Food Packaging: A Comprehensive Review and Future Trends

Jia-Wei Han, Luis Ruiz-García, Jian-Ping Qian, and Xin-Ting Yang

Abstract: Innovations in food packaging systems will help meet the evolving needs of the market, such as consumer preference for “healthy” and high-quality food products and reduction of the negative environmental impacts of food packaging. Emerging concepts of active and intelligent packaging technologies provide numerous innovative solutions for prolonging shelf-life and improving the quality and safety of food products. There are also new approaches to improving the passive characteristics of food packaging, such as mechanical strength, barrier performance, and thermal stability. The development of sustainable or green packaging has the potential to reduce the environmental impacts of food packaging through the use of edible or biodegradable materials, plant extracts, and nanomaterials. Active, intelligent, and green packaging technologies can work synergistically to yield a multipurpose food-packaging system with no negative interactions between components, and this aim can be seen as the ultimate future goal for food packaging technology. This article reviews the principles of food packaging and recent developments in different types of food packaging technologies. Global patents and future research trends are also discussed.

Keywords: antimicrobial, antioxidant, food packaging, food safety, nanotechnology

Introduction

Food packaging is used to protect food from environmental contamination and other influences (such as odors, shocks, dust, temperature, physical damage, light, microorganisms, and humidity), and it is key to ensuring the quality and safety of food, while also extending shelf-life and minimizing food losses and wastage (Carocho, Morales, & Ferreira, 2015; Narayanan, Loganathan, Valapa, Thomas, & Varghese, 2017; Ribeiro-Santos, Andrade, Melo, & Sanches-Silva, 2017; Robertson, 2012). The use of food packaging can be traced back to the 18th century (Gupta and Dudeja 2017). In the 20th century, many advancements in packaging technology appeared, including intelligent or smart packaging (IOSP; time-temperature indicators (TTIs), gas indicators, microwave doneness indicators, radiofrequency identification (RFID), and others), and active packaging (AP; such as oxygen scavengers, moisture absorbers, and antimicrobials) (Brody, Bugusu, Han, Sand, & McHugh, 2008). These innovations further improved food quality, food safety, and shelf-life.

Oxidation, microbial spoilage, and metabolism are the main causes of deterioration of many foods, such as apples, bananas, kiwifruit, pears, tomatoes, and mangoes, during production, processing, storage, and marketing. These processes are directly related to the loss of food quality (including safety), influence consumer buying decisions, and impact consumer health, and thus affect the overall economics of the food industry (Fernández-Pán, Carrión-Granda, & Maté, 2014; Nerín, Tovar, & Salafranca, 2008; Sanches-Silva et al., 2014; Zhao, Han, Yang, Qian, & Fan, 2016). The negative effects of oxidation on the nutritional and organoleptic characteristics of food include the following: (1) it decreases the nutritional value of food due to the destruction of essential fatty acids, proteins, and lipid-soluble vitamins (A, D, E, and K); (2) it decreases the energy (or caloric) content of food; (3) it produces rancidity (off-flavors); and (4) it produces color changes (darkening of fats and oils, degradation of pigments) (Nerin et al., 2008). The presence of pathogenic microorganisms increases the risk of food-borne diseases in humans and thus presents a problem for public health (Carbone, Donia, Sabbatella, & Antochia, 2016; Gram et al., 2002; Krepker et al., 2017). The U.S. Centers for Disease Control and Prevention (CDC) reports that approximately 76 million people in the United States develop food-borne diseases every year (causing 5,000 deaths and 325,000 hospitalizations) (Morris, 2011), which directly increases medical costs, causes deaths, and increases the economic burden of lost work, especially for low-income families (Scharff, 2010).

To delay oxidation, control foodborne pathogens, and meet the growing demand of consumers for safe and high-quality products, considerable effort has been devoted to in-depth studies of active food packaging and the development of new active food...
packaging technologies, which can include utilization of antioxidant properties (Brahmi et al., 2016; Hafs et al., 2016; Tongmuanchan, Benjakul, & Prodpnan, 2013; Wannes et al., 2010), antimicrobial properties (Choi, Singh, & Lee, 2016; Peng & Li, 2014; Souza, Goto, Mainardi, Coelho, & Tadini, 2013; Yun et al., 2015), or both (Jouki, Yazdi, Mortazavi, & Kooheki, 2014; Salgado, López-Caballero, GómezGuillén, Mauri, & Montero, 2013; Shojaee-Aliaabadi et al., 2013). AP can effectively improve food quality (including safety) and extend shelf-life by positively affecting the headspace of a packaged product and/or the product itself (for example, releasing an antimicrobial or antioxidant compound), but this packaging technique cannot provide visual information indicative of the shelf-life, safety, or quality of food, and it cannot warn about possible current or future problems. Food packaging innovations have gradually led to the development of intelligent packaging, which can convey detailed information about the condition of a packaged food or its environment throughout a logistical chain, as well as provide early warning to the consumer from the food manufacturer (Vanderroost, Ragaert, Devlieghere, & Meulenae, 2014). Thus, currently available intelligent packaging technologies can accomplish diverse functions such as monitoring, identifying, processing, recording, tracing, and communicating information, which promote decision-making efficiency, extend shelf-life, and communicate information about the state and/or quality of the product through the supply chain (Yam, Takhistov, & Milz, 2005).

As mentioned above, packaging acts as a physical barrier to protect food from external factors, so the stability of packaging materials is absolutely vital for enhancing food quality and safety and increasing shelf-life, as well as ensuring that packaging materials can fulfill their role in providing sturdy, attractive, economical, and convenient products to consumers (Gupta and Dudeja, 2017). Therefore, all food packaging materials must be rigorously tested by food safety agencies such as the U.S. Food and Drug Administration (FDA), the Brazil National Health Surveillance Agency (ANVISA), and the European Commission (EC), which are responsible for ensuring the safety of food packaging materials and additives before they can be used in food (Ribeiro-Santos et al., 2017). As the amount of packaging consumed increases, the environmental impacts of food packaging materials have gradually become a major issue worldwide, especially for companies and producers. To achieve sustainability in food packaging, promote recycling of packaging material, and alleviate environmental pollution, several studies have been devoted to creating new packaging innovations based on renewable resources that are eco-friendly, biodegradable, or compostable (Goffin et al., 2011; Licciardello, 2017; Peelam et al., 2013; Siracusa, Roccoli, Roman, & Rosa, 2008; Narayanan and others, 2017). However, providing eco-friendly packaging alternatives without compromising the key features of the packaging (such as barrier properties, mechanical properties, and extended product shelf-life) will require continued innovation and the development of new sustainable packaging technologies in the coming decades.

The goals of this article were to review the current commercial applications of food packaging technology and present an overview of research innovations and trends regarding different types of food packaging. Some challenging issues must be addressed to maintain and improve food quality and safety, increase consumer trust and acceptance of new packaging technologies, and reduce the harmful impacts of packaging waste and food loss on the environment. These issues are discussed with the goal of providing useful future directions for research in the field of food packaging technology.

### Food Packaging Trends

Changes in consumer demand, industrial production trends (such as mildly preserved, fresh, tasty, and convenient food products with enhanced shelf-life and controlled quality), retailing practices (such as transregional and transnational long-distance sales of food), and customer lifestyles (such as a fast-paced lifestyle resulting in less time spent shopping for fresh food at the market and cooking) are the main forces driving the evolution of novel and innovative packaging techniques that maintain and monitor food safety and quality, extend shelf-life, and reduce the environmental burden of food packaging (Dainelli, Gontard, Spyroulous, Zondervan-van den Beuken, & Tobbback, 2008). In the past 20 years, IOSP, AP, and sustainable or green packaging (SOGP) have been developed in response to market developments, changes in consumer preferences, and the need to reduce the environmental impact of food production while maintaining food quality and safety. Figure 1 shows the yearly trend of the total number of publications on IOSP, AP, and SOGP over the past 20 years. The number of peer-reviewed publications on food packaging innovations has increased steadily. For the past two decades, the research interest in IOSP has lagged far behind the interest in AP, which can be attributed to AP providing protection beyond traditional protection and inert barriers to the external environment; it offers a relatively large number of possible methods of decreasing food waste and loss. The following sections present detailed introductions and reviews for each type of food packaging (see Figure 2).

