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Scientific Status Summary

Innovative Food Packaging Solutions

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The Institute of Food Technologists has issued this Scientific Status Summary to inform readers of recent innovations in food packaging materials.

Keywords: absorption, active food packaging, adsorption, electronic product code (EPC), food scalping, intelligent food packaging, migration, nanocomposites, nanosensors, nanotechnology, nanotubes, oxygen scavenger, permselectivity, radio frequency identification (RFID), time-temperature indicator (TTI), traceability, uniform product code (UPC)

Introduction

Food and beverage packaging comprises 55% to 65% of the $130 billion value of packaging in the United States (Brody 2008). Food processing and packaging industries spend an estimated 15% of the total variable costs on packaging materials (Esse 2002). Industrial processing of food, reduced consumption of animal protein, importation of raw materials and ingredients to be converted in the United States, and scarcity of time to select/prepare food from fresh ingredients have enhanced innovation in food and beverage packaging. The continued quest for innovation in food and beverage packaging is mostly driven by consumer needs and demands influenced by changing global trends, such as increased life expectancy, fewer organizations investing in food production and distribution (Lord 2008), and regionally abundant and diverse food supply. The use of food packaging is a socioeconomic indicator of increased spending ability of the population or the gross domestic product as well as regional (rural as opposed to urban) food availability.

This Scientific Status Summary provides an overview of the latest innovations in food packaging. It begins with a brief history of food and beverage packaging, covering the more prominent packaging developments from the past, and proceeds to more modern advances in the packaging industry. The article then delves into current and emerging innovations in active and intelligent packaging (such as oxygen scavengers and moisture control agents), packaging mechanisms that control volatile flavors and aromas (such as flavor and odor absorbers), and cutting-edge advances in food packaging distribution (such as radio frequency identification and electronic product codes). Finally, the article discusses nano-sized components that have the potential to transform the food packaging industry.

History of Food and Beverage Packaging

Modern food packaging is believed to have begun in the 19th century with the invention of canning by Nicholas Appert. After the inauguration of food microbiology by Louis Pasteur and colleagues in the 19th century, Samuel C. Prescott and William L. Underwood worked to establish the fundamental principles of bacteriology as applied to canning processes (Wilson 2007). These endeavors to preserve and package food were paralleled by several other packaging-related inventions such as cutting dies for paperboard cartons by Robert Gair and mechanical production of glass bottles by Michael Owens. In the beginning of the 20th century, 3-piece tin-plated steel cans, glass bottles, and wooden crates were used for food and beverage distribution. Some food packaging innovations stemmed from unexpected sources. For example, Jacques E. Brandenberger's failed attempts at transparent tablecloths resulted in the invention of cellophane. In addition, wax and related petroleum-based materials used to protect ammunition during World War II became packaging materials for dry cereals and biscuits (Twede and Selke 2005).

Many packaging innovations occurred during the period between World War I and World War II; these include aluminum foil, electrically powered packaging machinery, plastics such as polyethylene and polyvinylidene chloride, aseptic packaging, metal beer cans, flexographic printing, and flexible packaging. Most of these developments helped immeasurably in World War II by protecting military goods and foods from extreme conditions in war zones.

Tin-plated soldered side-seam steel progressed to welded side-seam tin-free steel for cans, and 2-piece aluminum with easy open pop tops were invented for beverage cans, spearheading the exponential growth of canned carbonated beverages and beer during the 1960s and 1970s. The development of polypropylene, polyester, and ethylene vinyl alcohol polymers led the incredible move away from metal, glass, and paperboard packaging to plastic and flexible packaging (Lord 2008). Later 20th century innovations include active packaging (oxygen controllers, antimicrobials, respiration mediators, and odor/aroma controllers) and intelligent or smart packaging. Distribution packaging is already influenced by the potential role of radio frequency identification for tracking purposes.

Products such as retort pouches and trays, stand-up flexible pouches, zipper closures on flexible pouches, coextrusion for films and bottles, and an inexorable drive by injection stretch blow-molded polyester bottles and jars for carbonated beverages and water have emerged as rigid and semi-rigid packaging. Multilayer

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barrier plastic cans, microwave susceptors, dispensing closures, gas barrier bags for prime cuts of meat, modified atmosphere packaging, rotogravure printed full-panel shrink film labels, and dual ovenable trays are examples of innovations for the convenience attributes that have propelled food and beverage packaging into the 21st century. Moreover, some 21st century innovations are related to nanotechnology whose future may lie in improving barrier and structural/mechanical properties of packaging materials and development of sensing technologies. The principal drivers for most of these innovations have been consumer and food service needs and demands for global and fast transport of food. These packaging innovations are derived largely from industry research and development programs.

The Expanded Roles of Food and Beverage Packaging

The principal function of packaging is protection and preservation from external contamination (Robertson 2006). This function involves retardation of deterioration, extension of shelf life, and maintenance of quality and safety of packaged food. Packaging protects food from environmental influences such as heat, light, the presence or absence of moisture, oxygen, pressure, enzymes, spurious odors, microorganisms, insects, dirt and dust particles, gaseous emissions, and so on. All of these cause deterioration of foods and beverages (Marsh and Bugusu 2007). Prolonging shelf life involves retardation of enzymatic, microbial, and biochemical reactions through various strategies such as temperature control; moisture control; addition of chemicals such as salt, sugar, carbon dioxide, or natural acids; removal of oxygen; or a combination of these with effective packaging (Robertson 2006). Precise integration of the product, process, package, and distribution is critical to avoid recontamination. The ideal packaging material should be inert and resistant to hazards and should not allow molecular transfer from or to packaging materials (Robertson 2006).

