# The role of smart packaging system in food supply chain

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**Abstract:** Food supply chain is a rapidly growing integrated sector and covers all the aspects from farm to fork, including manufacturing, packaging, distribution, storing, as well as further processing or cooking for consumption. Along this chain, smart packaging could impact the quality, safety, and sustainability of food. Packaging systems have evolved to be smarter with integration of emerging electronics and wireless communication and cloud data solutions. Although there are many factors causing the loss and waste issues for foods throughout the whole supply chain of food and there have been several articles showing the recent advances and breakthroughs in developing smart packaging systems, this review integrates these conceptual frameworks and technological applications and focuses on how innovative smart packaging solutions are beneficial to the overall quality and safety of food supply by enhancing product traceability and reducing the amount of food loss and waste. We start by introducing the concept of the management for the integrated food supply chain, which is critical in tactical and operational components that can enhance product traceability within the entire chain. Then we highlight the impact of smart packaging in reducing food loss and waste. We summarize the basic information of the common printing techniques for smart packaging system (sensor and indicator). Then, we discuss the potential challenges in the manufacturing and deployment of smart packaging systems, as well as their cost-related drawbacks and further steps in food supply chain.

**Keywords:** flexible electronics, food safety, food waste, printing technologies, smart packaging, supply chain management, sustainability

## 1. INTRODUCTION TO FOOD SUPPLY CHAIN

In general, a supply chain can be broadly conceptualized as the interaction between various entities which are involved in the flow of products and services to their end customers (Mentzer et al., 2001). The emergence of the supply chain management as a discipline recognizes the concurrent shift away from individuals' businesses into wider networks with an emphasis on the benefits that network wide collaboration can bring (Carter, Rogers, & Choi, 2015; Jüttner & Maklan, 2011; Lambert, Cooper, & Pagh, 1998). A drawback from adopting this wider, holistic perspective is that it, in turn, makes managing and understanding such entities more complex than individual business units. Therefore, a supply chain can be conceptualized as a complex adaptive system, whereby interactions and nonlinearities across localized components (that is, one echelon or business unit) can influence overall system behavior (Levin, 1998).

As a result, supply chain activities (and accordingly research) can be delineated into operational, tactical, and strategic perspectives (Stevens, 1989), often defined according to temporal planning scope and resultant decision-making processes (Schmidt & Wilhelm, 2000). For a supply chain to be collaborative—and reap the benefits of a holistic integrative model—goals and metrics need to be aligned throughout these processes (Jaradat, Adams, Abutabenjeh, & Keating, 2017). Supply chains inherently deal with uncertainty (Flynn, Koufteros, & Lu, 2016), and the impact of uncertainty that propagates itself into various echelons of a supply network, both upstream toward suppliers (Lee, Padmanabhan, & Whang, 1997) and downstream toward customers (Ivanov, Sokolov, & Dolgui, 2014). Accordingly, the impact of minor delays or disruptions can cause widespread supply chain volatility, therefore, managers need to be in a position to exactly appraise the effect of various risks on supply chain operations (Fiksel, 2015; Sheffi & Rice Jr, 2005).

Although the supply chain literature offers discourse surrounding particular strategies for dealing with uncertainty, their applicability toward food supply chain (FSC) is not clear (Kamalahmadi & Parast, 2016; Sheffi & Rice Jr, 2005). For example, the common strategy of safety stock—holding additional goods to meet demand fluctuations is not easily transferable to FSCs due to the challenge of product deterioration (Ahumada & Villalobos, 2009; Chaturvedi & Martínez-de-Albéniz, 2016). FSCs are unique in that, in addition to the general considerations of supply chain management, FSCs often have to deal with issues surrounding perishability and product deterioration and waste (Aliakbarian, 2019; Amorim, Günther, & Almada-Lobo, 2012; Göbel, Nina, Antonia, Petra, & Guido, 2015). The products within these chains can be expressed as deteriorating in value and quality once they are produced (Govindan, Jafarian, Khodaverdi, & Devika, 2014). Accordingly, particular types of food products (for example, fresh products) have variability within their marginal shelf-life, or the "rate at which the product loses value over time in the supply chain" as described by Blackburn and Scudder (2009). Tying this back to the idea of supply chain volatility, issues, such as stock delays and increased inventories, can lead to widespread wastage for

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doi: 10.1111/1750-3841.15046

perishable products. The drivers of product deterioration within FSCs are varied, however, they can often be refined into two distinct categories: temporal and environmental factors. As products within FSCs are subject to the marginal value of time, products need to travel downstream within the FSCs as effectively as possible. This appears, at times, almost paradoxical, as a major challenge of FSCs is their long-lead time (Lowe & Preckel, 2004).

