP clearly have science-based functionalities that help address FLW reduction (see Supplementary Material), but the extent of the reduction remains difficult to assess. In previous studies, only qualitative data were obtained, while our interviewees provide some quantitative support as well, despite being mainly estimations when applying active packaging solutions. Still, valuable future research would be conducting case studies to further quantify FLW reductions and provide tangible data on the impact of SP. Secondly, in addition to improving SP robustness and reliability (Beshai *et al.*, 2020; Sani *et al.*, 2021; Müller and Schmid, 2019; Wang *et al.*, 2019), some interviewees emphasized the importance of improving SP performance with prediction models and with the ability to handle product variability. Therefore, the development of digital twins is suggested as interesting to explore since it can help better understand how quality evolves and what management decisions should be taken to improve logistics. Thirdly, according to Siracusa (2016), ethylene scavengers can have toxic components that contaminate food, being an unsafe packaging, which our interviewees confirm, but at the same time, they also propose novel SP technology. This technology passively absorbs ethylene in a paper-like filter, which is considered safer than ethylene scavengers. Fourthly, in the literature, sensors are stated as one of the most expensive forms of SP (Alam *et al.*, 2021), but interviewees also discussed different price ranges, within the same SP category, that vary considering their functionality, meaning that there are also, in this case, affordable sensors in the market. With this line of thought, more technical research should be conducted on SP alternatives. Fifthly, to increase SP acceptance, consumers should get information on the benefits and safety of SP (Kadirvel *et al*., 2025), but the interviewees believe that merely informing consumers is not enough. All supply chain actors must be informed on how SP functions and the value it brings to increase their awareness. Sixthly, authors mention that collaborations are needed, but interviewees add that agreements need to be created and costs must be shared through all supply chain actors. Moreover, some interviewees highlight the lack of collaboration, more specifically, of retailers, as the main influencing actors of SP adoption, which is a point not yet discussed in the literature. Seventhly, Alam *et al.* (2021) suggest the usefulness of using apps to engage consumers, but the interviewees also provide additional suggestions on what information these should contain (shelf life and healthy recipes) and that this information should be displayed and accessible to all family members, including children. Therefore, further research should be conducted on the development of such apps and their functionality. Eighthly, Müller and Schmid (2019) and Chen *et al.* (2020) emphasize that when consumers purchase smart-packed products, consumer picking behaviour is incentivized towards picking fresher products, which can possibly increase food waste at the retail level (as older products do not get bought). From the interviewees' perspective, consumers purchase smart-packed products when they shop less frequently and/or aim at higher quality products; therefore, this picking behaviour results in food waste prevention at the household level. To better understand the impact of consumer purchasing smart-packed foods on FLW, further research should be conducted on the quantification of food waste prevented and generated at household and retail levels. Lastly, the interviewees mentioned two additional influencing aspects that were not considered in the literature: (1) SP helps increase employment in developing countries, which can motivate SP adoption; but (2) some interviewees also question the business and consumer need for SP, being a potential barrier for SP adoption.

Finally, our empirical findings also contrast with the literature, which leads to issues that may be relevant for future research. Authors highlight that intelligent packaging has accuracy and reliability issues (Müller and Schmid, 2019; Sani *et al.*, 2021; Wang *et al.*, 2019), but some stakeholders mention that SP has no performance barriers, and other interviewees consider that active packaging has some performance barriers. Additionally, authors argue that governments should create new legislation on the application of such technologies for food (Wang *et al.*, 2019) and stricter specifications on the use and manufacture of smart labels (Fan *et al*., 2024). There is no doubt that the lack of comprehensive policies is challenging the adoption of new technologies in several industries (Saha *et al*., 2023). However, the interviewees consider it more important to have updated legislation on data protection, honest trade and binding FLW reduction targets (as currently being discussed in the EU) rather than creating legislation specific for the SP application. Therefore, a relevant future research direction would be to study the potential impact of different policies on SP adoption and food waste prevention and thus understand which approach would be more efficient. Furthermore, authors state that implementing intelligent packaging is complex (Müller and Schmid, 2019; Schaefer and Cheung, 2018), but no insights on this matter were explicitly mentioned in the interviews. IN19 solely argued that their active packaging solution is relatively simple to implement. Finally, previous research on SP technologies has provided some examples of reusable RFID tags (Poyatos-Racionero *et al.*, 2018) and biodegradable ethylene scavengers (Marzano-Barreda *et al.*, 2021), but these technologies were not mentioned by our interviewees, arguably confirming the gap between theory and practice mentioned in the introduction.