### IOSP

IOSP is capable of monitoring the condition of packaged food or its environment by using sensors or indicators (such as electronic, chemical, and mechanical triggers). IOSP can be used to monitor, sense, record, trace, and convey information about the quality of food, and it can be used with decisions concerning shelf life, safety, and quality, as well as alert people to possible problems with food (Yam et al., 2005). IOSP systems contain smart devices (small labels or tags), which can be printed onto or incorporated into food packaging materials to acquire information about the food's quality, store that information, and transfer it to the stakeholders (manufacturers, retailers, and consumers) (Dainelli et al., 2008; Fang, Zhao, Warner, & Johnson, 2017; Restuccia et al., 2010). The most commonly used smart devices in IOSP can be classified as indirect or direct indicators of food quality (see Figure 2). Indirect indicators cannot provide direct information to help consumers judge the quality and edibility of food. However, they can indirectly evaluate the effects of the environment surrounding the food on the shelf-life and quality of food which might lead to a hidden danger for consumers. Foods that have deteriorated or carry small amounts of a toxin, but which do not yet exhibit detectable signs of spoilage, may harm immunosuppressed populations, especially children and the elderly (Wang, Lu, & Gunasekaran, 2017). Direct indicators can directly present some information about the freshness, edibility, quality, and safety of food to consumers. These devices must usually be placed inside the primary packaging so that they have direct contact with the atmosphere surrounding the food or with the food itself. Therefore, direct indicators have become a main future direction of research in this area.

### TTIs

The shelf-lives of many food products are very sensitive to temperature variation, which is a major cause of deterioration and economic loss in these perishable goods during transportation, handling, distribution, storage, and consumption. To limit pathogenic microorganism growth or toxin formation for most
perishable products in our diets and include a wide range of natural, processed, raw, and cooked foods of both animal and plant origin, the FDA has defined these foods as TCS (time and temperature control for safety) foods that requires time and temperature control to ensure their quality and safety (FDA, 2013). However, uncontrolled temperature fluctuations are almost inevitable for all goods throughout the supply chain, and such fluctuations may lead consumers to make incorrect judgments regarding the sell-by or use-by dates of products based on the ideal label of the expiration date on the product package (Wang et al., 2015b, 2017). Therefore, temperature monitoring is vital to provide consumers with necessary information about food quality and safety throughout the process of food circulation. To address this issue, TTIs have been developed to monitor time- and temperature-dependent changes in product quality and/or safety; TTIs are typically indirect indicators and are commonly used in the food industry because they are relatively small, cost-effective, and user-friendly compared to other temperature-monitoring devices (Taoukis & Labuza, 1989).

TTIs are generally attached onto individual consumer packages or shipping containers, and they can be classified into three types based on their capabilities: (1) critical temperature indicators (these only show whether a product has been exposed to a temperature above, or sometimes below, a reference temperature); (2) critical TTIs (these indicate the cumulative effect of the time-temperature changes on product quality or safety when a product has been exposed to a temperature above a reference temperature); and (3) full history indicators (continuous monitoring of the manner in which the temperature varies with time throughout a product’s history) (Singh, 2000; Taoukis, Fu, & Labuza, 1991). The basic working principles of TTIs are the identification of irreversible responses in the form of enzymatic, electronic, chemical, nanoparticle, or biological changes after a product is exposed to a higher temperature (Fang et al., 2017; Kerry, O’Grady, & Hogan, 2006). Electronics-based TTIs are defined as an electronic device that can present a warning about the quality of a product by using a thermal sensor that converts temperature signals to electrical signals, after which it converts electrical signals to a final visual output (Wang et al., 2015b). Because the read-out devices for electronics-based TTIs are complex and specialized, TTIs are generally expensive and inconvenient, or they may require some training on the part of consumers, which leads to reduced market acceptance (by the product producer, consumer, and retailer) and limits the scope of commercial applications. However, compared with other types of TTIs, electronics-based TTIs have relatively high precision and are generally superior technologies for monitoring and recording the thermal history of a product. Moreover, most kinds of electronics-based TTIs are environmentally friendly and can be recycled. With the development of electronics-based TTIs, some novel electronic TTIs have been invented that do not require professional read-out devices or trained personnel to conduct the test (Haarer, Gueta-Neyroud, & Salman, 2012; Jensen, Debord, & Hatchett, 2013). This technology provides more convenience to consumers and increases the market demand for intelligent packaging. However, to facilitate the application of electronics-based TTIs in the global market without compromising precision and safety, TTIs must be smaller, lower in cost, and made from recyclable electronics.

For other types of TTIs (such as nanoparticle-based, enzyme-based, chemistry-based, and biology-based), an irreversible color change is the main way to determine the thermal history of the product. The color change can indicate time- and temperature-dependent changes in the quality and/or safety of the product. These types of TTIs are generally stuck on or incorporated into the product packaging by printing or coating, and they have a lower cost, are more convenient to read and are smaller than electronics-based TTIs. The size, shape, and surface morphology of metal nanoparticles change is based on the time/temperature scenario to which they are exposed; nanoparticles exhibit an irreversible color change when exposed to a particular temperature for a given length of time, and this property makes them extremely useful for TTIs. Lim, Gunasekaran, and Imn (2012) developed a gelatin/AuNP (gold nanoparticle)-based thermal history indicator (THI), which showed a clear color signal after 6 hr of exposure at 30 °C. The intensity of the color signal was proportional to the duration of exposure. Moreover, the color
intensity of the AuNPs was maximal at a gelatin concentration of 2\%. However, the gelatin/AuNP-based TTIs were designed specifically for low-temperature storage, and they have several disadvantages compared to alginate/AuNP-based THIs, including lower color-change sensitivity, a narrower range of temperature monitoring, and the inability to prepare solid-like THI matrices. Because of these characteristics, Wang et al. (2017) developed a plasmonic THI that takes advantage of the localized surface plasmon resonance of AuNPs synthesized \textit{in situ} in alginate, which can be made into a solid hydrogel by adding divalent calcium ions and is more suitable for certain end-use applications. In enzyme-based TTIs, the hydrolysis reaction of an enzyme with a substrate causes different degrees of color change depending on the real time-temperature history. The observed color of a TTI can reveal the cumulative effect of time and temperature, and that information can be used to implement a dynamic evaluation of the product's
remaining shelf-life. For example, Figure 3 shows a TTI label (Vitstab Checkpoint®) that is a typical example of enzyme-based TTIs. The TTI label can be activated by applying gentle pressure on the “window” to initiate an enzymatic reaction between the enzyme and substrate. The TTI window in the center of the words “Check Point” changes color from green to orange to red to indicate various stages of thermal exposure. A homogeneous green color in the “window” indicates mixing of the enzyme and substrate minipouches, which in turn indicates perfect shipping and storage conditions for the packaged foods. If the “Check Point” is yellow to light orange, it indicates that the TTI label has reached its preset time-temperature response time and the product is no longer acceptable (Fang et al., 2017). Chemical TTIs are based on many different chemical reactions (such as polymerization, photochromic, and oxidation reactions), and they present a distinct color change due to accumulation of changes in time and temperature. Currently, some examples of chemistry-based TTIs include Fresh-Check®, HEATmarker® (N.J., U.S.A.), and OnVuTM (Ciba Specialty Chemicals, Inc., Switzerland). Their operation principles and performance characteristics can be obtained by visiting the official websites of the product manufacturers. The operation principles of biology-based TTIs are generally based on a change in pH under certain conditions, especially at a certain temperature, which leads to a color change that reveals the cumulative effect of time and temperature (Wang et al., 2015b). Despite active research into indirect indicators, such indicators have many problems, such as increasing the cost of the entire supply chain, introducing safety issues due to potential undesirable migration of chemical components, having questionable accuracy and reliability under uncontrollable conditions (such as impact, compression, and vibration), and facing certain legislative restrictions in Europe (Dainelli et al., 2008). Therefore, to expand the range of applications for indirect indicators in the global market, future developments should be directed towards improving the stability and sensitivity of indicators to real-time temperature history, such as by using nontoxic and even edible biopolymers to indicate the thermal history of a product with an irreversible color change. Improvements can also be made to the legal regulations governing intelligent packaging.