Secondly, environment elements, including temperature and humidity, influence food quality, and therefore, the risk of product deterioration (van der Vorst et al., 2009). The impact of product deterioration within FSCs is twofold; firstly, though the decrease in quality as food products deteriorate, but also the increased risk of contaminated goods impacting food safety (Akkerman, Farahani, & Grunow, 2010). In addition to challenges surrounding product deterioration, FSCs also face challenges concerning increased regulation and environmental pressure. Increased regulatory pressures result in particular FSC strategies, for example, traceability, becoming mandatory components of operating within certain regions (Bosona & Gebresenbet, 2013). Adding to the overall complexity is that regulations are not universal and are occasionally selectively enforced (Aruoma, 2006), adding an extra challenge to FSCs that operate across international borders. Moreover, environmental pressure dictates the needs to ensure components of the FSC (such as packaging) address various sustainability issues, namely waste reduction and packing recycling (Vanderroost, Ragaert, Devlieghere, & De Meulenaer, 2014). These sustainability issues impact FSCs through both environmental impacts, but also stakeholder (that is, societal) concerns influencing corporate social responsibility (CSR) programs (Akkerman et al., 2010). A final issue that impacts the performance of FSCS is wastage. Although eliminating waste is a common problem within any supply chain, particularly those implemented lean philosophies, food wastage is often difficult to measure across FSCs and permeates all actors within a supply network (Devin & Richards 2018; Göbel et al., 2015; Mason-Jones, Naylor, & Towill, 2000; Naylor, Mohamed, & Danny, 1999). The causes of food waste are varied, however, wastage primarily happens at the end of the SC as the final product may become damaged or deteriorate during this stage (Liljestrand, 2017; Verghese, Helen, Simon, & Helén, 2015). Although packaging is often associated with waste within commercial supply chains, within the context of FSCs enhanced packaging techniques have been regarded as a tool to reduce food waste due to reductions in product deterioration (Verghese et al., 2015).

## 2. FOOD LOSS AND WASTE

Food loss and waste has become a huge problem and attracted great attention with continuous growth of world population. It is reported that around 30% of the global food supply and 40% of the U.S.A. food supply are lost or wasted each year (Hall, Guo, Dore, & Chow, 2009). According to the Food and Agriculture Organization (FAO), 1.3 billion tons of food products are lost or wasted per year, and these losses or wastes may occur at any step throughout the supply chain right from farm to fork (FAO, 2011). Global sustainability, environmental and human health and natural resources can be impacted by food loss and waste (Pham, Kaushik, Parshetti, Mahmood, & Balasubramanian, 2015; Xue et al., 2017). As a part of Sustainable Development Goals (SDG), the United Nations aims to "reduce 50% of the global food waste at retail and consumer levels and decrease the post-harvest food loss by 2030" (United Nations, 2018b).

Figure 1 shows the possible lost/waste generated at the different stages of the FSC for some representative food products. For instance, in the final consumption step, the consumer's behavior has a significant impact on food waste generation. Many people like to prepare oversized portions but finally waste the leftovers, however, rare of them are aware of the negative impact of food waste on human health and environment (Gunders, 2012). Contaminations and damages from inadequate safety controls, overstocking products in stores/homes, inappropriate labeling and product information missing are among the most important causes of the food loss and waste along the supply chain (Broad Leib et al., 2013; Kummu et al., 2012; Parfitt, Barthel, & Macnaughton, 2010; Waste & Resources Action Program (WRAP), 2011). Previous studies have demonstrated that fresh bakery products and perishables are contributing to most of the food waste which consecutively impacts all other parts in the supply chain (Griffin, Sobal, & Lyson, 2009; Kantor, Lipton, Manchester, & Oliveira, 1997; Mena, Adenso-Diaz, & Yurt, 2011). The major reason for this problem is usually either the overprepared surplus quantity beyond demands or the shorter shelf-life of the products or the poor storage and promotion measurements (Kaipia, Dukovska-Popovska, & Loikkanen, 2013; Mena et al., 2011). In addition, it should be noted that the underlying causes for food loss and waste may vary between the developed and the developing countries. For example, about 40% food loss occurs during the production step in the developing countries, while 40% of the food waste generates during the steps of distribution, marketing, and consumption in the developed countries (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011; Wunderlich & Martinez, 2018). Food loss/waste also intersected with public health issues in terms of food security, food safety, and nutrition (Neff, Kanter, & Vandevijvere, 2015), and negatively affects the socioeconomic development and environmental conditions (Shafiee-Jood & Cai, 2016; Wunderlich & Martinez, 2018). For example, the socioeconomic consequences of food waste may result in higher food prices, lower income, and worse poverty (Gills, Sharma, & Bhardwaj, 2015), and the wasteful practices can lead to the destruction of the soil, freshwater, oceans, forests, and biodiversity (United Nations, 2018a).

Different cutting-edge strategies and technologies need to be proposed based on the specific conditions suitable for the local, regional, and global background, and it is extremely important that the methods incorporated must be unique by considering energy and infrastructure limitation, targeted food loss in developing countries, and food waste in developed countries (Lipinski, Hanson, & Lomax, 2013; Mourad, 2016; Neff et al., 2015; Shafiee-Jood & Cai, 2016; Wunderlich & Martinez, 2018). However, to implement these strategies, several actions have to be taken by the various stakeholders (for example, donors, agencies, governments, and private sectors) for the challenges they are facing (Lipinski et al., 2013; Neff et al., 2015; Wunderlich & Martinez, 2018).