Other major functions of packaging include containment, convenience, marketing, and communication. Containment involves ensuring that a product is not intentionally spilled or dispersed. The communication function serves as the link between consumer and food processor. It contains mandatory information such as weight, source, ingredients, and now, nutritional value and cautions for use required by law. Product promotion or marketing by companies is achieved through the packages at the point of purchase (Kotler and Keller 2006). Secondary functions of increasing importance include traceability, tamper indication, and portion control (Marsh and Bugusu 2007). New tracking systems enable tracking of packages though the food supply chain from source to disposal. Packages are imprinted with a universal product code to facilitate checkout and distribution control. More recent innovations used include surface variations sensed by finger tips and palms, sound/music or verbal messages, and aromas emitted as part of an active packaging spectrum (Landau 2007). Gloss, matte, holograms, diffraction patterns, and flashing lights are also used.

Active and Intelligent Food Packaging

Traditional food packages are passive barriers designed to delay the adverse effects of the environment on the food product. Active packaging, however, allows packages to interact with food and the environment and play a dynamic role in food preservation (Brody and others 2001; Lòpez-Rubio and others 2004). Developments in active packaging have led to advances in many areas, including delayed oxidation and controlled respiration rate, microbial growth, and moisture migration. Other active packaging technologies include carbon dioxide absorbers/emitters, odor absorbers, ethylene removers, and aroma emitters. While purge and moisture control and oxygen removal have been prominent in active packaging, purge control is the most successful commercially. An example is the drip-absorbing pad used in the poultry industry (Suppakul and others 2003a).

In addition, active packaging technology can manipulate permselectivity, which is the selective permeation of package materials to various gases. Through coating, microperforation, lamination, coextrusion, or polymer blending, permselectivity can be manipulated to modify the atmospheric concentration of gaseous compounds inside a package, relative to the oxidation or respiration kinetics of foods. Certain nanocomposite materials can also serve as active packaging by actively preventing oxygen, carbon dioxide, and moisture from reaching food.

Intelligent or smart packaging is designed to monitor and communicate information about food quality (Brody and others 2001; Kerry and others 2006). Examples include time-temperature indicators (TTIs), ripeness indicators, biosensors, and radio frequency identification. These smart devices may be incorporated in package materials or attached to the inside or outside of a package. As of summer 2008, the commercial application of these technologies to food packaging has been small. However, the U.S. Food and Drug Administration (FDA) recognizes TTIs in the 3rd edition of the *Fish and Fisheries Products Hazards and Control Guidance*, so their importance may increase in the seafood industry. Moreover, Wal-Mart, Home Depot and other retail outlets use radio frequency identification, so it is likely to become very prominent as a mechanism for tracking and tracing produce and others perishable commodities.

Oxygen scavengers

The presence of oxygen in a package can trigger or accelerate oxidative reactions that result in food deterioration: Oxygen facilitates the growth of aerobic microbes and molds. Oxidative reactions result in adverse qualities such as off-odors, off-flavors, undesirable color changes, and reduced nutritional quality. Oxygen scavengers remove oxygen (residual and/or entering), thereby retarding oxidative reactions, and they come in various forms: sachets in headspace, labels, or direct incorporation into package material and/or closures. Oxygen scavenging compounds are mostly agents that react with oxygen to reduce its concentration. Ferrous oxide is the most commonly used scavenger (Kerry and others 2006). Others include ascorbic acid, sulfites, catechol, some nylons, photosensitive dyes, unsaturated hydrocarbons, ligands, and enzymes such as glucose oxidase. To prevent scavengers from acting prematurely, specialized mechanisms can trigger the scavenging reaction. For example, photosensitive dyes irradiated with ultraviolet light activate oxygen removal (Lòpez-Rubio and others 2004). Oxygen scavenging technologies have been successfully used in the meat industry (Kerry and others 2006).

Carbon dioxide absorbers and emitters

Carbon dioxide may be added for beneficial effects, for example, to suppress microbial growth in certain products such as fresh meat, poultry, cheese, and baked goods (Lòpez-Rubio and others 2004). Carbon dioxide is also used to reduce the respiration rate of fresh produce (Labuza 1996) and to overcome package collapse or partial vacuum caused by oxygen scavengers (Vermeiren and others 1999). Carbon dioxide is available in various forms, such as moisture-activated bicarbonate chemicals in sachets and absorbent pads. Conversely, high levels of carbon dioxide resulting from food deterioration or oxidative reactions could cause adverse quality effects in food products. Excess carbon dioxide can be removed by using highly permeable plastics whose permeability increases with higher temperatures.

Moisture control agents

For moisture-sensitive foods, excess moisture in packages can have detrimental results: for example, caking in powdered products, softening of crispy products such as crackers, and moistening of hygroscopic products such as sweets and candy. Conversely, too much moisture loss from food may result in product desiccation. Moisture control agents help control water activity, thus reducing microbial growth; remove melting water from frozen products and blood or fluids from meat products; prevent condensation from fresh produce; and keep the rate of lipid oxidation in check (Vermeiren and others 1999). Desiccants such as silica gels, natural clays and calcium oxide are used with dry foods while internal humidity controllers are used for high moisture foods (for example, meat, poultry, fruits, and vegetables). Desiccants usually take the form of internal porous sachets or perforated water-vapor barrier plastic cartridges containing desiccants. They can also be incorporated in packaging material. Humidity controllers help maintain optimum in-package relative humidity (about 85% for cut fruits and vegetables), reduce moisture loss, and retard excess moisture in headspace and interstices where microorganisms can grow. Purge absorbers remove liquid squeezed or leaking from fresh products and can be enhanced by other active additives such as oxygen scavengers, antimicrobials, pH reducers, and carbon dioxide generators (Brody and others 2001).