6. Conclusions and future research

To close the gap between theory and practice, in this research, we aimed at an improved understanding of the aspects that influence the decision on SP adoption on fresh fruits and vegetables and improvement directions to facilitate their wider SP adoption. Semi-structured interviews were conducted and analysed using the MOA framework complemented with relational diagrams to help understand the connections behind the influencing aspects. Although this paper is set in fresh fruit and vegetable supply chains, the findings are applicable to a broader context. Most importantly, several fresh foods have similar characteristics as fruits and vegetables, in terms of perishability, shelf life and sensitivity towards physical damage (e.g., meat, fish and eggs). Also, in the health care sector, the issue of managing short shelf life and SP are present (see Zilker *et al*., 2019). For this reason, the results presented here are useful for the adoption of SP in other short shelf life product supply chains.

6.1 Theoretical contribution

Our study offers theoretical contributions through both its methodological approach and empirical findings. The empirical data retrieved from interviews was structured and analysed using a combination of the MOA framework and relational diagrams. The use of these diagrams has been shown to be an effective and natural addition to the MOA framework, as this approach now not only explains the individual motivations, opportunities and abilities but also enables the identification of interactions between these. Such diagrams can easily be applied to other qualitative studies.

Our empirical findings confirm, complement and contrast with the literature, as described in the discussion section. Firstly, we confirm the SP potential to increase shelf life and reduce FLW because food quality and safety are enhanced (Chen *et al.*, 2020; Alam *et al.*, 2021; Wyrwa and Barska, 2017). SP facilitates logistics since it allows for longer transportation and storage, better information flow and inventory management (Janjarasskul and Suppakul, 2018; Schaefer and Cheung, 2018; Chaudhuri *et al*., 2018). Additionally, it can potentially bring economic benefits despite its expensive investment (Ganeson *et al*., 2023; Chaudhuri *et al*., 2018). In order to adopt SP, stakeholder collaborations are key but are rather challenging to establish (Saha *et al*., 2023; Valashiya and Luke, 2023). Finally, we confirm the challenging trade-off between FLW and packaging waste impact on the environment (Onwude *et al*., 2020; Buisman and Rohmer, 2023). Secondly, we complement the literature by providing further detailed estimations on the potential FLW reduction and further costing ranges of SP sensors (Alam *et al*., 2021). Also, some interviewees agreed with Siracusa (2016) about the safety of ethylene scavengers and mentioned an alternative technology to replace them. Moreover, to increase SP adoption, informing consumers is important (Kadirvel *et al*., 2025) but not sufficient since all supply chain actors must be informed and engaged as well. Additionally, the importance of retailers in the decision process towards SP adoption is highlighted. We also identified how SP can bring employment benefits in developing countries. Finally, our empirical findings complement the literature in regards to the impact of consumers purchasing smart-packed foods on food waste. Müller and Schmid (2019) believe that SP increases food waste at the retail level because it promotes consumers picking fresher products. The interviewees complement this view by noting that this picking behaviour at the retail level reduces food waste at the household level, as consumers are more likely to choose products with longer shelf lives. Thirdly, our results provided some contrasting points in regards to legislation. While Wang *et al.* (2019) and Fan *et al*. (2024) stress the importance of creating new legislation on the application of SP technologies on food products and on the use and manufacture of smart labels, the interviewees believe that is more important to create updated legislation on data protection, honest trade and binding FLW reduction targets.

