Intelligent Packaging: Concepts and Applications

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ABSTRACT: Intelligent packaging is an emerging technology that uses the communication function of the package to facilitate decision making to achieve the benefits of enhanced food quality and safety. In this paper, the term intelligent packaging is defined based on a proposed model of packaging functions, which is consistent with the historical development of food packaging. A conceptual framework is also developed to provide more precise meaning to the definition and to elucidate the anatomy of the intelligent packaging system. The latest advances in smart package devices including barcode labels, radio frequency identification tags, time-temperature indicators, gas indicators, and biosensors are reviewed. The applications of the conceptual framework to Hazard Analysis Critical Control Points and microwave ovens are illustrated. A research roadmap for intelligent packaging is also suggested.

Keywords: intelligent packaging, smart package devices, barcode, RFID, biosensors, active packaging, smart packaging

Introduction

To understand intelligent packaging, it is helpful to review the historical development of packaging. Traditionally, the basic functions of packaging have been classified into 4 categories (Figure 1): protection, communication, convenience, and containment (Paine 1991; Robertson 1993). The package is used to protect the product against the deteriorative effects of the external environment, communicate with the consumer as a marketing tool, provide the consumer with greater ease of use and time-saving convenience, and contain products of various sizes and shapes. Nevertheless, these functions are not totally exclusive; for example, the communication function of the package through warning labels and cooking instructions can also help to enhance food protection and convenience.

Although traditional packaging has contributed greatly to the early development of the food distribution systems, it is no longer sufficient because today's society has become increasingly complex. Innovative packaging with enhanced functions is constantly sought in response to the consumer demands for minimally processed foods with fewer preservatives, increased regulatory requirements, market globalization, concern for food safety, and the recent threat of food bioterrorism. How can the existing functions of a mature, and sometimes taken-for-granted, technology be enhanced? It probably requires rethinking and shifting the existing paradigm (Kuhn 1996). Active packaging and intelligent packaging are the results of "thinking outside the box."

During the past 2 decades, the popularity of Active Packaging (AP) has signified a major paradigm shift in packaging; namely, the protection function of packaging has been shifted from passive to active. Previously, primary packaging materials were considered as "passive," meaning that they functioned only as an inert barrier to protect the product against oxygen and moisture. Recently, a host of new packaging materials have been developed to provide "active" protection for the product. AP has been defined as a system in which the product, the package, and the environment interact in a positive way to extend shelf life or to achieve some characteristics that cannot be obtained otherwise (Miltz and others 1995). It has also been defined as a packaging system that actively changes the condition of the package to extend shelf life or improve food safety or sensory properties, while maintaining the quality of the food (Vermeiren and others 1999).

All AP technologies involve some physical, chemical, or biological action for altering the interactions between the package, the product, and the package headspace to achieve certain desired outcome (Rooney 1995; Brody and others 2001). Gas absorbing/emitting packaging (Smith and others 1995; Vermeiren and others 1999) is a group of technologies that use packaging films or sachets to absorb gases (such as oxygen, water vapor, ethylene) from the package headspace or to emit gases (such as carbon dioxide, ethanol) to the package headspace, so that a favorable internal package environment and thus an extension in shelf life are achieved. Controlled release packaging is a group of technologies that uses packaging materials as a delivery system to release active compounds (such as antimicrobials, antioxidants, enzymes, flavors, nutraceuticals) to protect against microbial spoilage and enhance food quality. Most attention in this group has been focused on antimicrobial packaging (Appendini and Hotchkiss 2002; Suppakul and others 2003a) and antioxidant packaging (Miltz and others 1988; Wessling and others 2000). Recently, an additional step forward was made by developing antimicrobial packages that contain natural instead of synthetic additives (Suppakul and others 2003b). Selective permeable films are breathable films that enable the control of the permeation of oxygen, water vapor, and carbon dioxide at rates beneficial to modified atmosphere packaging of fresh produce (Yam and Lee 1995). Microwave susceptors (Zuckerman and Miltz 1998; Waite 2003) are metallized polyester-based structures that interact with microwaves to provide crispness and browning of foods during microwave heating.

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Many years ago, active packaging was introduced as an almighty technology that performed every packaging function. However, the function of current AP technologies is limited mostly to enhancing the protection of package. To reflect this trend, we place AP above the protection function in our proposed model in Figure 1. This placement, however, does not prevent AP from performing other functions: For example, microwave susceptor is an AP technology that provides convenience and food quality. In retrospect, these technologies could simply be described as food packaging technologies with enhanced protection function. What was the usefulness of introducing the then-new term active packaging? An answer lies in the fact that a new term is sometimes able to inspire researchers to develop innovative technologies by thinking differently. This has turned out to be the case for AP.

In recent years, the terms Intelligent Packaging (IP) and Smart Packaging (SP) have also begun to appear with increasing frequency in conferences, symposiums, journals, and magazines. Unfortunately, clear and unequivocal definitions are not yet available. IP and SP are often used interchangeably in conferences and symposiums, but these terms are also used with different meanings by several authors in journals and magazines. Brody and others (2001) defined IP as a packaging system that sensed and communicated, while SP as one that possessed the capabilities of both AP and IP. Clarke (2000) defined IP as one that included logic capability and SP as one that communicated. Rijk (2002) defined IP as one that monitored the conditions of packaged foods to give information about the quality of the food during transport and storage. A major weakness of these definitions is that they were assigned freely without careful justification of meanings and purposes. The ambiguity and vagueness of these definitions also greatly limit their usefulness.