Antimicrobials

Antimicrobials in food packaging are used to enhance quality and safety by reducing surface contamination of processed food; they are not a substitute for good sanitation practices (Brody and others 2001; Cooksey 2005). Antimicrobials reduce the growth rate and maximum population of microorganisms (spoilage and pathogenic) by extending the lag phase of microbes or inactivating them (Quintavalla and Vicini 2002). Antimicrobial agents may be incorporated directly into packaging materials for slow release to the food surface or may be used in vapor form. Research is underway on the antimicrobial properties of the following agents (Wilson 2007):

- Silver ions – Silver salts function on direct contact, but they migrate slowly and react preferentially with organics. Research on the use of silver nanoparticles as antimicrobials in food packaging is ongoing, but at least 1 product has already emerged: FresherLonger^{TM} storage containers allegedly contain silver nanoparticles infused into polypropylene base material for inhibition of growth of microorganisms (NSTI 2006).
- Ethyl alcohol – Ethyl alcohol adsorbed on silica or zeolite is emitted by evaporation and is somewhat effective but leaves a secondary odor.
- Chlorine dioxide – Chlorine dioxide is a gas that permeates through the packaged product. It is broadly effective against microorganisms but has adverse secondary effects such as darkening meat color and bleaching green vegetables.
- Nisin – Nisin has been found to be most effective against lactic acid and Gram-positive bacteria. It acts by incorporating itself in the cytoplasmic membrane of target cells and works best in acidic conditions (Cooksey 2005).
- Organic acids – Organic acids such as acetic, benzoic, lactic, tartaric, and propionic are used as preservative agents (Cha and Chinnan 2004).
- Allyl isothiocyanate – Allyl isothiocyanate, an active component in wasabi, mustard, and horseradish, is an effective broad spectrum antimicrobial and antimycotic. However, it has strong adverse secondary odor effects in food.
- Spice-based essential oils – Spice-based essential oils have been studied for antimicrobial effects: for example, oregano oil in meat (Skandamis and Nyachas 2002), mustard oil in bread (Suhr and Nielsen 2005), oregano, basil (Suppakul and others 2003b), clove, carvacol, thymol, and cinnamon.
- Metal oxides – Nanoscale levels of metal oxides such as magnesium oxide and zinc oxide are being explored as antimicrobial materials for use in food packaging (Garland 2004).

Ethylene absorbers and adsorbers

Ethylene is a natural plant hormone produced by ripening produce. It accelerates produce respiration, resulting in maturity and senescence. Removing ethylene from a package environment helps extend the shelf life of fresh produce. The most common agent of ethylene removal is potassium permanganate, which oxidizes ethylene to acetate and ethanol (Lopez-Rubio and others 2004). Ethylene may also be removed by physical adsorption on active surfaces such as activated carbon or zeolite. Potassium permanganate is mostly supplied in sachets while other adsorbent or absorbent chemicals may be distributed as sachets or incorporated in the packaging materials.

Temperature control: self-heating and cooling

Self-heating packaging employs calcium or magnesium oxide and water to generate an exothermic reaction. It has been used for plastic coffee cans, military rations, and on-the-go meal platters. The heating device occupies a significant amount of volume (almost half) within the package. Self-cooling packaging involves the evaporation of an external compound that removes heat from contents (usually water that is evaporated and adsorbed on surfaces).

Advances in Controlling Volatile Flavors and Aromas

The mass transfer of components between and within food and packaging leads to the loss of volatile flavors and aromas from food. The most common methods of mass transfer food packaging systems are migration, flavor scalping (Figure 1), selective permeation, and ingredient transfer between heterogeneous parts of the food. Migration is the transfer of substances from the package into the food due to direct contact. Migration of packaging components to food must be understood and considered with toxicological risk analysis. Most incidences of migration occur in plastic packaging systems; thus, the most commonly studied migrants are plastic monomers, dimers, oligomers, antioxidants, plasticizers, and dye/adhesive solvent residues. Migration of packaging material components is examined in 2 ways, based on the migrating chemicals. One is global migration (that is, total migration); the other is specific migration of chemicals of interest. Migration of chemical substances is determined by the units of mg/kg for food or mg/m^2 for package surface. The degree of migration depends on several variables: contact area between food and package material, contact time, food composition, concentration of migrant, storage temperature, polymer morphology, and polarity of polymeric packaging materials and migrants (Brown and Williams 2003; Linssen and others 2003).

Flavor scalping is caused by the absorption of desirable volatile food flavors by package materials (for example, absorption of volatile flavors of orange juice and citrus beverages by polyethylene) (Roland and Hotchkiss 1991). Polyethylene materials are known to scalp many volatiles from food (Sajilata and others

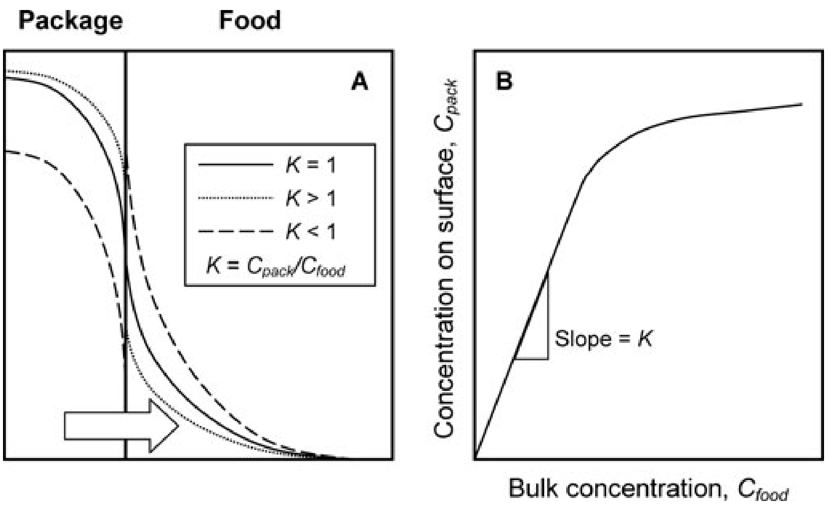

Figure 1 — Effect of interfacial partitioning of molecules on mass transfer between food and packaging materials: (A) migration of package constituents into foods, (B) scalping of food flavor into packaging materials. K is a partition coefficient of a migrant.

2007). This is due to polyethylene's lipophilic nature, which attracts large amounts of nonpolar compounds such as volatile flavors and aroma in foods. In fact, certain products—especially high-fat foods or vacuum-packaged foods—pick up odors from adjacent strong odor foods when stored or distributed in the same case, storage room, or trailer (Brown and Williams 2003). The absorption of undesirable flavors by packaging materials follows the same theory and principles of migration but is generally not considered flavor scalping. Unacceptable odor pick-up can be avoided by proper package wrapping with high-barrier materials. The use of high-barrier packaging materials can also prevent the absorption of other nonfood odors such as taints.

