Italian Packaging Technology Award (IPTA) Paper Competition

Special delivery: Controlled release of active ingredients from food and beverage packaging

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Introduction

Food and beverage packaging has been traditionally defined as a passive barrier to delay the adverse effect of the environment on the contained product. However, current research trends include the development of packaging materials that interact with the environment and with the food, playing an active role in preservation. Active packaging is primarily designed to prolong shelf life, improve safety and/or enhance sensory properties in foods and beverages. Intelligent packaging contains indicators such as time-temperature, gas atmosphere, microbial growth, and pathogen detection and is used for quality control of packaged food.

Active, controlled, and intelligent packaging systems have experienced explosive growth in the United States. Countries outside the U.S. are well-positioned as leaders with an 11.3% average annual growth rate through 2008 (*1*). During the past decade, active packaging has experienced significant growth and change as innovations have challenged the status quo of traditional food and beverage packaging. Food polymer packaging can serve as a reservoir or matrix from which active ingredients are delivered in a controlled manner into the product. The controlled release of active ingredients is one such innovation that can be categorized within the active packaging field. Antimicrobial preservative releasers, antioxidant releasers, and flavoring and aroma emitters are examples of active packaging systems for preservation and shelf life extension of foods or improving their quality.

In the 1960s, the modern view of drug delivery began in which drug performance was increasingly effective by specific targeting and timed delivery to control a therapeutic concentration for a longer duration than conventional dosing. Significant research on the incorporation of active compounds within food packaging and its subsequent controlled release to the packaged product began in earnest in the 1990s. The use of synthetic polymers as food packaging materials has increased enormously during the past decades due to their advantages over other traditional materials, such as metal, glass, and paperboard.

Controlled release packaging is well-suited for controlling continuous food degradation reactions, such as microbial growth and lipid oxidation, because constant replenishment of active compounds can maintain safety and quality. Controlled release may be defined as a process by which one or more active ingredients are made available at a desired site and time at a specific rate. Controlled release offers the following advantages: (a) active ingredients are released at controlled rates over prolonged periods of time, (b) ingredient loss during processing and cooking can be avoided or limited due to increased stability, and (c) reactive or incompatible components can be separated (*2*).

Controlled Release Systems in Packaging

The majority of release profiles by a controlled release system can be categorized into zero-order release and first-order release (*3*). *Zero-order release* is the simplest profile where the release rate remains constant until the package no longer contains an active compound. During *first-order release* kinetics, the release rate is proportional to the mass of active compound contained within the package. The rate declines exponentially with time in first-order release, approaching a release rate of zero as the package approaches emptiness.

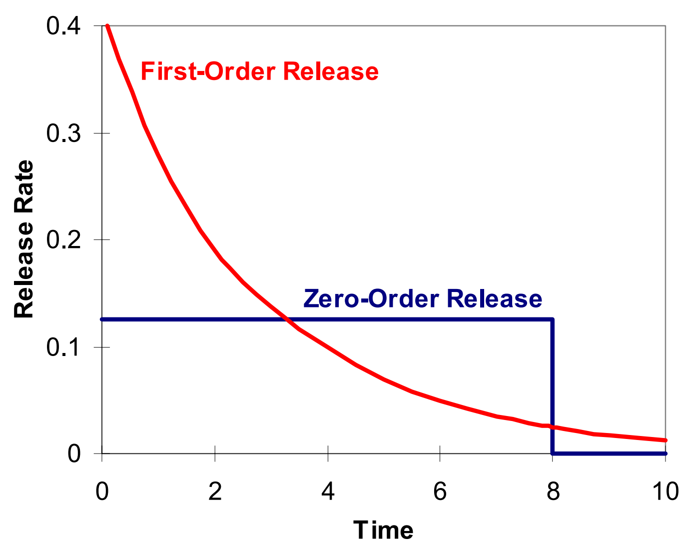

Figure 1: Zero-order and first-order release patterns from packaging containing the same initial concentration of active ingredient.