**RFID.** RFID is based on wireless communication (magnetic field or electromagnetic wave) that can provide real-time information about temperature, relative humidity, and nutritional and supplier information as the product moves through the supply chain, thus increasing traceability and ensuring food safety and quality (Bibi, Guillaume, Gontard, & Sorli, 2017). RFID is more convenient for product identification than traditional labels and barcodes, has a relatively large data storage capacity, has a longer reading range (up to dozens or even more than 100 m of distance), and does not require visual contact. RFID tags can be embedded in an item, placed inside food packing, or injected into the bodies of animals (Ruiz-Garcia & Lunadei, 2011). Therefore, RFID tags are now considered to be a replacement for barcodes. However, because of their relatively high cost (roughly $US 0.2 to 0.3 per tag), their usage is limited, and some companies have found that moving to RFID technology is unaffordable (Bibi et al., 2017; Fang et al., 2017). To overcome these obstacles, future studies are expected to be aimed at reducing the cost of RFID tags as much as possible.

Each RFID tag can be classified as passive, semipassive, or active according to its power supply mode. Passive tags do not contain onboard power sources and are powered by electromagnetic induction in magnetic fields, which is produced near the reader (Bai et al., 2017). In comparison with the other two types of tags, passive tags have a relatively short reading distance, and few tags can be read simultaneously; however, this type of tag has a long operational life in addition to being small, light, and low-cost, so these tags are potential candidates for developing low-cost devices (Bibi et al., 2017). Semipassive tags have a local power source that is used only for powering the chip. These tags still rely on the reader for electromagnetic wave emission, and most of the time they remain dormant except when awakened by the reader. Thus, the power source is inactive most of the time, which increases the lifespan of the tags. In contrast to passive tags, semipassive tags have a wider working range. Active tags have an embedded battery that is used to power the chip and to broadcast signals to the reader. Compared with the other two types of tags, these tags have the widest reading range (more than 50 m), and many tags can be read simultaneously. However, the widespread use of active tags is limited, because they are more expensive than passive or semipassive tags and have a limited lifespan (depending on battery life). Figure 4 shows the basic RFID systems and different operating frequencies. To add new functionalities to RFID tags, different types of sensors (such as TTIs, humidity sensors, and gas sensors) have been integrated into RFID tags, which can be used for sensing, communicating, and monitoring food packaging headspace. These tags provide real-time data about food quality, safety, and history through the supply chain. RFID tags coupled to sensors are also a major driving force for the application of RFID technology in intelligent packaging systems. Passive tags provide only information about identification and tracking; for sensing applications, it is necessary to use semipassive or active tags (Ruiz-Garcia & Lunadei, 2011). However, the integration of sensors into RFID tags also faces some challenges, such as the impact that increasing the cost of tags may have on the final cost of food products, which could lead to decreased sales. Furthermore, researchers must determine how to meet the functional requirements of RFID sensor tags and avoid direct contact between food and the tags by optimizing the elements used in the tags (such as antennae, chips or sensors). In addition, the operational life of RFID tags is limited because the sensors require power to function properly. All of these challenges should be studied in the future with the goal of facilitating widespread adoption of RFID tags in food packaging.

**Gas indicators.** The gas composition within food packaging changes due to the activity of the food product (such as respiration and transpiration of fresh horticultural produce, as well as spoilage due to microorganisms), the nature of the package (such as the gas permeability of the packaging material), and the environmental conditions (temperature or package leaks), and it is directly related to the integrity, shelf-life, quality, and safety of packaged food products (Fang et al., 2017; Yam et al., 2005). To monitor changes in gas composition inside the package and thereby provide a means of monitoring the quality and safety of food products, different types of gas indicators are used in food packaging in the form of package labels or package printing films that detect oxygen, ethanol, hydrogen sulfide (H₂S), water vapor, carbon dioxide, or other gas components. Oxygen can cause deleterious effects on food quality through oxidative rancidity, changes in color, and microbial spoilage; therefore, oxygen indicators are used widely in food packaging (Fang et al., 2017). In general, a gas indicator also provides an irreversible and visible color change on the packaging to respond to changes in gas composition. Wilhelm and Wolfbeis (2010) presented two different absorption-based opto-chemical indicators for oxygen, which consist of leuco dyes (leuco indigo and leuco thionindigo) incorporated into two kinds of polymer
matrices, poly(styrene-co-acrylonitrile) (PSAN, with 30 wt% acrylonitrile) and polymer hydrogel D4 (a linear polyurethane). The results showed that LI-D4 (leuco indigo incorporated into a highly oxygen-permeable hydrogel polymer) induces an irreversible color change (from pale yellow to deep blue) that indicates the presence of air (oxygen) within a few minutes, which is important for detecting leaks in food packed under a modified atmosphere. However, the LTI-PSAN indicator (leuco thioindigo incorporated into PSAN) required several hours to gradually change its color from yellow to red after exposure to air. This study provided a cost-effective means of visually detecting and monitoring the seal status and quality deterioration of packaged foods, including fish and meat. In addition, a reversible oxygen indicator was produced by DryPak Industries, which can be inserted into a container and changes color from pink to blue when the oxygen concentration is greater than 0.5%. This oxygen indicator is extremely similar to the Ageless Eye® product sold by Mitsubishi Gas Chemical Company. However, the two oxygen indicators cannot indicate the time of exposure under different oxygen concentrations (the color transition from blue to pink occurs at an oxygen concentration of less than 0.1%). Chatterjee and Sen (2015) developed a carbon dioxide indicator to respond to the presence of carbon dioxide via a color change from red to yellow. Other applications of carbon dioxide indicators include measuring the degree of fermentation in kimchi products during storage and distribution and displaying the concentration of carbon dioxide inside modified atmosphere packaging (MAP) (Ahvenainen, Eilamo, & Hurme, 1997; Hong & Park, 2000). In the near future, RFID coupled with gas indicators is likely to become an important technique used to realize real-time dynamic monitoring of changes in gas composition inside food packaging during the entire supply chain. However, to integrate gas indicators into RFID tags, gas indicators must be read automatically and changed into electrical signals, which is one of the most challenging problems facing food technology researchers.