Because they result in deterioration of quality and consumer preference of the packaged food, both migration and flavor scalping are unfavorable. However, some applications intentionally utilize these methods of mass transfer to improve the quality of packaged foods. The interactions can be used in active and intelligent packaging applications (Brown and Williams 2003). Examples are off-flavor absorbing systems and beneficial volatile release systems. Besides loss of flavor in food, nonpolar flavor components loosen the polymer structure to create more amorphous polymers. This causes undesired changes in the mechanical (seal strength, loss of laminations) and barrier (to oxygen, moisture, and volatiles) properties (Linssen and others 2003). Therefore, the effect of off-flavor absorption on essential characteristics of plastic packaging materials should be investigated.

Flavor and odor absorbers

In packaged foods, flavor and odor absorbers take in unwanted gaseous molecules such as volatile package ingredients, chemical metabolites of foods, microbial metabolites, respiration products, or off-flavors in raw foods (Rooney 2005). Examples are sulfurous compounds and amines produced biochemically from protein degradation, aldehydes and ketones produced from lipid oxidation or anaerobic glycolysis, and bitter taste compounds in grapefruit juice. Flavor- and odor-absorbing systems use the same mass transfer mechanism as flavor scalping to remove off-characteristics and are typically available as films, sachets, tapes/labels, and trays. Flavor and odor absorbers are usually placed inside packages or combined with other flavor permeable materials. Although scavenging of malodorous constituents is recommended to improve the quality of packaged foods, this technology should not be used to mask off-odors produced by hazardous microorganisms that could place consumers at risk (Nielson 1997).

Absorption is the dominant mass transfer phenomenon when porous materials absorb flavor molecules. Porous or fine-particulate materials have extremely large surface areas; therefore, even with low absorption rates, the overall absorption is very significant. Porous materials—such as zeolites, clays, molecular sieves, active carbon, maltodextrin, and cyclodextrin—have been found to increase flavor. Besides the absorption rate, the maximum absorption, which is also a significant factor, can be controlled by the thickness of films, with thicker films absorbing more flavors. The film thickness does not alter absorption kinetics (that is, surface adsorption rate and diffusion kinetics) but relates to the total amount of absorption. The overall absorption rate that includes the surface adsorption rate and in-structure diffusion rate is affected by molecular size of flavors, polarity of flavor molecules and packaging materials, porosity of packaging materials, storage temperature, morphology of plastic packaging materials (that is, glass transition temperature, crystallinity, and free volume), and relative humidity.

Polar plastic materials or corona treatment of film surface and/or high-barrier (or high-density and more-crystalline) materials can be used to prevent nonpolar flavor absorption. When nonporous plastic materials absorb flavor molecules without the occurrence of chemical reactions, the increase in adsorption kinetics and diffusion kinetics will accelerate the absorption rate. However, when the flavor absorption results in chemical reactions with the plastic material, reaction kinetics as well as adsorption and diffusion kinetics significantly affect the off-flavor elimination capacity. Alkali chemicals such as ammonia and amines can be absorbed and neutralized by packaging materials containing acidic ingredients. This acid–alkali reaction mechanism between volatile chemicals and polymer ingredients has been utilized to eliminate various alkali chemicals and aldehydes (Franzetti and others 2001; Day 2003; Vermeiren and others 2003).

High chemical barrier material innovations

High-barrier packaging can significantly reduce adsorption, desorption, and diffusion of gases and liquids to maintain the quality of food. It also prevents the penetration of other molecules such as oxygen, pressurized liquid or gas, and water vapor, which are generally undesirable for food preservation. There are various procedures to enhance the barrier property of packaging materials or packages.

Barrier properties can be improved by combining the package materials with other high-barrier materials through polymer blending, coating, lamination, or metallization. The morphology of the blend relates to its permeability. Laminar structure (such as coating or lamination) of high-barrier materials on packaging material decreases the permeability linearly with respect to the square thickness; also, blending with platelets or droplets of high-barrier materials reduces permeability but is less effective than coating or lamination at the same mass as that of high-barrier materials (Lange and Wyser 2003). Commercial examples are polyvinylidene chloride (PVdC) coating on oriented polypropylene (OPP), polyethylene terephthalate (PET) lamination on coextruded polypropylene/polyethylene, and aluminum-metallization on PET. Table 1 shows barrier properties of commercially available laminated (or coated) PET films. Orientation of crystalline polymers such as bi-axially oriented polypropylene (BOPP) and bi-axially oriented PET (BOPET) produces lamella structure of polymers. Other examples are blends of polymers with planar clay particles, a lamella blend structure (Avella and others 2005), and a mixture of beeswax in edible polymer as particulate system films (Han and others 2006). Other innovative technologies for barrier property enhancement with commercial feasibility include transparent vacuum-deposited or plasma-deposited coating of silica oxide on PET films, epoxy spray on PET bottles, and composites of plastics with nanoparticles (Lange and Wyser 2003; Lopez-Rubio and others 2004).

Factors affecting food packaging interactions and barrier properties

Regardless of the direction of mass transfer (for example, whether flavor absorption or release) or the intent of the mass transfer (for example, whether to achieve desirable transfer or to prevent an undesirable transfer), various factors of food, packaging, and distribution affect the mass transfer kinetics and amount. The transfer of chemicals is principally derived by the concentration difference in food and packaging materials. A small concentration gradient results in a little transfer while a large gradient results in transfer of a large amount of the compound at a fast rate. The nature of food is also an important factor: for example, food ingredients like lipids and flavors act as solvents of plastic materials, making them soft, even barrier plastic materials. Lipid and moisture content generally control the transfer of chemicals significantly.