Many active ingredients can be incorporated directly into the matrix of the polymer packaging. Any soluble additive may be removed from a polymer by two separate processes:

(a) the removal of material from the surface by evaporation or dissolution and (b) its replacement in the surface layer by diffusion from the bulk polymer phase. Researchers have studied the rate of loss of simple low molecular weight compounds from thick polymer slabs and from thin films and fibers (*4*). The rate of loss of low molecular weight compounds from a thick polymer slab was determined by bulk phase diffusion and the loss from thin films was primarily determined by the surface evaporation rate.

In the food industry, the most commonly applied method to attain controlled release is microencapsulation. Microencapsulation is defined as the technology of packaging solid, liquid, or gaseous materials in minute sealed capsules that release their contents at controlled rates under the influence of specific conditions. Cyclodextrins can be considered as empty capsules of molecular size that form complexes with guest molecules resulting in an encapsulation process on the molecular scale. Molecular encapsulation by cyclodextrins is unique compared to microencapsulation because an effective protection is available for every single guest molecule present in the system (*5*).

Cyclodextrins (CDs) are known for their ability to include hydrophobic molecules or parts of molecules inside their hydrophobic cavity. The most common CDs are alpha-, beta-, and gamma-, which contain six, seven, and eight glucose units, respectively. The CD molecule is described as a conical cylinder or shallow truncated cone (Fig. 2). Complexation of guest compounds with CDs provides certain benefits. Some of these benefits include: alteration of guest solubility, stabilization against the effects of light, heat, and oxidation, masking of unwanted physiological effects, and reduction of volatility (*6*). Cyclodextrins can be

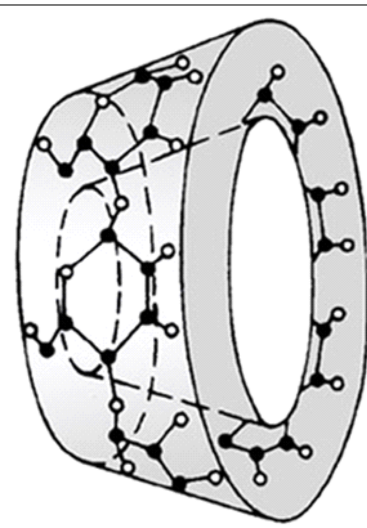

Figure 2: The truncated cone shape of the β-cyclodextrin molecule that enables molecular encapsulation of active guest compounds.

incorporated into food packaging polymer films with various additives included within the CD cavity.

Polylactic acid (PLA) is a biodegradable polymer commonly used in the biomedical industry for controlled release preparations, which is finding increasing utilization in plastics applications, such as packaging and films. PLA is produced by the fermentation of glucose into lactic acid, which is then polymerized to make PLA. Poly(lactide-co-glycolide) is the biodegradable copolymer of PLA and polyglycolide (PGA). Biodegradable polymers have been suggested as controlled release systems for active compounds from the inner liner or coating of food packaging. Degradation of PLA and PGA begins by diffusion of water into the polymer, followed by random hydrolysis, material fragmentation, and finally a more extensive hydrolysis (*7*). The polymer degradation by-products, such as lactic acid, are common food ingredients, and the only expected affect would be an increase in the acidity of the food or beverage.

Antimicrobial Release Packaging

The overall incidence of foodborne illness remains high despite important declines in the prevalence of several foodborne diseases. Microbial contamination of most foods occurs primarily at the surface due to post-processing handling. Therefore, incorporation of antimicrobial substances within or coated onto the packaging materials may be more efficient if inhibitory concentrations are maintained where they are necessary by slow release of the agents onto the food surface. Antimicrobial packaging materials are required to extend the lag period and reduce the growth rate of microorganisms to prolong shelf life and maintain food safety. Food manufacturers may be able to maintain the minimum inhibitory concentration of an antimicrobial to prevent growth of pathogenic and spoilage microorganisms by using controlled release packaging. The major potential product applications for antimicrobial films include meat, fish, poultry, bread, cheese, fruits, vegetables, and beverages (*8*).