In this paper, we propose a more precise and useful definition of intelligent packaging. Our definition is built upon the model in Figure 1, which is consistent with the historical development of packaging. Further, we develop a conceptual framework to sharpen the definition and provide details necessary to harness the concept of IP. We also present specific examples to illustrate the application of the conceptual framework.

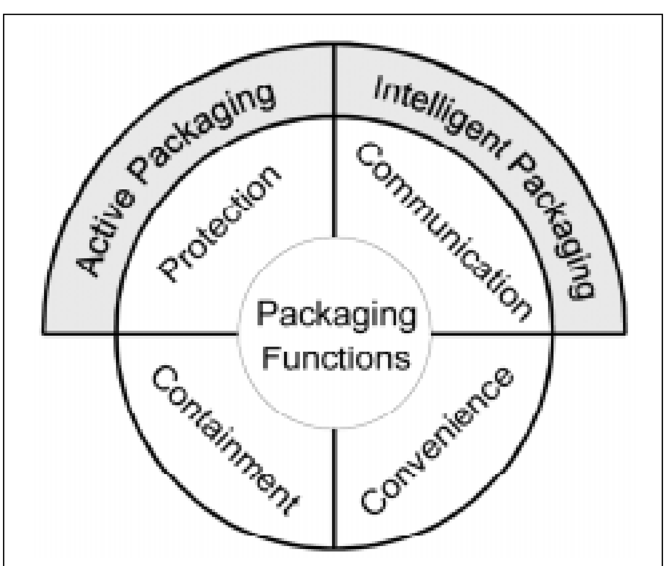

Figure 1—Model of packaging functions

Definition of intelligent packaging

According to the American Heritage Dictionary, the word "intelligent" is defined as "showing sound judgment and rationality" and as "having certain data storage and processing capabilities." A prerequisite of making sound decisions is effective communication—the ability to acquire, store, process, and share information—and this is where IP can make a significant contribution.

We define intelligent packaging as a packaging system that is capable of carrying out intelligent functions (such as detecting, sensing, recording, tracing, communicating, and applying scientific logic) to facilitate decision making to extend shelf life, enhance safety, improve quality, provide information, and warn about possible problems. We believe that the uniqueness of IP is in its ability to communicate: because the package and the food move constantly together throughout the supply chain cycle, the package is the food's best companion and is in the best position to communicate the conditions of the food. Accordingly, we place IP above the communication function in our proposed model of Figure 1, in which IP is a provider of enhanced communication and AP is a provider of enhanced protection. Thus, in the total packaging system, IP is the component responsible for sensing the environment and processing information, and AP is the component responsible for taking some action (for example, release of an antimicrobial) to protect the food product. Note that the terms IP and AP are not mutually exclusive; some packaging systems may be classified either as IP or AP or both, but this situation does not detract the usefulness of these terms. In appropriate situations, IP, AP, and the traditional packaging functions work synergistically to provide a total packaging solution.

According to our definition, a package is "intelligent" if it has the ability to track the product, sense the environment inside or outside the package, and communicate with human. For example, an intelligent package is one that can monitor the quality/safety condition of a food product and provide early warning to the consumer or food manufacturer. We have been careful not to introduce other terms such as responsive packaging, diagnostic packaging, and clever packaging, because too many terms tend to further complicate the already confusing terminology. It is important to emphasize that IP is a system that involves not only the package, but also the food product, the external environment, and other considerations.

We believe that the emergence of IP has signified another paradigm shift in the concept of food packaging—shifting the package from a mediocre communicator to an intelligent communicator. As alluded to earlier, the purpose of introducing IP is to inspire people to expand the communication function of packaging in an innovative and useful way. In the next section, we develop a conceptual framework to sharpen our definition of IP and to provide a roadmap to facilitate the systematic research in this field.

Conceptual framework of intelligent packaging

Intelligent packaging can play an important role in facilitating the flow of both materials and information in the food supply chain cycle. In Figure 2, the outer circles represent the supply chain cycle from raw material through manufacturing, packaging, distribution, product use, and disposal. The package, in one form or another (such as pouch, container, drum, pallet), is traditionally used to facilitate the flow of materials (represented by the arrows in the figure) from one location to another, by performing the basic functions of containment and protection of the product. Furthermore, the package can also facilitate the flow of information (represented by the communication links between the inner circle and outer circles), although this communication function has been largely overlooked. The package can indeed be a highly effective communicator—it can carry actual information in the direction of material flow (for example, via truck, train, or ship), and it can transmit information visually (for example, via an indicator) or electronically (for example, via a barcode or the Internet) throughout every phase of the supply chain cycle.

A conceptual framework describing the flow of information in an IP system is illustrated in Figure 3. The system consists of 4 components: smart package devices, data layers, data processing, and information highway (wire or wireless communication networks) in the food supply chain. The smart package devices are largely responsible for giving birth to the concept of IP because they impart the package with a new ability to acquire, store, and transfer data. The data layers, data processing, and information highway are collectively referred here as the decision support system.