Storage temperature, storage duration, and contact surface are also important factors. A high storage temperature accelerates transfer while longer storage duration raises the amount of transfer (Castle 2007). In addition, nonvolatile migrants and flavors can be transferred when the food and packaging are in contact. In such cases, migration time is related to the cumulative duration of contact of migrants to food. Moreover, a package's entire surface area may affect the migration of volatiles and flavors. The use of barrier packaging or inert materials always reduces this type of transfer. Therefore, simple lamination or coating on packaging material surfaces is a very practical way to modify the barrier properties and, consequently, to control the chemical interactions between food and the package. Use of inert packaging materials with hermetic seals can also be used to contain volatile flavors.

Table 1 — Oxygen transmission rate (OTR in $cm^3\ m^{-2}\ d^{-1}\ atm^{-1}$ at 23 °C, 50% RH) and water vapor transmission rate (WVTR in $g\ m^{-2}\ d^{-1}$ at 23 °C, 75% RH) of composite films based on 12 μm PET films (reproduced from Lange and Wyser 2003).

Film	OTR	WVTR	Specification (μm)
PET	110	15	12
PET/PE	0.93 to 1.24	0.248 to 0.372	12/50
PET/PVDC/PE	0.33	0.132	12/4/50
PET/PVAL/PE	0.13	0.26 to 0.39	12/3/50
PET/EVOH/PE	0.06	0.134 to 0.268	12/5/50
PET/Al-met/PE	0.06 to 0.12	0.006 to 0.03	12/-/50
PET/SiO_x	0.006 to 0.06	0.0024 to 0.06	12/-
PET/Al-foil/PE	0	0	12/9/50

PE = polyethylene low density; PVDC = poly(vinylidene chloride); PVAL = poly(vinyl alcohol); EVOH = ethylene vinyl alcohol; Al-met = aluminum metallization; SiO_x = silicon oxide; Al-foil = aluminum foil.

New Advances and Key Areas of Change

Sustainable food packaging

Three concepts populate the key areas of change within food packaging. The first is the trend toward more sustainable packaging. While there are multiple definitions of sustainable packaging, the Sustainable Packaging Coalition, an international consortium of more than 200 industry members, offers the most accepted definition. Sustainable packaging is characterized by the following criteria:

- It is beneficial, safe, and healthy for individuals and communities throughout its life cycle.
- It meets market criteria for performance and cost.
- It is sourced, manufactured, transported, and recycled using renewable energy.
- It maximizes the use of renewable or recycled source materials.
- It is manufactured using clean production technologies and best practices.
- It is made from materials healthy in all probable end-of-life scenarios.
- It is designed to optimize materials and energy.
- It is recovered effectively and used in biological and/or industrial cradle-to-cradle cycles (SPC 2007).

Sustainability initiatives led by global legislation, retailers, and corporations guide package material choices, design, and food packaging sales for food packaging professionals. The revised 1997 European Commission's Packaging and Packaging Waste Directive, the 2007 REACH (Registration, Evaluation, and Authorization of Chemicals), and the BS EN 13432 standard (which defines compost-ability, degradability, and biodegradability) are examples of effective global legislative guides in a majority of the Group of 8 countries (Canada, France, Germany, Italy, Japan, Russia, United Kingdom, United States, and the European Union), BRIC (Brazil, Russia, India, and China), and the developing world. In retail, IKEA and United Kingdom retailers have been long-term promoters of sustainable packaging and have launched impressive initiatives such as Plan A by Marks and Spencer, which defines food packaging material use. Also, Wal-Mart, the world's largest retailer, entered the sustainable packaging arena in 2006 (Warner 2006). Introduced in 2007, the Wal-Mart scorecard ranks packages compared with category competitors, based on environmental scores.

Finally, because a packaging material's source has been shown to be a defining factor in the final package's sustainability, corporations and environmental coalitions are working together to reduce the effect of packaging materials on global sources. International paper companies, the World Wildlife Fund, the Sustainable Forestry Initiative, and the Forest Stewardship Council verify the sources of wood for use in packaging. Groups such as the Confederation of European Paper Industries (CEPI) in the European Union are addressing solutions to the remaining high environmental impact of paper, which is heavily dependent on water, gas, and energy (Sand 2007). Other material-based working groups are taking similar actions.

Use of packaging supplier relationships for competitive advantage

The second key area of change in food packaging is the use of packaging-development value chain relationships for competitive advantage. Suppliers to the food packaging industry are adding value in relationships within the traditional package development value chain. This chain extends from raw material generation, to conversion, to production and distribution, to retail, to consumer use and disposal. But the formerly linear nature of this chain has become an integrated sphere that enables cross-fertilization of ideas from various supply-chain functions directly to the food manufacturer. Investing in packaging supply chain relationships offers opportunities for focus, innovation, and technology transfer for a competitive advantage.

For example, Starbucks engaged their packaging value chain—Mississippi River Corp., MeadWestvaco, and the Solo Cup Co.—to create an FDA-approved 10% recycled-fiber coffee cup. In addition, Green Mountain Coffee Roasters used its supply chain effectively when it introduced a compostable cup (the Ecotainer) with members of their supplier chain: DaniMer Scientific, NatureWorks, and International Paper. Also, Naturipe has used the value chain optimization to enable consistent packaging to stores from over 50 global locations (Sand 2008).

Evolution of food service packaging

The third and final key area of change in food packaging is the evolution of food service packaging. Food service has grown to become a major part of consumer spending. As this trend increases, packaging plays a key role in ensuring food safety and providing convenience to consumers. For instance, proper package labeling allows food preparers to know the source of a food, its proper holding temperature, and the adequate cooking needed. Ease of package opening allows for fewer utensils needed to open packages, which lessens contamination. While tracking and shelf-life extension technologies are employed in the food service industry to reduce the risk of foodborne illness, proper heating and heat retention continue to be challenges. Consequently, packaging's role in ensuring proper heating and heat retention continues to increase. For example, CuliDish is a new product that uses varying levels of aluminum within a tray to package foods that require heating together with those that do not require heating. The tray allows foods requiring high heat to be heated in the microwave at the same time with foods that do not require heat (such as salads). The food can be served in the same tray, thus reducing handling. More innovations in the areas of heat and heat retention are expected to assist in reducing food safety risks associated with improper cooking.