Chemical preservatives can be employed in antimicrobial releasing film systems including organic acids and their salts (sorbates, benzoates, and propionates), parabens, sulfites, nitrites, chlorides, phosphates, epoxides, alcohols, ozone, hydrogen peroxide, diethyl pyrocarbonate, antiobiotics, and bacteriocins (*9*). Typical antimicrobial multi-layer active films have a structure composed of four layers, including the outer layer, barrier layer, matrix layer, and control layer (Fig. 3) (*9*). The matrix layer contains the imbedded antimicrobial substance and its release from this layer to the food surface is controlled by the control layer adjacent to the matrix layer.

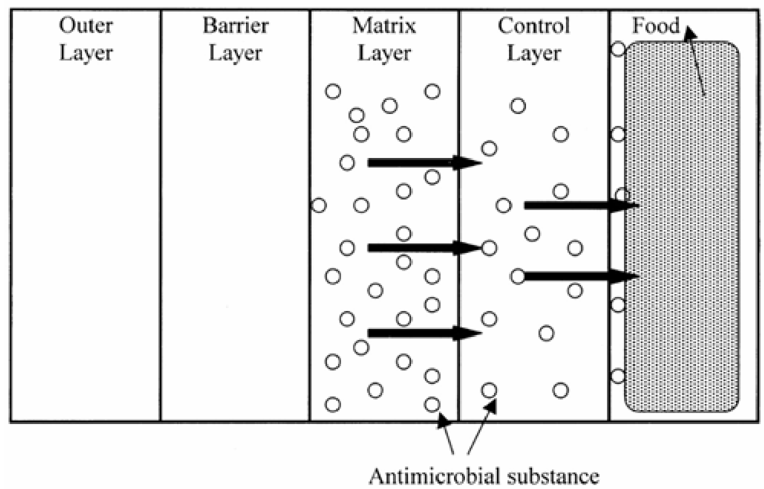

Figure 3: Structure of a common antimicrobial multi-layer active film (*9*).

Another design concept involves antimicrobial agents incorporated into a package that later are released into the headspace of the package, in contrast to direct diffusion into the food for control of target microorganisms. Direct contact between the package and the food surface is required for nonvolatile antimicrobial compounds, such as sorbates, benzoates, propionates, and parabens.

Antimicrobial coatings may be developed by incorporating nisin, lactoferrin, sodium diacetate, sorbic acid, and potassium sorbate into a coating material (*10*). Films containing nisin, sorbic acid, and potassium sorbate have the ability to inhibit the food-borne pathogen *Listeria monocytogenes*. Nisin has also been shown to inhibit microorganisms, including

Listeria, when coated onto methyl cellulose or hydroxypropyl methyl cellulose on LDPE package film (*11*). Nisin is a polypeptide produced by microbiological fermentation that remains a prohibitively expensive active ingredient (*11*).

Lysozyme is a naturally occurring antimicrobial that has been incorporated into both monolayer cross-linked polyvinyl alcohol (PVOH) film and a multilayer structure of cross-linked PVOH (*12*). The release rate of lysozyme can be controlled through the degree of cross-linking of the polymer matrix with no loss of antimicrobial effectiveness (*13*). Enzymes with antimicrobial activity, such as lysozyme, have low heat tolerance which restricts the application of these compounds to their sorption into the polymer surface, or coating or casting from solutions.

Antimycotics and antimicrobials have been added to food packaging films to delay outgrowth of mold. Potassium sorbate release from low-density polyethylene (LDPE) and high-density polyethylene (HDPE) films has been studied in food systems, including American processed and mozzarella cheeses (*14*). Sorbate-release from HDPE packaging has enabled processed American cheese to be free of microbial contamination for 5 months at room temperature storage. Antimycotic:CD complexes have been incorporated into films used to package hard cheeses and significantly extend the shelf life by inhibiting mold growth on the cheese surface (*5*).

A silver-substituted zeolite film is commercially available in Japan that slowly releases silver ions from the polymer film to the food (*9*). The silver inhibits reproduction, interrupts metabolism, and disrupts cell wall functions, thereby, inhibiting a broad range of bacteria, yeasts, and molds. Silver-zeolite films are produced in the form of thin layers, which are typically laminated on the inside of a food package, due to their high cost. In 2005, the European Food Safety Authority approved AgION Technologies' innovative silver-zeolite antimicrobial technology for the European food industry market (*15*). Antimicrobials released from food packaging can play an important role in reducing the risk of pathogen contamination, in addition to extending product shelf life.