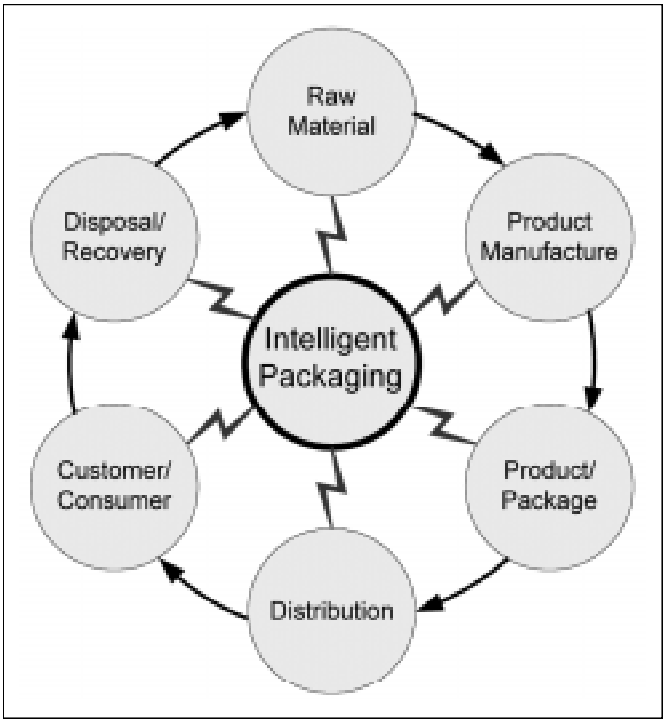

Figure 2—Material flow ( ) and information flow ( ) in the food supply chain cycle.

As shown in Figure 3, the smart package devices and the decision support system are designed to work together to monitor changes in the internal and external environments of the food package and to communicate the conditions of the food product, so that timely decisions can be made and appropriate actions taken. From the quality and safety viewpoint, the external environment can be further divided into the ambient, physical, and human environments (Robertson 1993), which are factors important for determining shelf life. However, the business environment is also an important factor; in fact, the development of smart package devices (especially data carriers) and the information highway is largely motivated by the desire to increase profit and operation efficiency. Presently, business data (such as product identification, quantity, and price) and business models (rules for processing information to maximize profits) are incorporated into the system to facilitate product checkout, inventory control, and product traceability. It is interesting to note that just a decade ago, IP was not an attractive concept because package devices and computer networks were expensive and quite limited. Today, more powerful and affordable information technology has created a favorable environment for IP to flourish.

A challenging question to the food-packaging scientist or technologist is whether more efficient delivery of safe and quality food products can also be achieved by superimposing an additional layer of food data and food models (capitalized in Figure 3) on the information highway of the food supply chain -- being able to achieve this is a goal of IP. The food data refers to data that are indicative of food quality and safety (such as time-temperature his-

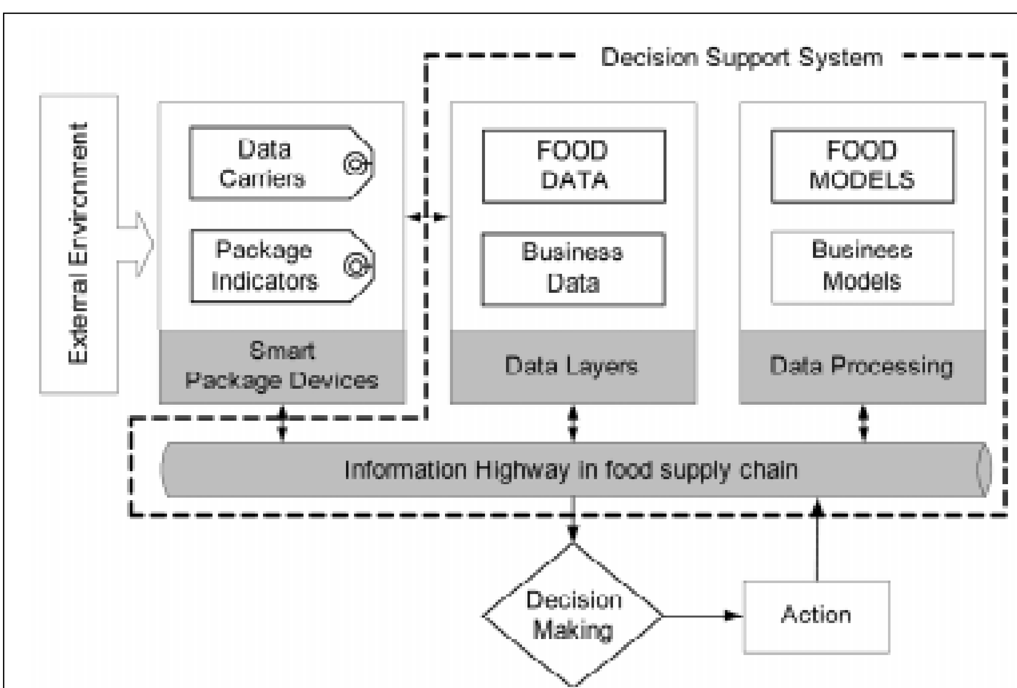

Figure 3—Information flow in intelligent packaging system

tory, microbial count, pH, water activity), and the food models refer to scientific principles or heuristic rules for processing the food data to enable sound decision making. The answer to this question is likely positive, although significant research and development is needed before the potential of IP for enhancing food quality and safety could be fully realized.

Smart package devices

Smart package devices are defined here as small, inexpensive labels or tags that are attached onto primary packaging (for example, pouches, trays, and bottles), or more often onto secondary packaging (for example, shipping containers), to facilitate communication throughout the supply chain so that appropriate actions may be taken to achieve desired benefits in food quality and safety enhancement. There are 2 basic types of smart package devices: data carriers (such as barcode labels and radio frequency identification [RFID] tags) that are used to store and transmit data, and package indicators (such as time-temperature indicators, gas indicators, biosensors) that are used to monitor the external environment and, whenever appropriate, issue warnings. As shown in Figure 3, these devices provide a communication channel between the external environment and other components in the system. These devices differ from each other not only in "hardware" (physical makeup), but also in the amount and type of data that can be carried and how the data are captured and distributed. In a typical IP system, multiple smart package devices are employed at several strategic locations throughout the supply chain.