Two major convenience trends—meals eaten in transit and multi-component meals—have also advanced the food service packaging industry. The popularity of meals eaten in transit is evident since only 60% of meals are prepared and eaten at home (Packaged Facts 2005) and 20% of consumers eat on their way to another location instead of in a fixed position. On-the-go food consumption has resulted in packaging that contains a greater variety of foods. Technologies that support this trend include edible films to enrobe food particles and edible wraps that peel off, allowing consumers to eat numerous foods while in transit. Food package design innovations such as modular folding cartons with flip-off lids, pouches that are easily opened or have a seatbelt flap to hold food close to consumers, and reusable packaging have contributed to the increase of eating while on the go.

The growth of multi-component meals in food service stems from multiple types of foods being ordered at quick-service restaurants. This innovation allows for ease of food service preparation and less waste. Multi-component packaging also provides consumers with a presentation platform that makes multi-component foods easy to consume. Examples include reusable trays that clip together into 1 larger serving tray such as that used in the Les Petits Grande line of products; KFC's triple dip strip cartons, which allow consumers to select from 1 of 3 dips when dipping chicken strips; and the folding tray that allows consumers to carry 2 cups of coffee with 1 hand.

Advances in Food Packaging Distribution

RFID systems for packaged foods: architecture and working principles

Radio frequency identification (RFID) is a system that uses radio waves to track items wirelessly. RFID makes use of tags or transponders (data carriers), readers (receivers), and computer systems (software, hardware, networking, and database). The tags consist of an integrated circuit, a tag antenna, and a battery if the tag is passive (most active tags do not require battery power). The integrated circuit contains a non-volatile memory microchip for data storage, an AC/DC converter, encode/decode modulators, a logic control, and antenna connectors. The wireless data transfer between a transponder/tag and a reader makes RFID technology far more flexible than other contact identifications, such as the barcode system (Finkenzeller 2003; RFID Journal Inc. 2005), and thus makes it ideal for food packaging. The working principles of an RFID system are as follows:

1. Data stored in tags are activated by readers when the objects with embedded tags enter the electromagnetic zone of a reader;
2. Data are transmitted to a reader for decoding; and
3. Decoded data are transferred to a computer system for further processing.

Tag frequency is related to the working principles of an RFID system (for example, magnetic coupling or electric coupling) and the reading range. Frequency depends on the type of tag, reader, and cost. The typical RFID frequencies are low frequency, high frequency, ultra high frequency, and microwave frequency. Generally, low frequency systems have short reading ranges, slow read speeds, and lower cost while higher frequency RFID systems are utilized when longer read ranges and fast reading speeds are required. Microwave frequency requires active RFID tags.

Electronic product codes

In 2004, Electronic Product Code (EPC) Global Network began developing a second generation RFID protocol: EPC Class 1 version 2 (also referred to as Gen 2). The main goal of Gen 2 is to create a single global standard that is compatible with ISO standards. The tags would work in various countries that have different commercial band frequency. EPC is the most significant function of RFID contributing to commercial industry. EPC improves the traceability of items and facilitates efficient product recall and authenticity. EPC is similar to Universal Product Code (UPC), which is commonly used in bar codes. Compared to UPC, which uses 12 digits of numbers, EPC has 64 to 256 bits of alphanumeric data. The most common EPC has 96 bits.

The first obstacle for wide utilization of RFID is the cost for tags. Tags are still too expensive for use on individual primary packages. The infrastructure required for RFID systems (including readers, database servers with communication systems, and other information technology to process huge amounts of data) is costly and needs to be shared with all users in supply chains. The global use of EPC also requires compatibility among various regulations and standards of radio frequency. The biggest hurdle to wide utilization of EPC for RFID is the potential problems of privacy protection. A hidden reading system could collect all data from tags of items and also RFID card holders for the purpose of data stealing or data removing. Guidelines for the ethical use of RFID systems for data collecting, data handling, and system security need to be established.

RFID for the food industry

RFID has recently found its way into numerous applications in the food industry, ranging from food monitoring and traceability to enhancing food safety, to improving supply chain efficiency. The major benefits of RFID technology in the food industry are greater speed and efficiency in stock rotation and better tracking of products throughout the chain, resulting in improved on-shelf availability at the retail level and enhanced forecasting. The technology is well suited for many operations in food manufacturing and supply chain management. An RFID-based resource management system can help users handle warehouse operating orders by retrieving and analyzing warehouse data, which could save time and cost. The use of RFID in the food industry is currently focused on tracking and identification. When RFID technology becomes more established in the food industry, the integration of food science knowledge will be necessary to develop the intelligent food packaging application for food quality and safety (Yam and others 2005).

Some food companies have already integrated RFID into manufacturing and distribution. Retail chains such as Wal-Mart and Home Depot have been testing the technology for distribution (Joseph and Morrison 2006). In 2003, Wal-Mart issued a mandate requiring its top 100 suppliers to use RFID tags on all cases and pallets entering its distribution centers by 2005. RFID compliance is a long-term project for Wal-Mart; more of its suppliers are expected to be compliant by the end of 2008. Other major players advocating RFID technology are the U.S. Department of Defense and major retailers such as Albertsons, Target, Tesco, and Marks & Spencer.

RFID technology also provides security and safety benefits for food companies through tracking the origin of supplies. For example, a small California winery uses RFID to track its barrels and to enhance wine making by streamlining data collection. The company planted RFID tags on tanks and harvesting bins, allowing better control of wine production and tracking. In addition, by attaching an RFID tag to a package, the package becomes intelligent because the stored data provide valuable information that can be stored and read by appliances. This intelligent packaging technology is also being extended to refrigeration and freezing. Appliances can communicate with the packages and identify information related to the storage of the packaged products. Despite these benefits, other factors such as cost of the technology and recycling ability need to be considered.