6.2 Managerial implications

Our study shows a number of actions that can facilitate the adoption of SP. Firstly, stakeholders should collaborate with policymakers to incentivize the creation of updated legislation on data protection and honest trade practices. This collaboration could be through the participation in organized policy roundtables that include stakeholders and policy makers to discuss gaps in current legislation and potential solutions. Regarding FLW reduction targets, the European Union has, for instance, reached a preliminary political agreement by 2025. As a technology that supports FLW reduction, SP stakeholders can benefit from this legislation and further build on it.

Secondly, stakeholders should focus on the sustainability aspects of SP, such as developing a circular economy system and prioritising recyclable and reusable packaging solutions. The increasing pressure to replace single-use plastic with reusable packaging requires many industries to revisit their packaging solutions already, and the additional consideration of SP might be beneficial. Moreover, building robust logistics infrastructures is also important. Stakeholders should act on the development of efficient reverse logistics networks, building partnerships with logistics providers to collect the packages, increasing the number of return stations and implementing tracking and data systems.

Thirdly, nurturing a consumer mindset that prioritizes sustainability is essential. Stakeholders should develop better marketing strategies for enhancing consumer engagement with SP, for example, consumer-friendly apps with interactive features for all family members, displaying information on food shelf life and healthy recipes. Additionally, applying deposit-refund systems or reward-based returns and sharing with consumers the impact of their collaboration in returning/recycling the packages are potential actions that could increase consumer adherence.

Fourthly, SP researchers and producers should develop frameworks to reduce SP associated costs and enhance SP performance, by using, for example, prediction models for handling product variability, logistics optimization models for materials sourcing and SP manufacturing, collaborating across industry to standardize and bulk-procure SP components to reduce costs and developing decision-making models for SP selection based on product value, risk and route complexity.

Lastly, collaboration among stakeholders should be enhanced for building trust and sharing information. Possible actions include establishing partnerships with cost-sharing agreements and transparent communication channels. Additionally, independent scientific validation studies can be helpful to provide unbiased and transparent insights but also to update SP technologies based on feedback from all stakeholders. This ensures practical integration and real-world feasibility.

6.3 Limitations and future research

Three limitations were identified in this research. Firstly, the results of this study were obtained in one-on-one interviews. We were unable to facilitate a discussion among supply chain participants in, e.g. a roundtable to exchange viewpoints and discuss our findings. Having a retailer exchange views with, e.g. a distributor or a packer, could have provided very interesting insights. Secondly, interviewees had experience with assessing the environmental impact of SP implementation in elements of the supply but not of the full supply chain. Thirdly, we did not have a complete balanced representation among the supply chain. For example, we had two retailers in our interview panel, but both can be labelled as discounters, and they shared similar insights.

The present study also allowed for the identification of specific topics for further research, as mentioned in the discussion section. Besides the previously mentioned topics, two additional further research topics can be identified. Firstly, it would be beneficial to increase the focus of research on the retailer perspective. This specific stakeholder was often mentioned by the interviewees as the actor that highly influences SP adoption. A wide range of retailers should be considered because of their potentially different scopes. Secondly, it would be interesting to assess the overall environmental impact of smart-packed fruits and vegetables. This would be valuable to understand in which scenarios SP could actually improve the environmental performance of specific fruits and vegetables, quantifying the trade-off between the expected food loss and waste savings and the possible additional impacts caused by the implementation of SP.