**Direct indicators.** After food packaging, volatile compounds can be generated within the package due to enzymatic reactions, microbial growth, or chemical changes in the fresh food product. These changes are directly related to the freshness, spoilage status, and edibility of packaged food. The quality and safety of packaged food products can be evaluated directly based on the levels of these volatile compounds. Evaluation of quality and safety based on concentrations of volatile compounds is the basic operational principle of direct indicators. Compared with indirect indicators, direct indicators can provide more precise and targeted information about quality attributes by responding to changes in packaging (such as maturation indicators for fresh fruits and vegetables based on the detection of a volatile aroma compound, or a fish freshness indicator based on the detection of volatile amines). Achieving dynamic responses to changes in volatile compounds is a major trend in the field of intelligent-packaging research (Dainelli et al., 2008). Kuswandi, Maryska, Jayus Abdullah, and Heng (2013) developed a simple and low-cost on-package color indicator by using bromophenol blue (BPB) with a cellulose membrane (highly
pH-sensitive in the range of pH 3.0 to 4.6). This indicator can be used for real-time visual monitoring of the freshness of packaged guavas, and it can be used to assess their period of salability under an ambient temperature in the range of 28 °C to 30 °C. During the development of the guava, the freshness indicator will change color from blue to green to indicate over-ripe fruit as a result of the manner in which the change in pH caused by volatile organic compounds (such as acetic acid) in the package headspace affects the BPB/cellulose membrane. Microbial growth is the main reason for the spoilage of most seafood products, and it leads to a pH change in the package headspace because of the formation of NH₃ and other volatile amines. Ma, Du, and Wang (2017) developed a shrimp freshness indicator based on a biosensor film by incorporating curcumin (Cur) into a tara gum (TG)/polyvinyl alcohol (PVA) film, which can be used to monitor shrimp spoilage. The biosensor film induces a reversible color change on the packaging to reflect an increase in pH caused by the release of NH₃. However, this study did not determine the relationship between the color change and NH₃ levels in shrimp or the level of shrimp spoilage. Chung, Le, Tran, and Nguyen (2017) designed a battery-free smart sensor tag by transforming a fully passive RFID tag, and this smart sensor can be used to predict the quality of packaged fish by accurately monitoring the temperature and concentrations of H₂S or NH₃ in the fish packaging. The novel smart-sensing tag module was powered by an energy harvesting circuit, which can collect sufficient RF energy from the reader by using RF energy coupling within a maximum distance of 30 cm. The design and implementation of the battery-free smart-sensor tag has promoted the development of RFID-equipped gas absorbers/scavengers, and antioxidant packaging (such as moisture absorbers, carbon dioxide-emitting/generating absorbers/scavengers, and antioxidant packaging) and active scavenging packaging (such as moisture absorbers, carbon dioxide absorbers/scavengers, and antioxidant packaging) and active releasing packaging (such as carbon dioxide-emitting/generating packaging and antimicrobial packaging) (Figure 5). The substances responsible for the active functions of the packaging (the “active” components) can be directly incorporated into the packaging material or onto its surface, in multilayer structures or in particular elements associated with the packaging such as sachets, self-adhesive labels, or bottle caps (Ahmed et al., 2017; Dainelli et al., 2008). According to the European Union legislation for food contact material (FCM) (such as Regulations 1935/2004/EC and 450/2009/EC) (European Commission, 2004, 2009), the active substances should not mislead the consumer (such as masking spoiled food), and they should be adequately labeled using the words “do not eat” or a symbol to prevent the nondie food from being mistaken for part of the food (such as loose sachets). Before they may be used commercially, the active materials must be approved and authorized by the U.S. FDA or EC based on evaluation and tests, such as migration testing, which includes overall migration tests and specific migration tests, and which sometimes includes dedicated tests for semisolid food (Lopez-Cervantes, Sanchez-Machado, Pastorelli, Rijik, & Paseiro-Losada, 2003). AP can be classified into two main types: active scavenging packaging (such as moisture absorbers, carbon dioxide absorbers/scavengers, and antioxidant packaging) and active releasing packaging (such as carbon dioxide-emitting/generating packaging and antimicrobial packaging) (Figure 5). The following sections provide a detailed introduction to different types of AP and their commercial applications.

**Moisture absorbers.** Moisture absorbers are the most well-known examples of active scavenging packaging and mostly rely on the adsorption of water by incorporating absorbing substances (such as silica gel, molecular sieves, calcium oxide, and natural clays) into a sachet for use with the packaging (Dainelli et al., 2008). Tray–formatted (overwrap and modified atmosphere)
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Figure 5—Schematic diagram for active food packaging systems.

Table 1—Commercially available moisture absorber packaging materials for food applications (Realini & Marcos, 2014; Suppakul et al., 2003).

<table>
<thead>
<tr>
<th>Year</th>
<th>Commercial name</th>
<th>Manufacturer</th>
<th>Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977*</td>
<td>MiniPax®</td>
<td>Multisorb Technologies, Inc., USA.</td>
<td>Sachet</td>
</tr>
<tr>
<td>1980*</td>
<td>Dri-Loc®</td>
<td>Novipax LLC, UK</td>
<td>Absorbent pads</td>
</tr>
<tr>
<td>1987*</td>
<td>StripPax®</td>
<td>Multisorb Technologies, Inc., USA.</td>
<td>Sachet</td>
</tr>
<tr>
<td>1991</td>
<td>Thermante®</td>
<td>Sealed Air Corporation, USA</td>
<td>Absorbent sheets</td>
</tr>
<tr>
<td>2003*</td>
<td>ToppanTM</td>
<td>Toppan Printing Co., Japan</td>
<td>Absorbent sheets</td>
</tr>
<tr>
<td>2005*</td>
<td>Linpac</td>
<td>Linpac Packaging Ltd., UK</td>
<td>Absorbent tray</td>
</tr>
<tr>
<td>2005</td>
<td>Sorb-it®</td>
<td>Healthy Culinary Products, USA.</td>
<td>Sachet</td>
</tr>
<tr>
<td>2008*</td>
<td>DesiMax®</td>
<td>Multisorb Technologies, Inc., USA.</td>
<td>Absorbent sheets</td>
</tr>
<tr>
<td>2011*</td>
<td>2-in-1TM</td>
<td>Glad Products Company, USA</td>
<td>Sachet</td>
</tr>
<tr>
<td>2013*</td>
<td>Fresh-R-Pax®</td>
<td>Maxwell Chase Technologies, USA.</td>
<td>Absorbent tray</td>
</tr>
<tr>
<td>2015*</td>
<td>TenderPac®</td>
<td>Sealpac, Germany</td>
<td>Dual-compartment system</td>
</tr>
<tr>
<td>2016*</td>
<td>PichitTM</td>
<td>Okamoto Industries, Inc., Japan</td>
<td>Sachet</td>
</tr>
<tr>
<td>NS*</td>
<td>Pad-Loc Fresh®</td>
<td>Novipax LLC, UK</td>
<td>Absorbent pads</td>
</tr>
<tr>
<td>NS*</td>
<td>Peakisorb®</td>
<td>Peakfresh Products Ltd., Australia</td>
<td>Absorbent sheets</td>
</tr>
<tr>
<td>NS*</td>
<td>MoistCatchTM</td>
<td>Kyodo Printing Co., Ltd., Japan</td>
<td>Absorbent pads</td>
</tr>
<tr>
<td>NS*</td>
<td>MeatGuard</td>
<td>McAirland Inc., USA</td>
<td>Absorbent pads</td>
</tr>
<tr>
<td>NS*</td>
<td>Nor®Absorbit</td>
<td>Nordenia International AG, USA</td>
<td>Microwavable film</td>
</tr>
</tbody>
</table>

NS: unknown year; *: still commercially available.

Moisture absorbers are an effective way of controlling excess water accumulation inside the packages of foods with high water content (such as meat, fish, poultry, and fresh produce), which is important for inhibiting bacterial growth, impeding mold growth, and enhancing product presentation (Realini & Marcos, 2014). To make the active system invisible and to avoid accidental swallowing by the consumer, moisture absorbers are typically incorporated into the packaging material as absorbing pads or trays for meat and fish packaging (Dainelli et al., 2008). Some commercial moisture absorbers are listed in Table 1.

**Carbon dioxide absorbers/scavengers.** Carbon dioxide (CO₂) efficiently inhibits surface growth by a range of aerobic bacteria and fungi by reducing relative oxygen levels and/or exerting direct antimicrobial effects (at concentrations of CO₂ between 10% and 80%) in food packaging. CO₂ is thus often used as a flushing gas in MAP systems to help maintain freshness and prolong shelf-life, especially for fresh meat, poultry, fish, and cheese packaging (Dong, 2016; Vermeiren, Devlieghere, Beest, Kruijff, & Debevere, 1999). However, for some CO₂-producing foods (such as fresh horticultural products and fermented foods), excess CO₂ accumulation in a package may cause high levels of CO₂ dissolution into foods and may increase the pressure (or volume) of the package due to low CO₂ permeation through the packaging.
film, which leads to undesirable changes in product quality, such as changes in the flavor and texture of products or/and the development of undesired anaerobic glycosis in fruits, and package collapse (Dong, 2016; Suppakul et al., 2003). Pears are sensitive to injury by CO₂ at concentrations higher than 2% (Wattkis, 2000). Additionally, some commodities, such as potato, lettuce, onion, cucumber, cauliflower, artichoke, apricot, peach, apple, and carrot, show various symptoms of CO₂ injury, such as discoloration, off-flavor development and internal tissue breakdown, when the level of CO₂ exceeds 5% (Wattkis, 2000). Caplicec and Fitzgeralda (1999) found that slightly reducing the CO₂ concentration promoted the growth of lactic acid bacteria and improved the quality of some fermented foods. In cases where reducing the level of CO₂ in food packaging can improve food quality, CO₂ scavengers on the quality of air-packaged straw-

duces in the product and can create a partial vacuum, as well as consume oxygen due to the release of CO₂ from inserted sachets based on either ferrous carbonate or a mixture of sodium bicarbonate and ascorbic acid (Rooney, 1995). However, the concentration of CO₂ is dynamically changed, and loss