Antioxidant Release Packaging

Oxidation of lipids in food systems is a major limiting factor in product shelf life. Antioxidants significantly extend the shelf life of foods susceptible to lipid oxidation such as vegetable oils, animal fats, nuts, processed meats and snack products. The need for antioxidants is not limited to high-lipid foods, but also includes products such as cereals and crackers, which contain only 2-5% lipids. The direct addition of antioxidants to food in one large initial dose is limited by the potential for rapid depletion of the antioxidants, in addition to very high initial concentrations. Antioxidant compounds may undergo loss of activity and even act as prooxidants at high concentrations (*16-18*). Therefore, a need exists in the food industry to develop polymer packaging which can deliver natural antioxidants in a controlled manner.

The cereal industry currently uses the antioxidants BHA or BHT by incorporating these additives into a wax liner (*19*). The antioxidants then are released from the liner by diffusion into the cereal flakes during storage of the product to protect the food from lipid oxidation. Approximately 80% of the added BHT diffuses out of the HDPE pouches and is lost to the environment, while the remaining 20% is transferred into the cereal by sorption and provides a degree of protection equivalent to when the antioxidant is incorporated directly into the food (*20*). The release of the antioxidant BHA from HDPE was found to follow a first-order release controlled by volatilization rather than diffusion (*21*).

Today's consumers show increasing concern with the use of synthetic chemicals and believe natural antioxidants are safer and of greater nutritional benefit. Packaging researchers have incorporated α-tocopherol into a heat seal layer of Surlyn/EVA® coextruded with an HDPE layer and determined a first-order release rate of α-tocopherol from the packaging film into a model product of linoleic acid (*22*). The natural antioxidant, α-tocopherol, would be expected to have a slower release rate from packaging into a food due to the larger molecular weight of α-tocopherol relative to BHT. The packaging film of the model linoleic acid product retained 36% of α-tocopherol and only 3% of BHT after 18 weeks of room temperature storage.

Modeling the loss of an antioxidant from a polymer at a specified temperature requires knowledge of its solubility in the polymer, its diffusion coefficient in the polymer, and the volatility of the pure additive (*4*). The antioxidant solubility in polymer films is described by the solubility coefficient, which is determined by the polymer morphology and the antioxidant's chemical properties (*23*). Researchers have also found important indications that the presence of a food product, such as oatmeal, within the package affects the loss of α-tocopherol from LDPE films compared to an empty package (*24*). Different characteristics of the food, such as contact phase properties, fat, alcohol, and acid content, influence the release of α-tocopherol in LDPE films (*25*).

α-Tocopherol release from polypropylene (PP) and LDPE films was different when the film was in contact with foods, such as mayonnaise, low-fat milk, and water, which may be attributed to the different glass transition temperatures of the polymers (*25*). The structure of PP would be more ordered and rigid relative to the LDPE structure, which is believed to have reduced the ability of α-tocopherol to be released from the polymer.

Researchers from Rutgers University and Clemson University have collaborated to develop a smart blending process that forms packaging films, which control the release of active compounds, such as tocopherols (*26*). Smart blending is a process based on chaotic advection, which uses two rods to blend polymers and creates unique film morphologies by controlling the number of rod rotations. The researchers suggest that smart blending may be used to alter morphologies and produce polymer blend films with selected release rates.

Researchers at Virginia Tech have studied poly(lactide-co-glycolide) films loaded with BHT, BHA, and α-tocopherol and their subsequent release into dry milk products (*7*). The use of biodegradable polymers as unique active packaging options for controlled delivery of antioxidants has the potential to limit lipid oxidation. Under Cargill ownership, NatureWorks® LLC (www.natureworksllc.com), is currently producing commercial PLA packaging for products, including water, organic salads, and fresh-cut produce, primarily due to the beneficial environmental properties of the polymer (*27*).