On the other hand, efforts have also been made to generate energy from food waste using different technologies such as anaerobic digestion, ethanol fermentation, incineration, pyrolysis, gasification and hydrothermal carbonization (Casazza et al., 2016; Pham et al., 2015; Sannita, Aliakbarian, Casazza, Perego, & Busca, 2012). Food wastes generated during the food processes have also been considered as natural sources of high-added value compounds with antioxidant properties (Aliakbarian et al., 2018; Aliakbarian, Casazza, & Perego, 2011; Aliakbarian, Fathi, Perego, & Dehghani, 2012; Aliakbarian, Paini, Adami, Perego, & Reverchon, 2017; Casazza, Aliakbarian, Mantegna, Cravotto, & Perego, 2010; Lopresto et al., 2014). Additionally, international organizations, such as FAO, World Food Program (WFP), and the United Nations Environment Program (UNEP), have taken significant

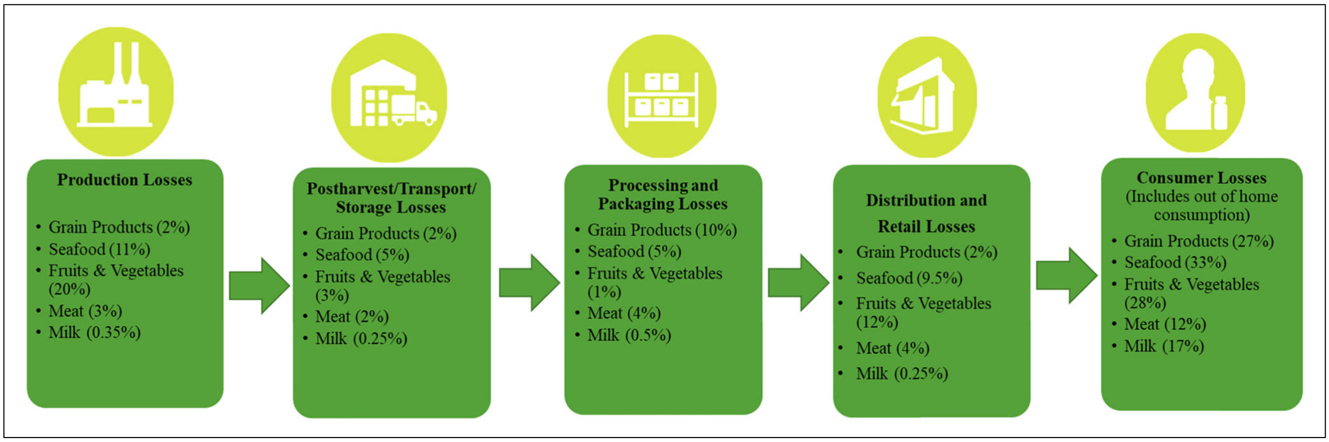

Figure 1–Food Losses at each step in the supply chain (Collectively for the US, Canada, Australia, and New Zealand; Source: WRI analysis based on FAO, 2011. Global food losses and food waste—Extent, causes, and prevention. Rome, Italy: UNFAO).

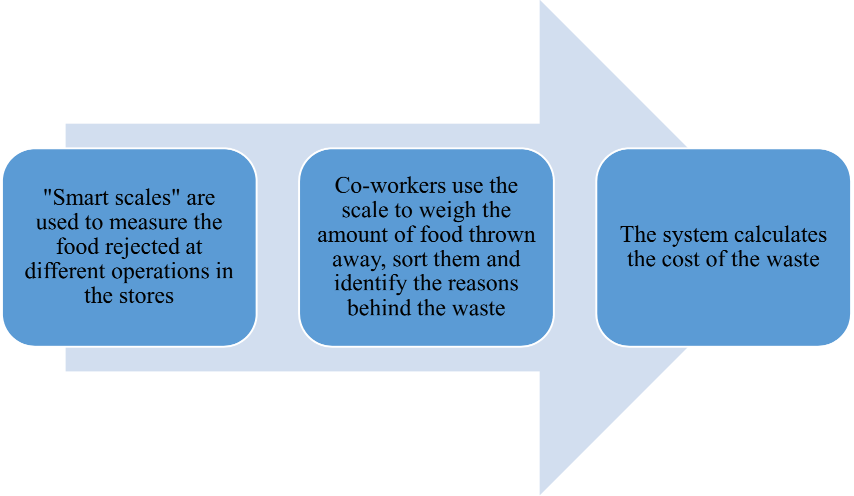

Figure 2–IKEA's strategy used in "Food Is Precious" Food Waste Initiative. Retrieved from http://flwprotocol.org/case-studies/ikea-food-food-precious-food-waste-initiative/

effort to raise the public awareness for food safety to achieve the goals of "zero loss or waste of food" in "Zero Hunger Challenge" vision (Alamar et al., 2018). World Resource Institute (WRI) has also developed a food loss and protocol to address the challenges needed to be faced to quantify food loss and waste across the globe World Resource Institute, (2018). In one case study of IKEA (Ingvar Kamprad Elmtaryd Agunnaryd), they described a simple strategy to identify the common factor behind the food waste and further provide solutions to combat the food waste issue (Figure 2).

In the next session, we will highlight the most advanced smart sensor-enabled packaging solutions that can reduce food loss and waste along the FSC, their most promising manufacturing techniques, and the issues related to each process.