<table>
<thead>
<tr>
<th>Year</th>
<th>Commercial name</th>
<th>Manufacturer</th>
<th>Form</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003*</td>
<td>ATCO® CO-450</td>
<td>Standia Industrie, France</td>
<td>Sachets</td>
<td>Ca(OH)₂(s)+CO₂(g) → CaCO₃(s)+H₂O(l)</td>
</tr>
<tr>
<td>2008*</td>
<td>LitholyteTM</td>
<td>Allied Healthcare Products, Inc., USA</td>
<td>Granules</td>
<td>CO₂+H₂O→H₂CO₃+2NaOH→Na₂CO₃+2H₂O+Energy</td>
</tr>
<tr>
<td>2017*</td>
<td>Ageless® E</td>
<td>Mitsubishi Gas Chemical Inc., Japan</td>
<td>Sachets</td>
<td>Ca(OH)₂(s)+CO₂(g) → CaCO₃(s)+H₂O(l)</td>
</tr>
<tr>
<td>NS*</td>
<td>Freshlock®</td>
<td>Multisorb Technologies Inc, USA</td>
<td>Sachets</td>
<td>Ca(OH)₂(s)+CO₂(g) → CaCO₃(s)+H₂O(l)</td>
</tr>
<tr>
<td>NS*</td>
<td>EMCO®</td>
<td>EMCO Packaging Systems, Kent, UK</td>
<td>Sachets</td>
<td>2NaCl+CO₂+NH₃+H₂O→Na₂CO₃+3/2H₂O₂+3/4O₂</td>
</tr>
<tr>
<td>NS*</td>
<td>Zeolite 4A</td>
<td>Wako Pure Chemical Industries Ltd., Japan</td>
<td>Beads</td>
<td>Physical absorbers</td>
</tr>
<tr>
<td>NS*</td>
<td>Active carbon</td>
<td>Junsei Chemical Co., Ltd., Japan</td>
<td>Powder</td>
<td>Physical absorbers</td>
</tr>
</tbody>
</table>

*NS*: unknown year; “*: still commercially available.

Carbon dioxide-emitting/generating packaging. As mentioned above, relatively high levels of CO₂ have direct antimicrobial effects on some microorganisms, mainly as a result of the high solubility of CO₂ in foods, especially at low temperatures (Chaix, Guillaume, & Guillard, 2014). Therefore, a high CO₂ concentration is included in the MAP system for chill-stored nonrespiring foods that are susceptible to microbial spoilage (Dong, 2016). In the case of oxygen scavenger packs, oxygen removal creates a partial vacuum that may result in the collapse of flexible packaging. Additionally, when a package is flushed with a mixture of gases including CO₂ and O₂, the CO₂ dissolves in the product and can create a partial vacuum, as well as consume oxygen due to the release of CO₂ from inserted sachets based on either ferrous carbonate or a mixture of sodium bicarbonate and ascorbic acid (Roonen, 1995). However, the concentration of CO₂ is dynamically changed, and loss
occurs because CO₂ dissolves in the meat and penetrates into the external environment through the packaging material (the permeability of CO₂ through most plastic films is 3 to 5 times higher than that of oxygen) (Coma, 2008; Ozdemir & Floros, 2004). Therefore, CO₂ emitters are beneficial and necessary for maintaining the desired CO₂ concentration in the packaging and ensuring the efficacy of a MAP system. Table 4 presents the commercial names, manufacturers, and forms of commercially available CO₂ emitters that can be used to control CO₂ concentrations in food packages. Microspheres® (Bernard Technologies, Inc., U.S.A.) can produce a controlled and sustained release of chlorine dioxide gas when they interact with moisture (exposure to humidity greater than 80%) and light, which results in high activity against a broad spectrum of microorganisms, including actively growing vegetative cells and spores. Microspheres® have been used to reduce food safety risks for meat, poultry, fish, dairy, confectioneries, and baked goods (Coma, 2008). The Verifrais™ package technology (SARL Codimer, Paris, France) consists of a standard MAP tray that has been successfully used to prolong the storage life of fresh meats. A porous sachet containing sodium bicarbonate/ascorbate is placed under the perforated false bottom of the tray, and it emits CO₂ when the exudates of the packaged meat drop onto the sachet. It has the dual effect of suppressing microorganisms and avoiding package collapse (Kerry et al., 2006). CO₂ FreshPads® (CO₂ Technologies, U.S.A.) are used for poultry, seafood, and meat packaging, and they have a CO₂-emitting process similar to that utilized by Verifrais™. A recent study on the effect of vacuum or MAP in combination with a CO₂ emitter on the quality parameters of cod loins (Gadus morhua) was conducted by Hansen, Møen, Rødjbott, Berget, and Pettersen (2016). The CO₂ emitters were prepared by adding 0.304 g NaHCO₃ and 0.237 g citric acid to a liquid absorber pad (Absorbent Pad Dri-Loc, Friedrichsdorf, Germany), which also functioned as a liquid absorbent pad. This study showed that the initial freshness was better preserved by adding a CO₂ emitter to both the vacuum and the MAP, and the shelf-life of the “MAP + CO₂ emitter” (approximately 13 days) was about 6 days longer compared to “Vacuum” (approximately 7 days). Additionally, CO₂ emitters can help reduce the gas-to-product-volume ratio and subsequent reduction of the packaging headspace compared to optimal MAP, thus improving the transport efficiency of the MAP without causing packaging collapse or compromising quality and shelf-life (Hansen, Morkøre, Rudi, Olsen, & Eie, 2007, 2009). As shown in Table 4, some commercial CO₂ emitters have dual functions because they contain combinations of CO₂ emitters and O₂ scavengers. However, very few studies have reported the development of films that can generate CO₂, scavenge O₂, or perform both functions. Producing films with this capability is a top priority for manufacturers of CO₂ emitters. Although this concept is still in the initial stage of research, a recent study was conducted to evaluate the effectiveness of three different antimicrobial packaging structures in controlling the quality of a ready-to-eat meat product (Chen & Brody, 2013). Cooked ham samples were packaged into three different antimicrobial packaging structures, including an oxygen barrier bag and an antimicrobial film with the capacity of generating CO₂ or allyl isothiocyanate (AIT) or scavenging molecular O₂. Samples in the packaging structures with an O₂ scavenger or a CO₂ generator can effectively control the bacterial populations, particularly Listeria populations, and the packaging structures with the AIT generator only exhibited limited antimicrobial effects. The combination of the three antimicrobial packaging systems showed synergistic antimicrobial activities (Fang et al., 2017).

**Antioxidant packaging.** High levels of oxygen in food packages can facilitate microbial growth (such as aerobic bacteria, molds, and insects), oxidation of lipids and pigments, and loss of O₂-sensitive nutrients such as vitamins A, C, and E, which lead to changes in flavor (typical of rancidity), color, texture, and nutritive value. These changes can render the product unacceptable for human consumption and may even result in the formation of toxic aldehydes due to the degradation of polyunsaturated fatty acids (PUFAs) that have been positively correlated with the prevention of cardiovascular disease (Fang et al., 2017; Gómez-Estaca, López-De-Diracstillo, Hernández-Muñoz, Catalá, & Gavara, 2014; Harris, 2007; Realini & Marcos, 2014). Additionally, oxygen has a considerable effect on the respiration rate and ethylene production rate of respiring foodstuffs such as fruits and vegetables (Lopez Rubio et al., 2004). Therefore, the removal of O₂ from the package headspace is crucial to improve the quality and safety of oxygen-sensitive food products, and it has long been a goal of food-packaging scientists. Although vacuum packaging or MAP combined with a good oxygen barrier in the packaging film can effectively limit the presence of oxygen, such techniques do not completely remove the oxygen inside the package because O₂ permeates from the exterior through the packaging film, because of residual O₂ at the time of packing, or because of poor sealing (Ahmed et al., 2017; Coma, 2008). Antioxidants can be directly added to food formulations by using certain processing steps such as spraying, immersion, or mixing, which may cause changes in food quality parameters (color or taste) and may affect consumer acceptance of the product. Furthermore, such methods may encounter the following limitation: once the active compounds are consumed in the reaction, the protection ceases, and the quality of the food degrades more quickly (Mastromatteo, Conte, & Nobile, 2018).
In these cases, active antioxidant packaging represents an innovative strategy to improve the stability of oxidation-sensitive food products and thus extend their shelf-life by incorporating antioxidant agents in a polymer. Compared to the direct addition of antioxidants to food, Mastromatteo et al. (2010) and Bolumar, Andersen, and Othien (2011) present some advantages of this technology, such as lower demand for active compounds, localized activity for antioxidant agents, the controllability of antioxidant release, and the exclusion of certain processing steps. Antioxidant AP systems can be classified as oxygen scavengers (independent antioxidant devices) and antioxidant packaging materials (Gómez-Estaca et al., 2014).