Supply chain management, traceability, and recall

As a tool for tracking, RFID is a promising technology to food supply chain management. According to the FDA, 1307 recalls of processed foods occurred between 1999 and 2003; these recalls could have been avoided with a technology such as RFID. Exposure to risk at any one of the stages of the processed food supply chain would result in a domino-effect breakdown that could affect the smooth running of an entire supply chain. All stages of the supply chain (from farming, processing, transportation, manufacturing, retailing, and warehousing to consumption) are equally critical to food recall problems (Stauffer 2005). If RFID technology were combined with Hazard Analysis and Critical Control Point systems, the supply chain stages would be integrated, traceable, and effectively managed by food processors to reduce the number of recalls significantly. The outstanding tracing abilities of RFID tags to individual food product could enable manufacturers to audit every single phase of a product in a retail unit, monitoring correct handling, transportation, storage, and delivery.

New tag for use on metal and metal packaging and high water content products

The RFID system is not infallible; it has some weaknesses, such as the shielding effect of metal, which affects signal transduction. Data cannot be read correctly when tags are attached to metal on the surface or inside the package. Until recently, high frequency RFID tags were used on metal beer barrels. However, low frequency RFID (125 kHz to 135 kHz) has less loss of radio signal by the metal materials in the high magnetic field of a reader compared to higher frequency signals.

Another issue is that water molecules can absorb microwave signals, resulting in signal loss or interference during data acquisition from microwave RFID tags. Since most foods contain high moisture, this signal interference requires further study to enable application of the technology in the food industry. It is worth noting that low, high, and ultra-high frequency (UHF) tags can be used in high water systems since water does not interfere with their signal; on the contrary, ice absorbs UHF radio signals. For example, a product such as ice cream (which is technically defined as partly frozen foam with ice crystals and air bubbles occupying a majority of the space) contains about 72% frozen water and thus interferes with UHF radio signals (Goff 2008). Ice cream manufacturers have overcome this product interference by placing tags over an air gap in the containers. Companies with diverse product lines and high levels of automation will likely encounter significant technical barriers to RFID implementation.

Nanocomposites and Other Emerging Nanotechnologies in Food Packaging

Nanotechnology has the potential to transform food packaging materials in the future. Such nanoscale innovation could potentially introduce many amazing new improvements to food packaging in the forms of barrier and mechanical properties, detection of pathogens, and smart and active packaging with food safety and quality benefits. The nanolayer of aluminum that coats the interior of many snack food packages is one common example of the role that nanotechnology already plays in food packaging. The market for nanotechnology in food packaging in 2006 was estimated at $66 million and is expected to reach $360 million in 2008 (Brody 2006).

Nanomaterials are abundant in nature and numerous techniques are available to fabricate various nanomaterials. Nanoparticles can be produced top down from larger structures by grinding, use of lasers, and vaporization followed by cooling. Alternately, bottom-up methods are commonly used for synthesis of complex nanoparticles. These methods include solvent extraction/evaporation, crystallization, self-assembly, layer-by-layer deposition, microbial synthesis, and biomass reactions (Doyle 2006). All of these are being researched for potential application in food packages in the future. One group of nanomaterials at the forefront of food packaging development is nanocomposites.

Nanocomposites

Nanocomposite packages are predicted to make up a significant portion of the food packaging market in the near future. Principia Markets, a consulting firm that tracks the plastics market, estimates that the market for nanocomposites will reach 1 billion pounds by 2010 (AZoNano 2004). Many nanocomposite food packages are either already in the marketplace or being developed. The majority of these are targeted for beverage packaging. In large part, the impetus for this predicted growth is the extraordinary benefits nanoscience offers to improve food packages. Improvements in fundamental characteristics of food packaging materials such as strength, barrier properties, antimicrobial properties, and stability to heat and cold are being achieved using nanocomposite materials.

In the late 1980s, Toyota was the 1st company to commercialize nanocomposite materials. They found that the addition of 5%-by-weight nano-sized montmorillonite clay significantly increased the mechanical and thermal properties of different grades of nylon (Weiss and others 2006). Nanocomposite materials are now used in gasoline tanks, bumpers, and interior and exterior panels (Ray and others 2006). Research on use of nanocomposites for food packaging began in the 1990s. Most of the research has involved the use of montmorillonite clay as the nanocomponent in a wide range of polymers such as polyethylene, nylon, polyvinyl chloride, and starch. Amounts of nanoclays incorporated vary from 1% to 5% by weight. Nanocomponents must have 1 dimension less than 1 nm wide. The lateral dimensions, on the other hand, can be as large as several micrometers, leading to high aspect ratios (ratio of length to thickness) of many of these materials. The high surface area results in unique properties when nanocomposites are incorporated into packages.

There are 3 common methods used to process nanocomposites: solution method, *in situ* or interlamellar polymerization technique, and melt processing. The solution method can be used to form both intercalated and exfoliated nanocomposite materials. In the solution method, the nanocomposite clay is first swollen in a solvent. Next, it is added to a polymer solution, and polymer molecules are allowed to extend between the layers of filler. The solvent is then allowed to evaporate. The *in situ* or interlamellar method swells the fillers by absorption of a liquid monomer. After the monomer has penetrated in between the layers of silicates, polymerization is initiated by heat, radiation, or incorporation of an initiator. The melt method is the most commonly used method due to the lack of solvents. In melt processing, the nanocomposite filler is incorporated into a molten polymer and then formed into the final material (Ray and others 2006).

Generally, there are 3 possible arrangements for layered silicate clay nanocomposite materials: nonintercalated, intercalated, and exfoliated or delaminated. In nonintercalated materials the polymer does not fit between the layered clay, leading to a microphase separated final structure. In intercalated systems, the polymer is located between clay layers, increasing interlayer spacing. Some degree of order is retained in parallel clay layers, which are separated by alternating polymer layers with a repeated distance every few nanometers. Exfoliated systems achieve complete separation of clay platelets in random arrangements. This is the ideal nanocomposite arrangement but is hard to achieve (Ray and others 2006).