Barcodes

Barcodes are the least expensive and most popular form of data carriers. The UPC (Universal Product Code) barcode was introduced in the 1970s and has because become ubiquitous in the grocery store for facilitating inventory control, stock reordering, and checkout (Manthou and Vlachopoulou 2001). To enable barcodes to communicate with scanners and printers, many standards have been developed over the years into commonly accepted languages known as "symbologies," although less than 20 of them are used today (Pearce and Bushnell 1997). The UPC barcode is a linear symbology consisting of a pattern of bars and spaces to represent 12 digits of data. Its meager storage capacity allows the containment of only very limited information such as manufacturer identification number and item number, leaving no room for encoding additional information.

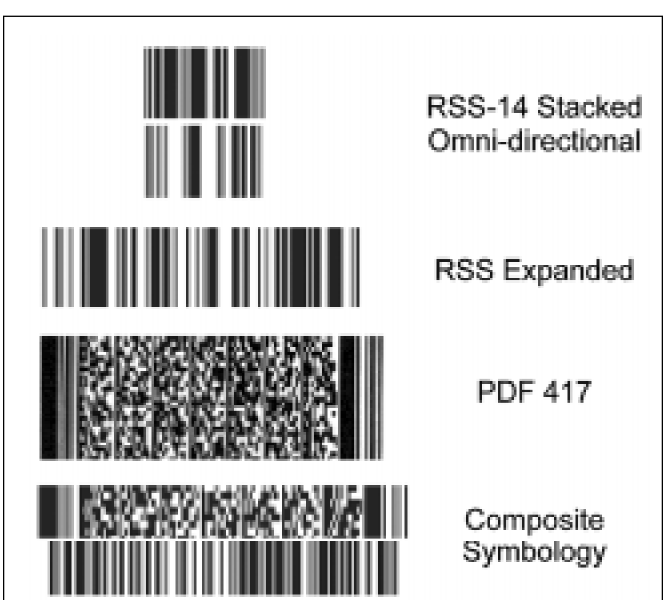

Figure 4—Examples of barcode symbologies

To address the growing demand for encoding more data in a smaller space, a new family of barcode symbologies called the Reduced Space Symbology (RSS) is recently being introduced (Uniform Code Council 2004). Some of those family members are particularly well suited for product identification at point-of-sell and for product traceability in the grocery industry (Figure 4). The RSS-14 Stacked Omni-directional barcode encodes the full 14-digit Global Trade Item Number (GTIN), and it may be used for loose produce items such as apples or oranges where space limitation requires a narrow symbol. The RSS Expanded Barcode (also available in stacked format) encodes up to 74 alphanumeric characters, and it may be used for variable measure products (for example, meat and seafood that are sold by weight) where larger data capacity is required to encode additional information such as packed date, batch/lot number, and package weight.

As scanners are becoming more powerful and affordable, two-dimensional barcodes (Figure 4) are also gaining popularity. The PDF 417 (where PDF stands for Portable Data File) is a 2-dimensional symbol that carries up to 1.1 kilobytes data in a space of a UPC barcode (Anonymous n.d.). It allows the encoding of additional information not possible with linear barcodes, such as nutritional information, cooking instructions, Web site address of food manufacturer, and even graphics. The advantage of portable data is that they are available immediately, without having to access an external database. To provide more versatility, the Uniform Code Council has also introduced a new symbology called Composite Symbology (Figure 4) by combining a 2-D barcode such as PDF 417 with a linear barcode such as UPC (Anonymous 2002a).

With the advent of wireless handheld barcode scanners, barcode scanning is finding new and innovative applications. In the hospital, barcodes may be used to ensure that the right medication is given to the right patient at the right time and dosage (Anonymous 2001). Immediately prior to administrating, the medication barcode and patient's identification tags are scanned, and the information is sent over a wireless Local Area Network (LAN) to check for accuracy.

Radio frequency identification tags

The RFID tag is an advanced form of data carrier for automatic product identification and traceability. Although RFID has been available for many years for tracking expensive items and livestock (Anonymous 2003), its broad application in packaging has only begun in recent years. In a typical RFID system, a reader emits radio waves to capture data from an RFID tag, and the data is then passed onto a host computer (which may be connected to a local network or to the Internet) for analysis and decision making (Want 2004b). Inside the RFID tag is a minuscule microchip connected to a tiny antenna. RFID tags may be classified into 2 types: passive tags that have no battery and are powered by the energy supplied by the reader, and active tags that have their own battery for powering the microchip's circuitry and broadcasting signals to the reader. The more expensive active tags have a reading range of 100 feet or more, while the less expensive passive tags have a reading range of up to 15 feet. The actual reading range depends on many factors including the frequency of operation, the power of the reader, and the possible interference from metal objects. At the time of this writing, a passive tag costs between 50¢ and $1 depending on the quantity ordered, but the industry is working to reduce it to 5¢ in the next few years (Goodrum and McLaren 2003). An active tag may cost as much as $75, but the cost is expected to fall considerably and rapidly (Goodrum and McLaren 2003).

Compared with the barcode, the RFID tag has several unique characteristics. Line-of-sight is usually not required: that is, the RFID tag does not need to be oriented toward the reader for data transfer to occur because radio waves travel through a wide array of non-metallic materials. A significantly larger data storage capacity is available (up to 1 MB for high-end RFID tags), which may be used to store information such as temperature and relative humidity data, nutritional information, and cooking instructions. Read-write operations are supported by some RFID tags, which are useful in providing real-time information updates as the tagged items move through the supply chain. Multiple RFID tags may be read simultaneously at a rapid rate. Nevertheless, the RFID tag is generally not considered as a replacement for the barcode. Because both data carriers have advantages and disadvantages, they will continue to be used either alone or in combination, depending on the situation. A RFID tag may also be integrated with a time-temperature indicator or a biosensor to carry time-temperature history and microbiological data (Nambi and others 2003; Want 2004a).