Oxygen scavengers containing antioxidant agents that are separate from the food product are added to a conventional “passive” package, which can be used to packaging systems in different forms (labels, pads, or sachets) (Gómez-Estaca et al., 2014). Currently, O₂ scavengers based on the oxidation of fine powders of iron and ferrous oxide are the most effective and commonly used scavengers available commercially. However, to prevent metallic tastes from being imparted to foods, nonmetallic oxygen scavengers such as ascorbic acid, sulfites, catechol, ascorbate salts, and enzymes such as ethanol oxidase or glucose oxidase have also been utilized (Ahmed et al., 2017; Brody et al., 2008). To prevent scavengers from acting prematurely because of the ubiquitous presence of oxygen, specialized mechanisms can be used to induce the scavenging effect. For example, photosensitive dyes irradiated by using ultraviolet (UV) light activate the process of O₂ removal, whereas elevated moisture can trigger the scavenging reactions of iron-based scavengers (Lopez Rubio et al., 2004). Furthermore, to avoid ingestion of the active substance in the sachet following accidental rupture, the current trend in commercial applications has been to incorporate O₂ scavengers into the packaging material (Suppakul et al., 2003). Some previous articles have extensively reviewed the uses and applications of oxygen scavenging packaging (Brody et al., 2008; Gómez-Estaca et al., 2014; Suppakul et al., 2003). Some commercially available O₂ scavengers that could be used to control O₂ levels and objectionable odors in food packaging are shown in Table 5. Additional examples of commercially available O₂ scavengers can be found in Table 4.

Antioxidant packaging materials are being developed by incorporating antioxidant agents into the packaging film walls (a polymer matrix) or within the product containers to exert their mode of action by reducing the presence of reactive oxygen species inside the headspace and/or by releasing antioxidant compounds into the food product or the headspace surrounding it (Ahmed et al., 2017; Gómez-Estaca et al., 2014). To choose the most appropriate active material for each type of food, the affinity of food products and the active materials should be evaluated (Granda-Restrepo et al., 2009). In addition, some authors have observed that antioxidant activity does not always increase linearly with increasing amounts of incorporated antioxidant (Bentayeb, Rubio, Batlle, & Nerin, 2007; Lopez-de-Dicastillo, Alonso, Catala, Gavara, & Hernandez Munoz, 2010) and it may even decrease in some cases (Samra, Chedea, Economou, Calokerinos, & Kefalas, 2011; Zuta, Simpson, Zhao, & Leclerc, 2007). This finding can be attributed to an interaction between the antioxidant compounds and the polymer matrix, or a reduction in activity due to an excessive antioxidant concentration. Further investigation must be carried out to control the diffusion/release rate of the active compounds from/into the practical packaging of foods, which will allow the agent concentration in the headspace or the food products to be controlled. Furthermore, the manufacturing process of an antioxidant packaging material is selected by considering the properties of the antioxidant compounds and the types of polymer. If the antioxidant activity of the packaging material is activated by migrating antioxidant agents into the foods, the antioxidant agents released must be permitted as food additives and should follow the relevant regulations in accordance with their maximum permissible concentration (Fang et al., 2017).

Antioxidant packaging material is produced by intimately mixing the antioxidant agents (or the active substance that produce the antioxidant agents) with the packaging material through the following procedures: (1) dissolving both into a suitable solvent prior to the application of the solution to a substrate via coating technologies, (2) melting the polymer and slotting and mixing the agent into the melted polymer by using extrusion technologies, or (3) immobilizing the antioxidant agents on the surface of the film (Ahmed et al., 2017; Gómez-Estaca et al., 2014). Traditionally, synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), tertiary butyl hydroquinone (TBHQ), propyl gallate (PG), and organophosphate and thioster compounds have been used extensively to enhance the shelf-lives of food products by providing oxidative stability. Torres-Arreola, Soto-Valdez, Peralta, Cardenas-Lopez, and Ezquerra-Brauer (2007) reported that incorporation of BHT into low-density polyethylene delayed lipid oxidation and protein denaturation. However, the presence of synthetic antioxidants in food can have potential toxic and carcinogenic effects, and strict statutory controls are required. To avoid potential risks and meet the consumer need for safe natural foods, natural antioxidants such as plant extracts, tocopherol, or essential oils from herbs and spices can be used as alternatives to synthetic antioxidants, and will likely be utilized widely in food packaging to confer antioxidant activity (Barbosa-Pereira, Aurrekoetxea, Angulo, Paseiro-Losada, & Cruz, 2014; Realini & Marcos, 2014). In addition to having preservative roles, plant extracts and essential oils in the packaging also provide health benefits to the consumer through their antioxidant and antimicrobial activities in the human body once ingested (Ahmed et al., 2017; Fang et al., 2017). Gutiérrez, Echeverría, Ihl, Bifani, and Mauri (2012) incorporated a water extract of Murta leaves into carboxymethylcellulose–montmorillonite (CMC-MMT) nanocomposite films. Compared to the CMC control film, the antioxidant capacity of the films was increased more than 18-fold according to the ABTS (2,2-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid radical) radical scavenging assay. Yang, Lee, Won, and Song (2016) reported that pork meat wrapped with DP (distiller dried grains with solubles) protein films containing green tea extract (GTE), oolong tea extract (OTE), and black tea extract (BTE) had less lipid oxidation than did the control, as measured by the DPPH (2,2-diphenyl-1-picryl-hydrazyl-hydrate radical) and ABTS radical-scavenging assays. Among the tea extracts, the DP film containing GTE had the greatest antioxidant activity. However, the incorporation of an antioxidant into films and coatings might influence their mechanical, optical, or barrier properties. Sripatrawan and Harte (2010) noticed that the incorporation of green tea extract into chitosan films lowered their water vapor permeability (WVP) and improved their mechanical properties, and Wang et al. (2014) observed that extracts from Lycium barbatus fruit, which contains carotenoids, flavonoids, and polysaccharides, improved the WVP of chitosan films due to bonding with the hydroxyl and amino groups of the matrix, but they decreased the elongation and tensile strength (TS) limit of the film. Peng, Wu, and Li (2013) also found a similar result with the addition of extracts from black or green tea.
Therefore, the effects of incorporated antioxidant agents on the mechanical and physical properties of films and coatings should be evaluated before adding antioxidants (Ganiari and others 2017). To obtain the optimal formulation with the highest antioxidant activity and the best physical properties for active food packaging, Dickstlto and others (2016) developed a cross-linked methylcellulose (MC) film (an active film based on maqui berry extract) by adding glutaraldehyde (GA), which decreased the water solubility, swelling, and WVP of MC films. The release of antioxidant substances from the active materials increased with the concentration of GA. Furthermore, a cross-linking effect was induced to hydroxypropylmethylcellulose (HPMC) films containing ascorbic or citric acid, which resulted in better mechanical properties and lower WVP and oxygen permeability (OP) (Ataréz, Pérez-Masiá, & Chiralt, 2011). The use of antioxidant nanoparticles with enlarged contact area, compared to conventional antioxidant agents, might allow for a reduction of the amount of active substances, which would efficiently reduce and/or avoid the effect of active substances on the natural properties of the base packaging material (Fang et al., 2017). In the past few years, to meet environmental concerns and minimize waste disposal problems, incorporation of natural antioxidants into biodegradable films is being investigated as a new method of preventing food oxidation (Contini and others 2014; Rodriguez-Aguilera and Oliveira 2009).