Appendix 1

Table A1. Interview guide

Interview guide
Introduction
What is your role in *company name*?
How are you related to smart packaging?
Have you ever heard about smart packaging?
If yes: How do you define smart packaging?
If no: Explain the definition found in literature
Smart packaging implementation
Do you produce/use smart packaging?
If yes:
What type of smart packaging?
For which food products?
Why do you produce/use that specific smart packaging for this product?
In which countries is your smart packaging used?
What smart packaging do you have for fruits and vegetables?
In which countries is it used?
Is there any particular fruit or vegetable that benefits more with your smart packaging?
If yes: Which fruit/vegetable? Which type of smart packaging is used?
If no:
Why don’t you produce smart packaging?
Have you ever produced smart packaging?
If yes: How was that experience?
From your point of view, to what extent is smart packaging implemented on fruits and vegetables?
In your opinion, what aspects influence the implementation of smart packaging on fruits and vegetables?
What impact do you consider that smart packaging has on loss and waste of fruits and vegetables?
If they use/produce smart packaging: How much loss and waste did you manage to reduce after implementing smart packaging?
If they do not use/produce smart packaging: Do you have any idea of how much food loss and waste could be reduced after implementing smart packaging on fruits and vegetables?
Smart packaging improvement directions
If they produce/use smart packaging: In your opinion, how can smart packaging be improved to be more commercially adopted on fruits and vegetables?
If they do not produce/use smart packaging: What does your company need to start introducing smart packaging for fruits and vegetables?
Closing questions
Do you have any final remarks?
Do you have any contacts that I could reach?

Source(s): Authors’ own work.

Appendix 2

Table A2. Interviewees description

Code name	Role	Company	Smart packaging usage/ production
IN1	Packaging expert	Research in a Dutch University	Not applicable
IN2	Packaging expert	Research in a Dutch University	Not applicable
IN3	CSR manager	Group of companies focused on marketing, packaging and distribution of fruits and vegetables to UK, Germany, France and the Nordic countries	Do not use it yet, but are currently conducting research for future implementation
IN4	Packaging expert	Research in a Dutch University	Not applicable
IN5	Packaging manager	Dutch company that imports, packs and distributes organic fruits and vegetables in Europe, the USA, Canada and the far East	Implemented it in the past but no longer use it
IN6	Packaging manager	Discount retailer in the Netherlands	Do not use it
IN7	Innovation consultant	Management consulting company	Not applicable
IN8	Packaging manager	Importer of fruits and vegetables in Europe	Do not use it
IN9	Sustainable consultant responsible for packaging, food waste, energy and emissions	Retailer in the Netherlands that offers quick, easy and cheap solutions for its customers	Do not use it but are currently conducting research for future implementation
IN10	Analyst in the food and agribusiness supply chain team in the Netherlands	Financial services provider for the food and agribusiness sector	Not applicable
IN11	Marketing manager	Packaging manufacturer in the Netherlands	Do not produce it
IN12	Responsible for the global packaging suppliers within the food safety and quality team in the UK	Multinational food and beverage company	Do not use it
IN13	Packaging manager	Dutch company that supplies and distributes fruits and vegetables to international supermarkets, wholesalers, caterers and the processing industry	Do not use it
IN14	Communications director	A smart packaging association which aims at reducing waste and increasing the profitability of supply chain actors by the implementation of smart packaging technology	Not applicable
IN15	Analyst in the food and agribusiness supply chain team in the USA. Within the team, there is more focus on consumer, food, logistics and packaging	Financial services provider for the food and agribusiness sector	Not applicable
IN16	Global market manager in post-harvest care in Chile	Company from Spain which offers post-harvest solutions for air filtration and gas purification	Produce active packaging (ethylene scavenger sachet)

(*continued*)

Table A2. Continued

Code name	Role	Company	Smart packaging usage/ production
IN17	Senior sustainable packaging expert	Institute from the Netherlands that advises companies about sustainable packaging	Not applicable
IN18	Project manager	Consortium of companies from Belgium, in the food and packaging industry and their suppliers, responsible for helping companies to improve their food packaging and supports them with daily packaging and innovations	Not applicable
IN19	Technical sales director	Company from the UK that produce innovative technologies that extend the freshness and quality of fresh food	Produce active packaging

Source(s): Authors' own work.

Supplementary material

The supplementary material for this article can be found online.

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Corresponding author
Oana Butuc can be contacted at: oana.butuc@wur.nl