In recent years, there has been an overwhelming interest from major retailers, companies, government agencies, and researchers in using RFID tags for various applications such as supply chain management, asset tracking, security control, and feed pattern of live stocks (Schwartzkopf-Genswein and others 1999; Falkman 2000; Anonymous 2003; Anonymous 2004a). An impetus for this technology is that several major retailers including Wal-Mart stores and Metro Group have issued mandates requiring their leading suppliers to use RFID tags on shipping crates and pallets. Such mandates are accelerating the adoption of the technology and further development of the RFID information highway.

A large amount of information on RFID is scattered in online journals (more notably, the *Smart Packaging Journal* and the *RFID Journal*), white papers published by technology companies (Anonymous 2004d; Anonymous 2004f; Linster and others 2004), and the Internet. On the contrary, very limited information on RFID was found in peer-reviewed scientific journals, particularly those relating to food science. This fact does not imply that food science knowledge is not important. It simply reflects that this technology is still at its early stages of implementation and at present, the focus is on simple tasks such as product identification and tracking, and not on complicated matters that involve the application of scientific food principles. When RFID technology becomes more established, the integration of food science knowledge will be required to develop the necessary decision support system for enhancing food safety and quality.

Time-temperature indicators

Temperature is usually the most important environmental factor influencing the kinetics of physical and chemical deteriorations, as well as microbial growth in food products. Time-temperature indicators (TTIs) are typically small self-adhesive labels attached onto shipping containers or individual consumer packages. These labels provide visual indications of temperature history during distribution and storage, which is particularly useful for warning of temperature abuse for chilled or frozen food products. They are also used as "freshness indicators" for estimating the remaining shelf life of perishable products. The responses of these labels are usually some visually distinct changes that are temperature dependent, such as an increase in color intensity and diffusion of a dye along a straight path. There are 3 basic types of commercially available TTIs: critical temperature indicators, partial history indicators, and full history indicators (Singh 2000). Their operating principles and performance have been reviewed extensively in the literature (Singh and Wells 1985; Taoukis and others 1991; Selman 1995; Claeys and others 2002; Taoukis and Labuza 2003; Smolander and others 2004).

In the early 1990s, Lifelines Technologies (Morris Plains, New Jersey) demonstrated a concept of using a laser optical wand to scan a TTI/barcode label to simultaneously obtain product information and temperature history (Taoukis and others 1991). The concept was unfortunately not embraced by the industry at that time, because scanners were expensive and the information highway in the supply chain was not ready to support this innovation. Today, powerful and affordable scanner and wireless technologies have provided a more favorable environment for companies to develop advanced TTI systems for tracking and controlling the quality of perishable food products (Bhushan and Gummaraju 2004). For example, Bioett (Lund, Sweden) has developed a TTI/barcode system in which data may be read by a hand-held scanner, displayed on a computer monitor, and downloaded into a database for analysis (Anonymous 2004b). KSW Microtec (Dresden, Germany) has developed a battery-powered TTI/RFID tag using a technology in which thin-film batteries are printed onto a flexible substrate (Nitzan 1999; Collins 2003). Infratab (Oxnard, California) is also developing a battery powered TTI/RFID tag (Giaglis and others, 2003). Unlike the traditional TTI that is based on diffusion or a biochemical reaction, the TTI/RFID tag uses a microchip to sense and integrate temperature over time to determine the shelf life of a product.

Gas indicators

The gas composition in the package headspace often changes as a result of the activity of the food product, the nature of the package, or the environmental conditions. For example, respiration of fresh produce, gas generation by spoilage microorganisms, or gas transmission through the packaging material or package leaks, may cause the gas composition inside the package to change. Gas indicators in the form of a package label or printed on packaging films can monitor changes in the gas composition, thereby providing a means of monitoring the quality and safety of food products.

Oxygen indicators are the most common gas indicator for food-packaging applications, because oxygen in air can cause oxidative rancidity, color change, and microbial spoilage. A number of oxygen indicators are designed to show color changes due to leaking or tampered packages (Krumhar and Karel 1992; Inoue and others 1994). Ahvenainen and others (1997) and Smiddy and others (2002) used oxygen indicators to detect improper sealing and quality deterioration of modified atmosphere packages containing pizza or cooked beef. Gas indicators for water vapor, carbon dioxide, ethanol, hydrogen sulfide, and other gases are also useful. For example, Hong and Park (2000) used a carbon dioxide indicator consisting of a carbon dioxide absorbent and a chemical dye in a polymeric film to measure the degree of fermentation in kimchi products during storage and distribution.

It is expected that the future integration of gas indicators into barcode labels or RFID tags will enable gas indicator signals to be transmitted not only visually but also electronically. Advances in smart ink and printing technology will also allow gas indicators to be read automatically from a distance using optical systems.

Biosensors

The broad spectrum of food-borne infections is changing constantly over time as most known pathogens are controlled and new ones have emerged. There is a need for rapid, accurate, on-line sensing for in situ analysis of pollutants, detection and identification of pathogens, and monitoring of post-processing food quality parameters.