**Antimicrobial packaging.** One of the main reasons for the deterioration of food quality is microbial growth, which leads to discoloration, off-flavor development, textural changes, and the loss of nutritive value, and thus reduces the shelf-life of foods and increases the risk of food-borne illness (Biji and others 2017). In the past few years, to meet environmental concerns and minimize waste disposal problems, incorporation of natural antioxidants into biodegradable films is being investigated as a new method of preventing food oxidation (Contini and others 2014; Rodriguez-Aguilera and Oliveira 2009).
Antimicrobial AP extends the lag period and slows the growth of microorganisms in order to extend shelf-life and maintain food quality and safety (Han, 2000). Antimicrobial food packaging materials can be classified into 2 types. One type of antimicrobial food packaging is used in direct contact with the food surface, so that antimicrobial agents can be evaporated (volatile substances) or migrated (volatile substances) into the food product. This 1st type of antimicrobial food packaging is suitable for vacuum-packed products or those wrapped with film. The other type of antimicrobial food packaging is used without making direct contact with the food surface and includes technologies like MAP (Fang et al., 2017; Kerry et al., 2006; Realini and Marcos 2014). Although a large number of antimicrobial agents has been tested for the purpose of inhibiting the growth of microorganisms in foods, such as ethanol, carbon dioxide, silver ions, chlorine dioxide, antibiotics, bacteriocins, organic acids, essential oils, and spices (Jayasena and Jo 2013; Malhotra et al., 2015; Suppakul et al., 2003), antimicrobial packaging has very limited commercial availability, except for silver-based antimicrobial materials, which are commonly used in many countries such as the United States and Japan (Realini and Marcos 2014). Mulla and others (2017) chemically modified the surface of linear low-density polyethylene (LLDPE) by chromic acid treatment, coated the surface with clove essential oil, and assessed the antimicrobial properties of the resulting material. The composite films improved the UV-barrier property of the material and exhibited strong antimicrobial activity against L. monocytogenes and Salmonella typhimurium (Salmonella enterica subsp. enterica) in packed chicken samples for 21 d of refrigerated storage, but the melting and crystallization temperatures of the films with incorporated oil were significantly lower than the neat and etched LLDPE films. Although many essential oils show promise because of their effects against microorganisms, some limitations have also been identified in the application of essential oils in antimicrobial AP (Jayasena and Jo 2013). For example, Hylgaard and others (2012) reported that the antimicrobial potency of essential oil constituents depends on the pH, temperature, and level of microbial contamination present in the food. In practice, much higher concentrations of essential oils were required to achieve antimicrobial effects in foods in comparison with those required at laboratory-scale (Malhotra et al., 2015). In addition, the use of essential oils may cause negative sensory effects because of their intense aroma, which partially limits their use as preservatives in food. To alleviate these problems, lower levels of essential oils can be combined with other antimicrobial compounds and/or preservative technologies such as MAP, high hydrostatic pressure, or low-dose irradiation to obtain a synergistic effect without compromising antimicrobial activity (Jayasena and Jo 2013). Several authors have reported that better results can be obtained by incorporating the volatile components of essential oils into films or edible coatings, but better results can also be obtained through the encapsulation of essential oils in polymers with edible and biodegradable coatings, sachets, or nanoemulsions (Donsi and others 2011; Noshirvani and others 2017; Ozogul and others 2017; Pola and others 2016).

Although an increasing effort has recently been devoted to the development of antimicrobial packaging solutions, there are considerable differences in the ways antimicrobials are used at laboratory-scale and in real-time applications, and, together with regulatory issues and technical constraints, these differences are some of the main factors limiting the commercialization of antimicrobial packaging systems (Realini and Marcos 2014; Malhotra et al., 2015). Some of these differences in the characteristics of antimicrobials at laboratory-scale and in real-application environments may be attributed to the fact that real food systems have more salt, less water, and lower levels of nutrients, carbohydrates, fats, and proteins, which are found to interact with antimicrobials (Burt 2004; Busatta and others 2008; Grower and others 2004). To successfully implement antimicrobial packaging solutions in the market, it is essential to select the right package for the antimicrobial agent and the environmental conditions faced by a particular food product. A multidisciplinary approach involving researchers from all fields of biotechnology, particularly microbiology, food technology, engineering, and materials science, will be necessary to create antimicrobials with a promising future in the food packaging industry (Malhotra et al., 2015). Several types of antimicrobial packaging have been commercialized (Ahmed et al., 2017; Fang et al., 2017; Suppakul et al., 2003).

SOGP

With constantly increasing environmental concerns and regulations, reducing the environmental burden of food packaging has become a major force driving innovation in food packaging materials, in addition to satisfying the growing consumer demand for high-quality, safe food (Davoudi and Sturzaker 2017; Liciardello, 2017). Indeed, it is unquestionable that all types of food packaging have an environmental impact that varies with their life cycles (Huang & Ma, 2004; Ingrao et al., 2015, 2017). This environmental impact is especially dependent on the manner in which the raw materials for the packaging were produced and processed, as well as the end-of-life phase of the packaging, which may include recycling, incineration, or landfill disposal (Liciardello, 2017). SOGP, which is designed to be environmentally friendly, has become a focus among researchers aiming to minimize the environmental impact of the entire product-packaging chain and improve the environmental sustainability of food packaging systems (Peelman et al., 2013). As reported by Peelman et al. (2013), SOGP can be achieved at three levels. First, on the level of raw materials, the use of recycled materials and renewable resources reduces CO₂ emissions and dependency on fossil resources. Second, on the level of the production process, SOGP utilizes lighter and thinner packaging that is produced using relatively energy-efficient processes. Third, on the level of waste management, reuse or recycling of food packaging that is biodegradable and/or compostable can contribute to alleviating the problem of municipal solid waste. In the past decade, the pace of bioplastic development and application in food packaging has increased because of interest from the food packaging and distribution industry, which has taken up the challenge of replacing traditional synthetic polymers in at least some applications. According to the European Bioplastics Organization, bioplastics are plastics based on renewable resources (biobased) or plastics that are biodegradable and/or compostable. However, not all biopolymers are biodegradable. For example, polyethylene (“green-PE”) and polyethylene terephthalate (“bio-PET”) are obtained from renewable resources and are chemically identical to conventional polymers (Liciardello, 2017). To date, a wide range of biodegradable biopolymers have been used in food packaging, including polyhydroxyalkanoates (PHAs), polyactic acid (PLA), zein, soy protein isolate, starches, cellulose, gluten, whey protein isolate, and chitosan (Peelman et al., 2013). However, several major limitations restrict the application of bioplastics in food packaging materials, including their high cost compared to conventional plastics, brittleness, thermal instability, low melt strength, difficult heat sealability, high water vapor, high oxygen permeability, bad processability, and poor impact resistance (Cyps, Soledad, & Analía, 2009; Jamshidian, Tehrany, Imran, Jacquot, & Desobry,
2010; Mensitieri et al., 2011; Rhim, Hong, & Ha, 2009). To improve the properties of bioplastics (especially their barrier capacities toward gases and water), different strategies and techniques have been investigated, such as coating biobased films, incorporation of nanoparticles or biopolymer cellulose, and chemical/physical modification, such as crosslinking (Peelman et al., 2013). For example, Hirvikorpi, Vähä-Nissi, Nikkola, Harlin, and Karpinnen (2011) reported that a thin (25 nm) and highly uniform Al₂O₃ coating can significantly improve the oxygen and water vapor barrier performance of several materials (PLA-coated board, PLA film, nano-fibrillated cellulose film, PHB) by using the atomic layer deposition (ALD) technique. Sanchez-Garcia, Lopez-Rubio, and Lagaron (2010) showed that the addition of mica-based nanoclays to PLA reduced their UV transmittance. Sanuja, Agalya, and Umapathy (2014) demonstrated that incorporation of nano magnesium oxide and clove essential oil into a chitosan matrix increased its tensile strength (TS), elongation limit, and water barrier performance. Rodriguez, Galotto, Guarda, and Bruna (2012) developed cellulose acetate films with organic montmorillonite as a nanofiller, which reduced the transmission rates of oxygen and water through the film by 50% and 10%, respectively, compared to those of cellulose acetate films without nanofillers. This reduction can be attributed to the fact that the polymer molecules were confined between the dispersed nanoparticles, which provided a tortuous path and thus forced the water and gas molecules to travel a longer path to diffuse through the film (Peelman et al., 2013).