Bayer produces transparent nanocomposite plastic films and coatings called Durethan, which contains clay nanoparticles dispersed throughout the plastic. Large amounts of silicate nanoparticles are interspersed in polyamide films. These nanoparticles block oxygen, carbon dioxide, and moisture from reaching fresh meats and others foods. The nanoclay particles act as impermeable obstacles in the path of the diffusion process, thereby extending the shelf life of foods while improving their quality. The final package is also considerably lighter, stronger, and more heat-resistant (ETC Group 2004).

In years past, packaging beer in plastic bottles was not possible due to oxidation and flavor problems. Recently, however, this challenge has been overcome using nanotechnology. For example, Nanocor, a subsidiary of Amcol International Corp., is producing nanocomposites for use in plastic beer bottles that facilitate a 6-mo shelf life. By combining the nanocomposite and oxygen scavenger technologies, a new family of barrier nylons was recently developed for use in multilayer, co-injection blow-molded PET bottles. In the near future, nanocrystals embedded in plastic bottles may increase beer shelf life up to 18 mo by minimizing loss of carbon dioxide from and entrance of oxygen into bottles. Similar materials are being developed to extend the shelf life of soft drinks. Another advantage of these nanocomposite bottles is that their weight is considerably less, thereby reducing transportation costs (ETC Group 2004).

A considerable amount of research is also occurring in the area of biodegradable nanocomposite food packages. By pumping carbohydrates and clay fillers through high shear cells, films can be produced with exfoliated clay layers. These films act as very effective moisture barriers by increasing the tortuosity of the path water must take to penetrate the films. Significant increases in film strength are also frequently achieved in these types of materials. Starch and chitosan are two of the most studied biodegradable matrices (Weiss and others 2006). In the future, these types of biodegradable nanocomposite food packages may be found in the marketplace.

Other nanotechnologies

Carbon nanotubes are cylinders with nanoscale diameters that can be used in food packaging to improve its mechanical properties. In addition, it was recently discovered that they may also exert powerful antimicrobial effects. *Escherichia coli* died immediately upon direct contact with aggregates of carbon nanotubes. Presumably, the long, thin nanotubes punctured the *E. coli* cells, causing cellular damage. Single-walled carbon nanotubes may eventually serve as building blocks for antimicrobial materials (Kang and others 2007). Nano-wheels were also recently developed to improve food packaging. Inorganic alumina platelets have been self-assembled into wagon-wheel shaped structures that are incorporated into plastics to improve their barrier and mechanical properties. This was the first time large wheel-shaped molecules had been formed (Mossinger and others 2007).

The addition of nanosensors to food packages is also anticipated in the future. Nanosensors could be used to detect chemicals, pathogens, and toxins in foods. Numerous research reports describe detection methods for bacteria, viruses, toxins, and allergens using nanotechnology. For example, adhering antibodies to *Staphylococcus* enterotoxin B onto poly(dimethyl-siloxane) chips formed biosensors that have a detection limit of 0.5 ng/mL. Nanovesicles have been developed to simultaneously detect *E. coli* 0157:H7, *Salmonella* spp., and *Listeria monocytogenes*. Liposome nanovesicles have been devised to detect peanut allergen proteins (Doyle 2006). In addition, AgroMicron has developed a NanoBioluminescence detection spray containing a luminescent protein that has been engineered to bind to the surface of microbes such as *Salmonella* and *E. coli*. When bound, it emits a visible glow that varies in intensity according to the amount of bacterial contamination. This product is being marketed under the name BioMark (Joseph and Morrison 2006). Nanosensors Inc. is another company pursuing this potential. Through a license agreement with Michigan State University, a nanoporous silicon-based biosensor has been developed to detect *Salmonella* and *E. coli*. A prototype nanobiosensor was recently tested to detect *Bacillus cereus* and *E. coli* and was found to be able to detect multiple pathogens faster and more accurately than current devices (Liu and others 2007). Finally, Mahadevan Iyer and his colleagues at Georgia Institute of Technology are experimenting with integrating nanocomponents in ultra-thin polymer substrates for RFID chips containing biosensors that can detect foodborne pathogens or sense the temperature or moisture of a product (Nachay 2007).

DNA biochips are already under development to detect pathogens. Researchers at the Univ. of Pennsylvania and Monell Chemical Sciences Center have used nano-sized carbon tubes coated with strands of DNA to create nanosensors with abilities to detect odors and tastes. A single strand of DNA serves as the sensor and a carbon nanotube functions as the transmitter. Using similar technologies, electronic tongue nanosensors are being developed to detect substances in parts per trillion, which could be used to trigger color changes in food packages to alert consumers when food is spoiled. A unique aspect of these biochips is that the DNA is self-assembled onto the chips and repairs itself if damaged (Univ. of Pennsylvania 2005). In addition, researchers at Cornell Univ. have invented synthetic DNA barcodes to tag pathogens and monitor pathogens. The nanobarcodes fluoresce under ultraviolet light when target compounds are detected (Steele 2005).

Another color-changing film that could find its way into food packages is polymer opal films. Scientists at the United Kingdom's Univ. of Southampton and the Deutsches Kunststoff Inst. in Germany developed these unique self-assembled structures from arrays of spheres stacked in 3 dimensions. Polymer opal films belong to a class of materials known as photonic crystals. The crystals are built of tiny repeating units of carbon nanoparticles wedged between spheres, leading to intense colors that mimic the colors associated with the photonic crystals found on butterfly wings and peacock feathers (Pursiainen and others 2007). Photonic crystals could be used to produce unique food packaging materials that change color.

Conclusion

The food industry has seen great advances in the packaging sector since its inception in the 18th century with most active and intelligent innovations occurring during the past century. These advances have led to improved food quality and safety. While some innovations have stemmed from unexpected sources, most have been driven by changing consumer preferences. The new advances have mostly focused on delaying oxidation and controlling moisture migration, microbial growth, respiration rates, and volatile flavors and aromas. This focus parallels that of food packaging distribution, which has driven change in the key areas of sustainable packaging, use of the packaging value chain relationships for competitive advantage, and the evolving role of food service packaging. Nanotechnology has potential to influence the packaging sector greatly. Nanoscale innovations in the forms of pathogen detection, active packaging, and barrier formation are poised to elevate food packaging to new heights.

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