In general, a biosensor is a compact analytical device that detects, records, and transmits information pertaining to biochemical reactions. This smart device consists of 2 primary components: a bioreceptor that recognizes a target analyte and a transducer that converts biochemical signals into a quantifiable electrical response. The bioreceptor is an organic or biological material such as an enzyme, antigen, microbe, hormone, or nucleic acid. The transducer can assume many forms (such as electrochemical, optical, acoustic) depending on the parameters being measured. Some important characteristics of a biosensor are its specificity, sensitivity, reliability, portability, and simplicity. Matrubutham and Sayler (1998), Simonian and others (1998), D'Souza (2001), and Velasco-Garcia and Mottram (2003) have reviewed the principles and potential applications of biosensors. Alocilja and Radke (2003) have analyzed the pathogen detection industry and concluded that biosensors are a growing market. This paper relates primarily to biosensors that can be placed inside the food package or integrated into the packaging material, although there are also hand-held or desktop biosensors.

Presently, commercial biosensors for intelligent packaging are not available, although several prototypes are being developed. For example, SIRA Technologies (Pasadena, Calif., U.S.A.) is developing a biosensor/barcode called Food Sentinel System to detect pathogens in food packages (Ayala and Park 2000; Anonymous 2004f). In this system, a specific-pathogen antibody is attached to a membrane-forming part of the barcode; the presence of contaminating bacteria will cause the formation of a localized dark bar, rendering the barcode unreadable upon scanning. Toxin Alert (Ontario, Calif., U.S.A.) is also developing a diagnostic system called Toxin Guard that incorporates antibodies into plastic packaging films to detect pathogens (Anonymous 2000; Bodenhamer 2002; Bodenhamer and others 2004). When the antibodies encounter a target pathogen, the packaging material displays a clear visual signal to alert the consumer, retailer, or inspector. This system is intended for detecting gross contamination, because it is not sensitive enough for detecting very low levels of pathogens that can cause disease.

Applications of intelligent packaging

Enhancing food safety and biosecurity

Intelligent packaging, especially when integrating with science-based principles, is a useful tool for tracking products and monitoring their conditions, facilitating real-time data access and exchange, and enabling rapid response and timely decision making. These qualities are essential for any food safety or biosecurity strategy. The applications of IP in enhancing traceability systems and Hazard Analysis Critical Control Points (HACCP) systems are discussed below.

Traceability, tracking and recordkeeping of product flow through the production process and supply chain, is generally considered as a key in enhancing food safety and biosecurity (Anonymous 2002b; Anonymous 2004e; Golan and others 2004). The existing traceability systems vary in breadth, depth, and precision; these terms refer to what data are recorded, how far backward or forward along the supply chain is the data tracked, and how precisely is the product location pinpointed, respectively (Golan and others 2004). Because tracing all information with high precision is virtually impossible, only a limited set of variables is usually traced. In tracing beef, for example, variables such as global trade item number, batch/lot number, and country of origin are recommended (Anonymous 2002c). However, these variables do not provide technical information about the safety and quality of the food product.

Intelligent packaging could be integrated into existing traceability systems to create more effective communication links. Bar codes and RFID tags can enable electronic recordkeeping and information sharing, especially when interfaced with external instruments capable of rapidly measuring quality attributes and monitoring food safety. For example, pH meters, water activity meters, rapid microbial detection devices (Guan and Levin 2002; Bhagwat 2004), or nondestructive quality measurement instruments (Lu 2004; Saranwong and others 2004) may be placed at strategic locations along the supply chain where they exchange data with read/write bar codes or RFID tags. Nevertheless, increasing the breadth and depth of a traceability system alone is not sufficient to improve food safety; science-based food models and user-friendly software are also required to fully utilize the additional food related data layer available.

In recent years, HAACP has become an internationally recognized system for managing the risk associated with food safety. HAACP is a science-based system that consists of 7 principles: conduct hazard analysis, determine critical control points, establish critical limits, establish monitoring procedures, establish corrective actions, establish verification procedures, and establish record keeping and documentation procedures (Natl. Advisory Committee on Microbiological Criteria for Foods 1998). The implementation of these principles requires storing, sharing, and processing information so that timely decision and corrective actions could be made.

Figure 5 outlines a system based on the conceptual framework of IP and HACCP principles for managing information flow and ensuring food safety. An important point about this system is that information is shared among multiple devices at multiple locations. Information obtained from multiple devices and multiple locations, especially when the devices are networked, is far more useful than information obtained from a single device and at a single location. It is generally recognized that microbial detection alone is not a complete solution to ensure food safety; however, when it is coupled with physical and chemical measurements, timely detection and correction of safety problems may be achieved more readily. The multiple devices include smart package devices coupled with sensing devices such as pH and water activity meters that are placed along the supply chain.

When applying the HACCP principles, special attention should be paid to designing the decision support system. The hazard analysis should determine not only the flow of materials, but also the flow of information. The critical control points and the sensing devices required at specific locations should be identified. The limits of critical control points (such as time and temperature) may be encoded in bar codes or RFID tags to enable electronic data retrieval. Monitoring of the critical control points may be achieved by using TTI labels or other sensing devices at strategic locations. Read/write RFID tags and computer networks may facilitate record keeping and documentation. Decision for corrective actions may be facilitated using data processing software, which should incorporate science-based knowledge such as risk assessment and predictive microbiology models (McMeekin and others 2002; Anonymous 2004c). The development of IP-based HACCP system is in the early stages, and significant research work is needed for its further development and implementation.

Enhancing food quality and convenience

The current application of IP has been focused mostly on using TTI labels to monitor temperature, although many other applications are also possible. For example, it may be applied to cooking appliances such as the intelligent microwave oven system shown in Figure 6 (Yam 2000). The uniqueness of this system is in its use of information sharing to enhance food quality and convenience. The

PDF 417 barcode in the package carries data about the food product, and the data processing system generates the proper heating instructions for the microwave oven. Information exchange also occurs through the user interface (such as a touch screen or voice recognition system) and the Internet.