## 3. SMART PACKAGING (SP) AND ITS IMPACT IN REDUCING FOOD LOSS AND WASTE

The terms of "intelligent packaging" and "smart packaging" are often interchangeably used or misinterpreted for discussing the packaging systems. SP is considered to be a broad concept, which includes both the intelligent and active packaging which can monitor the internal and external changes occurred in a product (intelligent) and further respond (active) by communicating with an external interface (electrical or optical) (Vanderroost et al., 2014). The ultimate purpose of applying SP is to extend the shelf-life of the product and keep its freshness, exchange quality information with consumers, enhance product's safety, and improve traceability of the product while moving across the supply chain. Active packaging which serves as the primary alternative to traditional packaging aims to support and maintain high quality and to extend freshness of food products. To realize that, different components can be embedded into the system which are capable of releasing/absorbing substances from/ into the packaged food to avoid spoilage (Arvanitoyannis & Stratakos, 2012; Prasad and Kochhar, 2014). On comparison, the intelligent packaging is primarily employed to track and monitor conditions of packaged foods, to capture and provide data of the product's condition during the processes of storage and transportation (Kerry, O'grady, & Hogan, 2006). Thus, intelligent packaging systems usually involve hardware elements, for example, gas detectors, freshness, and ripening indicators, time–temperature indicators (TTI), and radio frequency identification (RFID) devices (Kerry et al., 2006). There are also "data carriers" systems which could be used for storage and data transfer for displaying the information afterwards (Müller & Schmid, 2019). In this review, "SP" is primarily referred as a substitute for intelligent packaging unless otherwise statement.

Technological advances related to the safety issue of food is one of the top measures in preventing the loss and waste of foods (Vilariño, Franco, & Quarrington, 2017). Some of these include temperature controlled and energy-efficient storage systems, novel packaging materials and designs, as well as smart monitoring systems (Bahadur, Haque, Legwegoh, & Fraser, 2016; Foscaches, Sproesser, Quevedo-Silva, & de Lima-Filho, 2012; HLPE, 2014). Especially, advanced packaging techniques, including active packaging and SP, have been investigated and proved to be an essential tool for reducing the food waste, by guaranteeing food safety and fulfilling consumer expectations (Lipinski et al., 2013; Olsmats & Wallteg, 2009; Poyatos-Racionero, Ros-Lis, Vivancos, & Martínez-Máñez, 2018; Pradeep, Junho, & Sanghoon, 2012). Although the electronics for SP have been significantly developed, like electrochemical sensors, E-Tongues, and E-Noses, current devices are usually complicated and expensive and are not yet ready to be integrated with real packages (Poyatos-Racionero et al., 2018; Zou, Wan, Zhang, Ha, & Wang, 2015). Nowadays, the "best before" and "sell by" or "use by" has become a norm in the food industry, however, it fails to deliver information on the state of food inside the package, thus "dynamic shelf-life systems" should be introduced for simple interpretation (Poyatos-Racionero et al., 2018). In this aspect, the environmental performance of the packaging materials is a matter of concern, hence, research on mapping the packaging performance assessment on the environment is crucial to provide guidance to the packaging design engineers (Heller, Selke, & Keoleian, 2018).

There is a compelling need for new technologies to guarantee food security. The applications of advanced technologies in SP systems are emerging and recently being adopted by pharmaceutical and food industries not only to complement conventional packaging functions but also as a tool or a solution to extend the shelf-life of food products, making it convenient for the production process, minimizing food loss and waste, eradicating preservatives, and most importantly providing high quality and variety to ensure consumer safety and satisfaction (Janjarasskul & Suppakul, 2018; Poyatos-Racionero et al., 2018). Targeting specifically chemical or biological markers in food is still the major challenge in developing advanced packaging systems for food products. The decision to choose target marker depends on the prior knowledge for the relevant microbial agents and their occurrence under various conditions in different kinds of food products, as well as the release of reaction substances produced during the process of spoilage (Aliakbarian et al., 2015).

Food spoilage is a complex process that could be initiated by an array of physical, chemical, or enzymatic, and microbiological actions. Both the growth and metabolism of bacterial may lead to changes in pH, and generate toxic substances, off-odors, gas, and slim-formation. Chemical processes, such as oxidation, irradiation, and lipolysis, may lead to undesirable flavors and formation of adverse effects. In addition to intrinsic parameters (physicochemical and structural), extrinsic factors (temperature, pH, and humidity) may also affect chemical, physical, and biological food spoilage. There are many technologies for reducing food spoilage, such as integrity indicators, food spoilage indicators, ripeness indicators, rancidity indicators, microwave doneness indicators, and RFIDs (Han, Ruiz-Garcia, Qian, & Yang, 2018; Janjarasskul & Suppakul, 2018).