Some biopolymer-based nanocomposites and their enhanced material properties, processing methods, and levels of incorporation were reported recently by Mihiendukulasuriya and Lim (2014). Mu et al. (2012) revealed that the addition of dialdehyde carboxymethyl cellulose (DCMC) as a cross-linker to a glycerol-plasticized gelatin edible film caused a significant improvement in its optical, physical, thermal, and mechanical properties compared with those of the untreated film. Garavand, Rouhi, Razavi, Cacciotti, and Mohammadi (2017) reported that using carboxylic acids and calcium ions as crosslinking agents can improve the physiochemical, thermal, and mechanical properties of most biopolymers such as alginate, pectin, whey proteins, chitosan, starch, and gelatin. From environmental, cost, and health perspectives, the crosslinking approach is a more cost-effective and efficient method of improving the permeability and/or thermomechanical attributes of film-forming biopolymers compared to nanotechnology, especially for naturally occurring crosslinking agents, such as some nanoparticles, which can induce intracellular damage, pulmonary inflammation, and vascular disease when they migrate into food (Das, Saxena, & Dwivedi, 2008; Ecchengoy & Nerin, 2013). However, more studies are needed to better understand the advantages and disadvantages of nanomaterials, enhance their positive effects on health, safety, and the environment, and decrease the tendency for migration of undesired nanoparticles in food product (Mihiendukulasuriya & Lim, 2014).

Another important issue in SOGP is packaging reduction, which has 2 meanings. First, avoid excessive packaging or overpackaging by reducing the amount of packaging materials used without compromising the appearance of packaged products. Second, reduce the weight and thickness of packaging without affecting product shelf-life standards. Avoiding overpackaging can improve environmental sustainability and reduce the cost of product processing, which can lower the price of the product. These features are undoubtedly very beneficial for consumers and small and medium-sized companies. High-weight food packaging directly increases the costs of processing, transport, and distribution and results in a relatively severe environmental burden; such foods include carbonated soft drinks, wine, and beer in PET bottles, glass bottles, and aluminum cans (Amienyo, Guijba, Stichnothe, & Azapagic, 2013; Bonamente et al., 2016; Cinini and Moresi 2016). Several different strategies can be used to reduce the weight of packaging, such as reducing the packaging thickness, changing the package geometry, and utilizing alternative materials. However, for most beverage products, CO₂ content is the key parameter determining the taste and shelf-life of the product; thus, minimization of packaging weight should not affect the CO₂ retention performance/CO₂ barrier performance or shelf-life standards of the product (Licciodello, 2017). Packaging thickness can be reduced by innovation and development to produce new and improved packaging materials with better barrier performance, enhanced mechanical performance, and/or other superior functional properties. Although nanotechnologies have not yet reached widespread application in food packaging, because of toxicological concerns and technical limitations, they have great promise as raw materials that could be used to develop packaging materials with improved performance and reduced thickness (Mihiendukulasuriya & Lim, 2014; Wyser et al., 2016). Additionally, a close-knit collaboration between producers and food packaging scientists is needed to synergistically address food packaging sustainability.

**Future Trends**

**Implementation of the ultimate packaging**

IOSP is used to monitor the condition of packaged food or the environment surrounding the food and to convey food quality and safety information to stakeholders (such as manufacturers, retailers, and consumers) in food supply chains, which facilitates decision-making about the freshness and edibility of foods (European Commission 2004; Ghaani, Cozzolino, Castelli, & Farris, 2016; Restuccia et al., 2010). However, intelligent packaging does not directly improve the quality and safety of foods or extend shelf-life. AP is intended to extend the shelf-life of packaged food or to maintain or improve its properties based on the interactions between active compounds and food and/or packaging headspace (European Commission 2004). Therefore, the combination of intelligent packaging and AP will be an important issue for food packaging innovation in the future. To improve environmental sustainability, future developments in food packaging should be directed towards the “ultimate” packaging, which will combine all of the benefits of IOSP, AP, and SOGP.

**Safety and economic issues**

Although technological innovations in food packaging can enhance the safety and quality of food products, safety concerns and limitations must be considered. Such concerns and limitations include the migration of active and intelligent substances, accidental leakage of active components from a sachet, and human ingestion of active and intelligent substances. Sachets used in packages should be clearly marked “do not eat,” or they should be replaced by directly incorporating active components into or onto the package. Natural extracts can also be used to improve food safety. The overall tendency for migration of compounds from active and intelligent packaging to packaged foods must be investigated prior to the use of any new type of packaging materials, and a threshold of regulation must be established by the U.S. FDA and EC regarding maximum levels of transfer of active materials and nanoparticles to food products (Ahvenainen, 2003; Chaudhry et al., 2008). Furthermore, the commercial application of innovative food packages might cause an increase in individual...
product unit costs and prices, especially during the early phases of product introduction, which may directly affect consumer behavior and acceptance (Mihindukulasuriya & Lim, 2014). From the manufacturer's point of view, the profit margins of food are relatively low compared to those of other consumer products (Dainelli et al., 2008). Therefore, the use of innovative packages in the food industry should be based on proper cost-benefit analyses to justify their implementation (Restuccia et al., 2010). Further research and development in the field of packaging materials represents a viable path toward lowering product cost without affecting improvements in food shelf life.

Integral performance evaluation of packaging innovations

Food waste (or loss) can cause unnecessary environmental impacts in addition to carrying ethical concerns, especially for household food waste. A survey carried out in Europe estimated the avoidable food losses over the whole food value chain at approximately 280 kg per person per year (Gustavsson, Cederberg, Sonesson, & van Otterdijk, 2011), 45% of which was generated at the household level. As Beretta, Stoessel, Baier, and Hellweg (2013) reported, most of the losses occurring at the harvesting, storage, transportation, and processing levels are unavoidable, and they are usually less relevant from an environmental point of view because they can be used for feeding. Losses occurring in households and in restaurants are mainly avoidable; also, wasted materials do not find an alternative use and are usually entirely lost. Williams, Wikström, Otterbring, Löfgren, and Gustafsson (2012) found that 20% to 25% of household food wastes are associated with food packaging. Therefore, packaging innovations can reduce the environmental impact of food waste by prolonging shelf life and reducing waste along the distribution chain and at the household level (Licardello, 2017). Additionally, secondary shelf-life extension (after package-opening) should receive future research attention because it is very helpful for reducing food waste at the household level (Manfredi, Fantin, Vignali, & Gavara, 2015). However, to assess the equilibrium between technological innovation and environmental protection, the environmental impact of packaging innovations and food losses should also be examined by using the life-cycle assessment (LCA) methodology (including raw material extraction and processing, packaging manufacture, transport, and retail, and disposal of food and packaging, even at the household level) in addition to evaluating the impact on food shelf-life or packaging characteristics such as optical, physical, thermal, and mechanical properties.

Conclusions

Food packaging technologies are improving continuously in response to lifestyle changes and the ever-increasing demand for high-quality and safe foods. Food packaging helps extend shelf-life and maintain the sensory properties, quality, and safety of packaged food, and researchers studying packaging seek to promote environmental sustainability. However, additional effort should be focused on overcoming the technical constraints and high costs associated with these technologies, which have been the main factors preventing wider implementation and the development of additional commercial applications for new types of packaging materials in the food packaging industry. However, advances in nanotechnology offer great potential for overcoming existing challenges associated with packaging materials and cost reduction. Finally, to increase the safety and effectiveness of new food packaging technologies and ensure the sustainable growth of modern societies, continuous research and development should be performed based on collaboration between government regulatory agencies, industries, consumers, and multidisciplinary experts.

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Author Contributions

J. Han was responsible for searching and interpreting the literature, and writing the manuscript; L. Ruiz-Garcia and J. Qian were responsible for checking grammar and formatting the manuscript; X. Yang gave valuable assistance regarding major revisions of the manuscript.

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