Because microwave ovens come in different sizes and power outputs, the heating instructions printed on microwaveable food packages are deliberately vague to accommodate the many different ovens in the market. Using these vague instructions often does not allow for achievement of good food quality. This problem may be overcome by scanning the bar code to enable the decision support system to match the microwave oven and the food package. To achieve a higher level of quality, temperature and moisture sensors may be placed inside the microwave oven to provide feedback for the data processing system.

Scanning of the bar code eliminates the need for manually entering heating instructions. This is particularly useful for microwave/convective ovens that use complicated instructions. These combination ovens are capable of providing higher food quality than the conventional microwave ovens, but their heating instructions are complicated and involve multiple steps because both microwave energy and convective heat are employed. Scanning of the bar code is also helpful for people who are visually impaired or have difficulties in understanding the language. The Internet connection provides convenient access to information relating to the packaged food such as the manufacturer's Web site, recipes, food allergen information, and product recall.

The development of the intelligent microwave oven system requires the application of scientific knowledge to design the data layers and the data processing system. The data layers should contain information relating to the food, the package, and the microwave oven. The architecture of the data layers could be rather com-

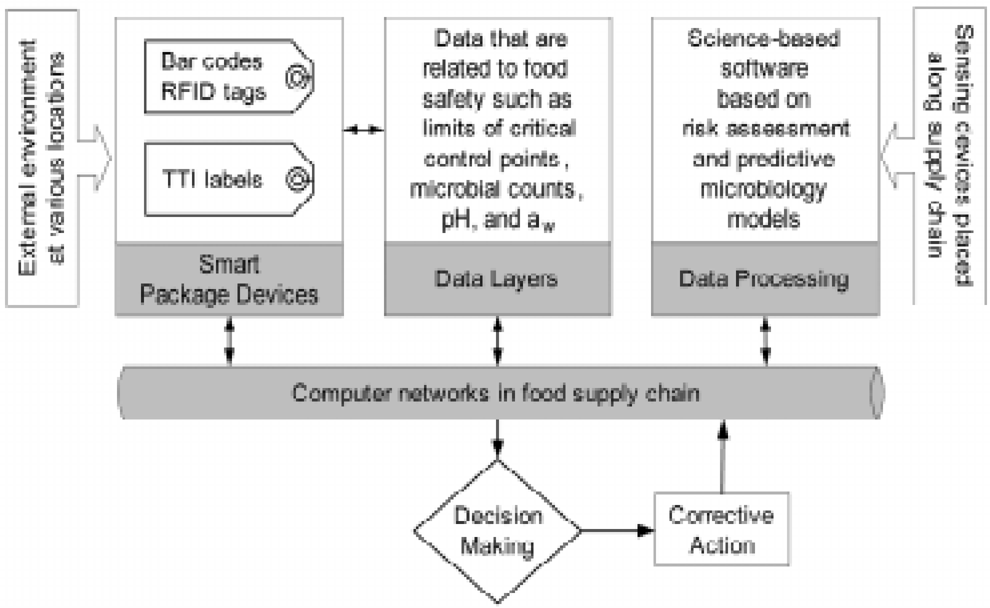

Figure 5—An example of intelligent packaging and HACCP system

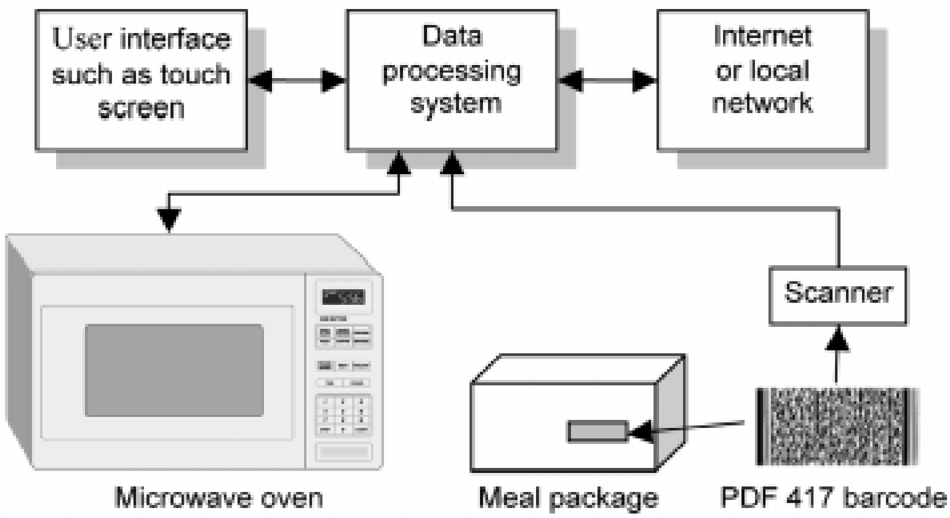

Figure 6—Intelligent microwave oven system

plicated because data may enter the system in different ways. For example, the food manufacturer may encode the food and packaging information in the barcode, the oven manufacturer may store the oven information in a database connected to the information processing system, the consumer may enter his or her preferences through the touch screen, and information may be exchanged via the Internet. The data processing system should include algorithms that are based on heat transfer principles and heuristic rules relating to food quality and safety, to generate instructions for controlling the magnetron and turntable (if available) of the microwave oven. In addition, the algorithms may have other abilities such as obeying the requirement or preferences of the consumer, warning the consumer against food allergens, and tracking the dietary intake of the consumer.