Smart RFID tags aim to evaluate the quality of the stored product based on the integration of sensing elements. These sensor-enable RFID tags can detect changes in food properties, such as pH, conductivity, dielectric constant, viscosity, food volatiles, and gases, through chemical elements like a responsive coating, an optical label, a litmus paper, and pH or conductivity electrodes (Abad et al., 2007; Kim et al., 2009; Sample, Yeager, Powledge, Mamishev, & Smith, 2008). Some examples include applying different food volatile responsive films on the RF structure and detecting the change in response through color changes of specific dyes induced by volatiles from specific food or due to change in the food pH for colorimetric sensing, monitoring the variation of the dielectric constant of food as it spoils (Occhiuzzi, Rida, Marrocco, & Tentzeris, 2011; Potyrailo et al., 2012). Volatile compounds are emitted by food as degradation byproducts (Ordonez, De Pablo, Perez de Castro, Asensio, & Sanz, 1991). Molecules, like dimethylamine, trimethylamine, ammonia, histamine, carbon, sulfuric compounds, and ethanol, are among the byproducts of metabolism of bacteria which can be utilized as different kinds of indicators for food spoilage (Bibi, Guillaume, Gontard, & Sorli, 2017). Solid-phase microextraction combined with the gas chromatography-mass spectrometry (Mikš-Krajnik, Yoon, Ukuku, & Yuk, 2016), UV-VIS spectroscopy (Aliakbarian, Bagnasco, Perego, Leardi, & Casale, 2016), and near-infrared spectroscopy (Aliakbarian et al., 2015) have been used to identify and quantify the volatile compounds in food. However, most of these techniques are expensive, complicated, and labor intensive when compared with smart sensor-enabled RFIDs which have been considered as cost effective, nonobtrusive, and user friendly technique for food packaging (Badia-Melis, Mc Carthy, Ruiz-Garcia, Garcia-Hierro, & Villalba, 2018; Fidders & Yan, 2013). Moreover, these packaging systems can become powerful tools to reduce food waste as they possess indicators which can interact with the food ingredients and metabolites in the head space and/or extrinsic environmental factors, thus, enabling the monitoring of the condition of the food product.

Chromogenic chemosensors are another most-upcoming easy handling disposable systems, not only because they are less expensive, versatile, and easily printed on the package, but also because their color change with time can be easily detected through transparent films by naked eye. The limitation of these sensors is the lack of specificity (Poyatos-Racionero et al., 2018). TTIs offer a visual summary of a complete temperature profile (or part of it) of a product by recording both the time and temperature effects (Janjarasskul & Suppakul, 2018). Different kinds of TTIs have been developed according to the working mechanisms (chemical, enzymatic, microbiological, and mechanical types) (Kim, Kim, & Lee, 2012), however, most TTIs fail to provide the biochemical changes occurring in food. For example, Rokugawa & Fujikawa (2015) developed a new time–temperature integrator in 2015 on the basis of the Maillard reaction. Such integrator is able to monitor and manage the temperature of the food between 4 and 32 °C. The color change was observed as a result of time and temperature and the rate constant for the color changing was expressed by Arrhenius model. They confirmed the capability of this sensor as an indication of the growth of food microorganisms at different temperatures. Kulchan, Boonsupthip, Jinkarn, and Suppakul (2016) developed a colorimetric indicator to record the rancidity reaction of oxygen-sensitive instant milk powder. The indicator labels contained a combination of two pH-sensitive substances, bromothymol blue and methyl red dyes, which could respond to volatile compounds released because of oxidation during storage. Bromothymol blue shifted from basic to acidic with a color change from blue to yellow and pH change from 7.6 to 5.8 respectively, whereas similarly for methyl red, the pH dropped from 6.2 to 4.5 with a color change from yellow to red. The color change from light green to orange could serve as a signal of warning or rejection.

According to the report from Boston Consulting Group (BCG) last year, there has been a slow progress in eliminating food wastage through the whole supply chain because of insufficient infrastructure, lack of effort, regulations and collaboration across the value chain. It is projected that improving the supply chain infrastructure and efficiency alone could diminish food loss by $270 billion (in value) equivalent to $1.5 trillion by 2050. In this regard, SP systems can play a critical role by minimizing food waste and enabling a more sustainable supply chain (Han et al., 2018; Janjarasskul & Suppakul, 2018; Poyatos-Racionero et al., 2018). For instance, data carriers will help connect the information within the supply chain to make the process more efficient by assuring traceability, automatization, theft, or counterfeit protection (McFarlane & Sheffi, 2003). RFIDs will provide more advantages to the overall supply chain by supporting inventory management and traceability, thereby, promoting food quality and safety (Kumar et al., 2009). Similarly, TTIs will assist in monitoring the proper temperature profile or a cold chain in an entire supply chain (Fang, Zhao, Warner, & Johnson, 2017). Thus, SP will not only reduce food waste and loss through improving the distribution efficiency in supply chain and effectively detecting the food spoilage, but also address the issues of food safety. Furthermore, not only the time and material costs for analysis of packaged foods are minimized but reduction in cost will also occur when SP eliminates food waste (Müller & Schmid, 2019; Vanderroost et al., 2014). It is expected that novel bioactive SP may be a future trend, which will have the potential to open new scopes, increase market demand, and be adopted by more food industries (Lopez-Rubio et al., 2004; Majid et al., 2018). Furthermore, continuous improvements in data collection of food waste are highly desired to contribute to the decision making as well as promotion of these packaging design (Heller et al., 2018; Sohail, Sun, & Zhu, 2018). Moreover, advanced manufacturing technologies are needed to cut the mass-production cost and reduce the complexity of the integration of smart devices into the current packaging lines. Further investigation needs to be done on the safety issues and the feasibility and possibility to be incorporated into a broad range of applications. Lastly, customers should be well-informed of these advanced packaging systems, their associated cost and benefits, and more importantly their willingness to spend (Fuertes et al., 2016).