Research roadmap

Future research is needed to ensure the safe and smooth adoption of intelligent packaging. In developing a research agenda, the role of IP in the model in Figure 1 should be carefully considered, and the roadmap should be based on a sound conceptual framework such as the one in Figure 3. Conducting the research frequently requires a system approach involving interactions between researchers in food packaging, food engineering, biotechnology, microelectronics, software engineering, nanotechnology, and other disciplines. Below are some major research areas that are based on our conceptual framework.

Development of decision support system

In the business world, decision support systems are now available for analyzing data and facilitating decision making. However, those decision support systems are not adequate for IP applications—what is lacking is the scientific knowledge necessary for food quality and safety enhancement. Although there is a vast amount of scientific knowledge about foods in the *Journal of Food Science* and other journals, further research is still needed to transform the existing knowledge into a form that can be incorporated into the data layer and food models for the IP system. Traditionally, mathematical models (for example, kinetic models for quality deterioration and microbial growth) have been useful for quantitatively describing the behavior of food systems, but those models alone are not sufficient to handle complex real-time data, such that those obtained from multiple package devices at multiple locations. To compensate for this deficiency, artificial intelligence (AI) tools such as knowledge-based expert systems, fuzzy logic, inductive learning, and neural networks may be used (Pham and Pham 1999). These AI tools are designed to deal with complex real-life data and transfer expert knowledge to quantitative functions (in the form of rules-of-thumb) that can be processed by computers. The utility of those tools have recently been demonstrated for microbial growth modeling (Jeyamkondan and others 2001), food processing (Torrecilla and others 2004), controlling cheese ripening (Perrot and others 2004), and other food applications (Linko 1998).

Yam and Saba (1998) have also described a decision support system for modified atmosphere packaging for fresh produce, with the goal of extending the shelf life of the product by creating and maintaining a desirable modified atmosphere inside the package. This is a complicated system that involves many variables and the dynamic interactions among the respiring product, the package, and the distribution environment. The product parameters include the respiration rates for O_2 consumption and CO_2 evolution, the product weight, and the desired modified atmosphere; the package parameters include the O_2 and CO_2 permeabilities, package thickness, and package surface area; the distribution environment parameters include temperature and relative humidity. A challenge is to deal with these many complex and constantly changing variables. Figure 7 shows the block diagram of a generic decision support system that may be used for this and other food packaging applications. The *data input* consists of 2 sets of data, dynamic data and knowledge base. Examples of dynamic data are climatic conditions, respiring rates, and initial quality of the product that can change daily. Examples of data stored in the knowledge base are gas permeabilities of packaging films, package dimensions, and regulatory requirements that are not likely to change frequently. The knowledge base will be updated periodically, for example, when a new package design is used or when the regulatory requirements are changed. The *data processing* consists of mathematical models and AI tools. The mathematical models are those based on the scientific principles describing the interactions among the respiration of the product, the O_2 and CO_2 permeabilities of the package, and environment conditions (Yam and Lee 1995). The AI tools include fuzzy logic sets containing rules or algorithms for dealing with complex factors and relations such as product variability, consumer acceptance, market conditions, and relationship between respiration rate and quality attributes. The mathematical models and AI tools work together to enable more rapid and reliable decision making.

Further development of smart package devices

A multidisciplinary approach is needed to develop smaller, more powerful, and less expensive smart package devices for IP applications. Advanced smart package devices such as biosensors are still at the early development stage, whereas most of the prototypes are limited by slow response time or short shelf life. Yet possibilities also exist in combining biotechnology and nanotechnology to develop biosensors to overcome these and other limitations (Scott and Chen 2003). Research opportunities also exist to integrate data carriers (such as barcode and RFID) and package indicators (such as TTI and gas indicator) into small hybrid devices. As various smart package devices are being developed, it is imperative to establish universal standards to allow efficient data exchange.

Integration of IP into total packaging system

It is important to emphasize that IP is only 1 component of the total packaging system, and thus future research is needed to integrate it smoothly and efficiently into the model in Figure 1. Combining IP and AP offers many intriguing possibilities: for example, a packaging system may consist of a TTI/biosensor to sense the environment, and whenever necessary, release an antimicrobial and/or an antioxidant to extend the shelf life of food. In the future, it is anticipated that hybrid IP/AP systems will become increasingly sophisticated. History will once again determine whether it will serve a useful purpose to add yet another new term on top of IP and AP in the model in Figure 1 to describe the hybrid IP/AP system.

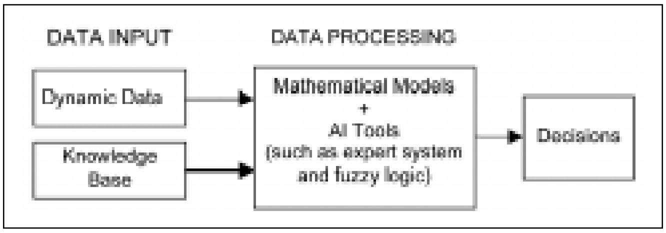

Figure 7—Block diagram for a decision support system

Conclusions

Intelligent packaging is emerging as a new branch of packaging science and technology that offers exciting opportunities for enhancing food safety, quality, and convenience. The advancement in this technology will require researchers to continue to think outside the box and use nontraditional packaging approaches to meet new challenges. A conceptual framework such as the one described in this paper is imperative for guiding the concerted research efforts in the future. For the 1st time, packaging science, food science, biotechnology, sensor science, information technology, nanotechnology, and other disciplines are coming together to develop a breakthrough packaging technology. As this technology is unfolding, issues such as those relating to legislation, economics, and consumer privacy also need to be addressed.

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