## 4. MANUFACTURING TECHNOLOGIES AND COST FOR SP

As discussed above, SP plays a significant role in the FSC, by improving distribution efficiency to reduce food waste and loss, detecting food spoilage to address safety problems, and as a result, saving time and costs involved. However, there is a trade-off between the potential cost related to food waste and loss as well as safety issues (w/o SP) and the extra cost of adopting smart packages, that is, the manufacturing cost of SP. Sensors or smart labels are key elements in SP system to monitor the food quality or storage conditions or to determine the exterior environment of a packaged product (both for manufacturer and consumer needs) (Jiang et al., 2014; Neethirajan & Jayas, 2011; Wyser et al., 2016). Suitable techniques to fabricate these smart elements which are compatible for the current packaging standards need to be developed and improved to reduce the related manufacturing costs but at the same time, broaden their range of applications for various food products. Among the existing manufacturing techniques, the methods of printable electronics have received significant attention not only from the academia but also from industrial manufacturing communities due to their great abilities to directly deposit electronics (for example, sensors, batteries, RFID tags, and displays) on flexible substrates (for example, polyimide, polyethylene terephthalate, polyether ether ketone, elastomer, and even paper) in a cost-effective manner, on a large scale and efficiently (Kraft, Berger, & Lupo, 2017; Leenen, Arning, Thiem, Steiger, & Anselmann, 2009; Semple, Georgiadou, Wyatt-Moon, Gelinck, & Anthopoulos, 2017), along with other properties such as light weight, portability, bendability, foldability, and large active area. In the past decade, manufacturers have gradually employed printing methods to produce some conventional electronic devices to reduce the costs (Jiang et al., 2014; Neethirajan & Jayas, 2011; Wyser et al., 2016). For instance, Thin Film Electronics ASA has successfully demonstrated a printable, battery powered temperature-tracking sensor system suitable for monitoring fresh foods (Thin-Film, 2013). Xerox proposed a highly secure, printed label (Xerox Printed Memory) which can be used to examine if a product is genuine and can track the product's handling during distribution (Xerox, 2015). For a better understanding of the position of fabricating printable electronics in supply chain, we will briefly discuss the different printing techniques with advantages, weaknesses and overall cost, which will help in the decision making of SP in the early stage of FSC.

There are a few printing methods commonly used in fabricating printable electronics: gravure, flexography, screen, inkjet, and aerosol jet printings (AJPs) (Chu, Qian, Chahal, & Cao, 2018; Grau et al., 2016). In the case of gravure printing, the design should be stamped or loaded on a cylindrical roller and pressure is used to directly transfer the ink to rolls of substrate. This method is considered to produce low-cost smart labels with a high rate of manufacturing speed. For example, roll-to-roll (R2R) gravure printing has been utilized to fabricate SP labels (Jung et al., 2014). It also has excellent scalability and competitive resolution (Grau et al., 2016). This type of printings is suitable for mass production if combined with a R2R printing configuration (Khan, Lorenzelli, & Dahiya, 2015). Flexography, a technique usually compared with rotogravure, is mainly used for packaging applications, mostly for the manufacturing of electronic devices with high-speed printing capabilities, SP, and RFID (Maksud, Yusof, & Abdul Jamil, 2012). The printing plate consists of a softer material and the print unit has ink supply, anilox roller, plate cylinder, and impression cylinder. It can be used on nearly any nonabsorbent material. Gravure image carriers cost typically much more than flexography but has a longer press run time. According to the data from CI-Flexo-Tech, the average cost of flexographic plate is about USD 0.03∼0.045 per square centimeter. Like inkjet printing, screen printing produces thick and patterned layers of highly viscous materials, thus, maintaining high throughput and resolution (Pardo, Jabbour, & Peyghambarian, 2000). Screen printing is suitable for both inorganic and organic materials with different viscosities despite layer function or substrate flexibility. Screen printing and its requirements for printing ink compositions with nanoparticles were also studied and discussed for SP (Hrytsenko, Shvalagin, Grodziuk, & Granchak, 2017). As for inkjet printing, droplets of ink are injected from a nozzle onto either a rigid or flexible substrate (Calvert, 2001; Singh, Haverinen, Dhagat, & Jabbour, 2010; Song et al., 2008). Inkjet printing strikes a balance between printing resolution and scalability and without using any mask can be used to develop relatively detailed patterning (Singh et al., 2010). Compared to other printing techniques, inkjet printing has low

**Table 1–Comparison of the major printing fabrication methods for smart packaging system.**

| Printing method | Viscosity (Pas) | Thickness of layer (μm) | Feature size (μm) | Registration (μm) | Throughput (m$^2$/s) | References |
|---|---|---|---|---|---|---|
| Gravure printing | 0.01 to 0.2 | <0.1 to 8 | 75 | >20 | 3 to 60 | Grau et al., (2016); Khan et al. (2015) |
| Flexography printing | 0.05 to 0.5 | 0.04 to 2.5 | 80 | <200 | 3 to 30 | Maksud et al. (2012) |
| Screen printing | 0.5 to 50 | 0.015 to 100 | 20 to 100 | >25 | 2 to 3 | Khan et al. (2015); Pardo et al. (2000) |
| Inkjet printing | 0.001 to 0.04 | 0.05 to 20 | 20 to 50 | 5 to 20 | 0.01 to 0.5 | Calvert (2001); De Gans et al. (2004); Secor et al. (2013); Singh et al. (2010); Tortorich and Choi (2013) |
| Aerosol jet printing | 0.001 to 2.5 | 0.1 to 5 | 10 to 200 | 5 | 0.01 to 0.5 | Cao et al. (2017); Onses et al. (2015) |

(almost zero) waste generation and lower initial startup costs (Secor, Prabhumirashi, Puntambekar, Geier, & Hersam, 2013). However, highly viscous and particle inks with high aspect ratio, for example, organic dielectrics and carbon nanotubes (CNTs), cannot be easily managed by inkjet printing due to the blockage of the nozzle (Calvert, 2001; De Gans, Duineveld, & Schubert, 2004; Tortorich & Choi, 2013). Inkjet printing has been employed to print, at the same time of the packaging, some information about the product manufacturing and expiration date (Hrytsenko, Hrytsenko, Shvalagin, Grodziuk, & Kompanets, 2018). Furthermore, as a promising smart element for SP, RFID tags can be made by inkjet method. Compared to RFID tags via silicon semiconductor technologies, printed RFIDs are expected to be cheaper by using conducting polymers, metallic inks, and even CNTs (Demoustier, Minoux, Le Baillif, Charles, & Ziaei, 2008; Kuswandi, Wicaksono, Jayus, Abdullah, & Ahmad, 2011; Tentzeris, 2008). Moreover, printing methods would facilitate the combination of RFID tags with chemical sensing functions like ethylene and moisture sensing (Jedermann, Behrens, Westphal, & Lang, 2006; Potyrailo, Mouquin, & Morris, 2008). Another new approach is the AJP with a printing precision of approximately 10 μm. Different solutions, including high-aspect-ratio CNTs solutions as well as organic and inorganic inks with a high viscosity, can be used through AJP to produce layer thickness ranging from tens of nanometers to a few micrometers (Cao, Andrews, & Franklin, 2017; Onses, Sutanto, Ferreira, Alleyne, & Rogers, 2015). Another advantage lies in its unique capability to print patterns on non-flat (3D) surfaces. Inkjet printing is a cheaper approach for printing when compared with this new technique, AJP (an industry AJP printer costs around 500k USD). In conclusion, for high volume fabrication, R2R techniques are ideal, while for superior printing resolution, other techniques, such as inkjet printing, screen printing, and AJP, are more favorable (Nomikos, Politis, Renieri, Tsigonias, & Kakizis, 2014). Table 1 summarizes a comparison between different appropriate techniques that can be used to fabricate SP systems.

Although printed flexible electronics have a bright prospect for SP applications and the state-of-the-art manufacturing processes have already allowed mass production of certain printed electronics, there are still some key points that should be emphasized and issues should be addressed during the entire FSC. When used in food packaging, SP mainly focuses on detecting pathogens and contaminants using sensors/indicators. These smart elements should be first being able to be integrated into the packaging, provide a clear and easily recognized feedback (for example, color change), and being low-cost to manufacture (Kumari, Narsaiah, Grewal, & Anurag, 2015). The materials used for the smart elements need to be printable, low-cost, user- and environmentally friendly, precise, manageable, and reproducible. In this aspect, many nanomaterials have been intensively applied for the printing of SP applications (Duncan, 2011; Hrytsenko et al., 2018; Jiang et al., 2014). The most convenient strategy may be firstly print SP labels and then attach them on the package surface. These labels with either sensors or indicators are sensible and will react to changes caused by spoilage, defrosting, and so on. These reactions could be by changing their optical, mechanical, or electrical characteristics (Fuertes et al., 2016; Kerry & Butler, 2008; Pacquit et al., 2007). In addition, the lower performances of printed electronics may hinder their practical applications further (Fuertes et al., 2016; Vanderroost et al., 2014) with the related issues: (1) how to determine the optimal receptor or electronic ink formulations with high sensitivity and selectivity; (2) how to increase the robustness of electronics and minimalize power consumption; (3) how to reduce the variations in production process by optimizing the printing parameters and material characteristics; and (4) how to effectively integrate smart RFID tags. These challenges about printed sensors have resulted in numerous investigations (Esser, Schnorr, & Swager, 2012; Jung et al., 2014; Monereo et al., 2011; Neethirajan & Jayas, 2011). Furthermore, it should be noticed that the benefit of SP is still not well-marketed at present, which has become a hinder for market penetration of intelligent devices. Retailers are worrying about the reduction in their selling caused by alerts and messages provided by the SP that can influence the consumer decision to buy only newly displayed items (Dainelli, Gontard, Spyropoulos, Zondervan-van den Beuken, & Tobback, 2008). On the other hand, consumers are not sure about the accuracy and quality of the information about the product provided by smart packages (Vanderroost et al., 2014). In addition, there is a lack of effective marketing strategies to maximize the impact of SP. Significant efforts from academia and industry are needed to boost the applications of the SP in the supply chain.

## 5. CHALLENGES FOR THE INTEGRATION OF SP IN FSC

Although the selection of printing methods is decided in the early stage of the entire supply chain, it does affect the remaining stages in the whole chain, including cost allocation among fabrication, production, storage, transportation and market, the quality and safety related with SP's reliability (characteristics of the fabrication method), and innovative interactions among consumer, product, and manufacturer. The need to address the challenges within FSCs is paramount, as the consequences can often be severe, as misalignment or inadequate product control often leads to waste, with resultant financial loss to supply chain businesses (Wang & Li, 2012). As with all supply chains, there is no simple one-size-fits-all approach toward FSC design (Blackburn & Scudder, 2009). The delineation of SCM into three perspectives (operational, tactical, and strategic) leads to a vast number of strategies to address SC challenges within these perspectives (van der Vorst et al., 2009).

From a strategic-level, integrated supply chain processes refer to a series of activities that align business practices toward common goals across internal, supplier, and customer characterizations (Flynn, Huo, & Zhao, 2010). Serving as both a means of creating customer value (Mentzer et al., 2001) and reducing uncertainty (Flynn et al., 2016), integration has long been regarded as a core component of supply chain management (Mentzer et al., 2001; Stauffer, 2003). Integration has been linked to performance increases (Flynn et al., 2010; Vander Vaart & van Donk, 2008), in particular, surrounding quality (Leuschner, Rogers, & Charvet, 2013). Accordingly, its interest to research surrounding FSCs is evident; as enhanced integration permeates into the operational and tactical decision-making processes within a supply chain.

From a tactical and operational perspective, challenges surrounding FSCs are often addressed through mechanisms involved in the distribution process. Technological components, such temperature control mechanisms, can be implemented to prevent both rapid degradation and bacterial contamination (van der Vorst et al., 2009). Often, temperature control manifests itself within three types of supply chains: frozen, chilled, and ambient (Akkerman et al., 2010). Another emergent technological strategy is intelligent packaging that aims to communicate accurate information about a product's condition and packaging integrity throughout the FSC (Vanderroost et al., 2014). Indeed, enhanced packaging techniques may also assist in increasing the shelf-life for particular food products (van der Vorst et al., 2009). Vanderroost et al. (2014) provides an interesting overview of emergent technological trends related to intelligent food packaging, notably concerning sensors, nose systems, indicators, and RFID as major innovations within FSC packaging systems. Another important function of an integrated FSC is to enhance product traceability within everyday operations. Generally speaking, traceability means the ability to provide accurate information about the geolocation of the product at any time and point within the supply chain (Kelepourist, Pramatari, & Doukidis, 2007). Often, traceability can be delineated into backward traceability (or tracing) and forward traceability (or tracking), depending upon the intended trajectory of the product (Bosona & Gebresenbet, 2013).

The proliferation of strategies related to SCM across their various perspectives provides a rich source of literature that are often transferable toward FSCs. However, the unique challenge of FSCs—namely product deterioration—has a number of implications for FSCs strategies. Integration is often regarded as an ideal strategic focus of SCM, and this can manifest itself within tactical and operational levels in rather unique ways. Emergent technologies play an increasing important role in these levels, as they are often the operational component to enhance product traceability within an integrated FSC. More collaborative scientific and industrial efforts are needed to completely clarify all tactical and operational levels of FSC components that can be impacted by the integration of emerging technologies such as SP solutions (Aliakbarian, 2019).

## 6. CONCLUSIVE REMARKS AND PROSPECT

FSC as one of the fast-growing industrial sectors deems quality, safety, integrity, and sustainability as top priorities. Such characteristics could be improved through the integration of SP solutions. As we discussed in the manuscript, SP technologies could add several benefits to the system by enabling the real-time monitoring as well as traceability of the products while they are moving along the supply chain. These capabilities that are based on the integration of cutting-edge technologies could provide accurate data of the products condition and, thus, could prevent theft, protect brand, and compliance as well as reducing food loss and waste. The implementation of the new technologies into existing and traditional packaging is complex and recalls a multidisciplinary collaboration of experts with different engineering, science, communication, and business backgrounds. We believe that, supply chain management principles should be used as a potential tool to facilitate this cross-collaboration and the successful implementation of the new technologies into the traditional system.

## ACKNOWLEDGMENTS

This research was supported by The Axia Institute—Michigan State University (Award#RG100358-17P10).

## AUTHOR CONTRIBUTIONS

Shoue Chen (S.C.), Sandrayee Brahma (S.B.), Jonathon Mackay (J.M.), Changyong Cao (C.C.), Bahar Aliakbarian (B.A.), S.C. and C.C. contributed to the Section 3 (Manufacturing Technologies and Cost for SP). S.B. contributed to the Section 2 (Impact of Smart Packaging (SP) in Reducing Food Waste and Food Loss). J.M. contributed to the Section 4 (Challenges and Integration in Food Supply Chain). B.A. conceived the idea and designed the draft. All authors commented and revised the manuscript.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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