A 2003 review in *Food Science and Biotechnology* (*23*) reports that "sufficient knowledge to characterize the chemical and biological response of antioxidant-impregnated food packaging is lacking. Further research on antioxidant-impregnated food packaging will provide a better understanding of the inhibition of lipid oxidation and will allow the shelf life of food products to be prolonged."

Flavor and Aroma Release Packaging

The incorporation of pleasing food aromas into the polymer material can be used to improve food aroma to attract consumers when the package is opened, and also to balance any detrimental effects of aroma loss. Plastics are in an equilibrium between aroma absorption and release that depends on several factors regarding both plastic and aroma characteristics, which must be carefully examined during active package design. Commonly used polymers for the release of aromas are PE, PP, ethylene vinyl acetate (EVA), ionomer, nylon, polyester, and polyvinyl chloride. The manufacturing methods used for the preparation of these active polymers are injection molding, film blowing and casting, sheet extrusion, foaming, hot-melt adhesives, and hot-melt coating.

Several types of flavoring and aroma emitting plastics exist in current markets. The Japan Liquid Crystal Corporation commercializes a CD that contains a volatile guest compound and both are molded with a permeable polymer (*8*). The use of CDs to encapsulate the volatile compounds facilitates the manufacturing of aroma emitters, because otherwise most of the added aroma would be released during the high temperatures experienced in package formation. The incorporation of CDs into polymer matrices can modify the additive release mechanisms (*28*). Researchers at Clemson University have also incorporated flavor volatiles (*d*-limonene, alpha-pinene, and 2-methoxy-3-methylpyrazine) included within beta-CD into flexible packaging materials for controlled release (*29*). LDPE films containing these encapsulated flavor compounds have been successfully produced and the release rate has been found to be suitable for extended shelf life food packaging.

ScentSational Technologies' (www.scentsationaltechnologies.com) CompelAroma®, Encapsulated Aroma Release™ technology is a multifunctional process, enticing consumers with aroma brand association outside the package, releasing flavors and fragrances inside, and improving taste by releasing aroma on the outside (Fig. 4) (*30*). NutriSystem, Inc. has introduced a powerful new weight loss aid, Aquaescents™, by employing CompelAroma® technology (*31*). Aquaescents™ refillable water bottle and fruit caps, flavored with natural lemon, peach, or berry, may increase consumer enjoyment of water without the addition of calories, sweeteners, or preservatives.

Encapsulated, food grade flavors can be added directly into packaging materials at the time of manufacturing. During processing, the flavors and associated aromas result in the packaging becoming aromatized. ScentSational technology can be applied to all existing manufacturing processes and does not require new tooling to implement this olfactory packaging technology.

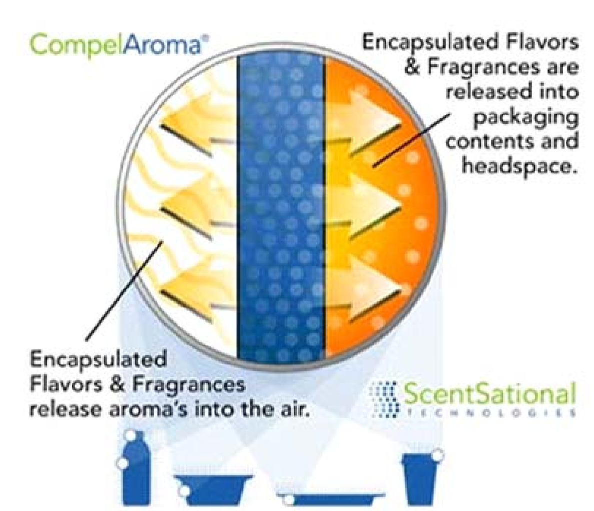

Figure 4: ScentSational Technologies CompelAroma® enhances flavor inside a package by adding flavor inside and aroma outside (*30*).

The aromatic packaging can be manufactured to control aroma release in order to differentiate between specific products and stimulate brand awareness. The polymer may release aroma on the store shelf to accent a product, inside a package to add aroma when a product is opened or cooked, or released into a product gradually to compensate for gradual flavor loss during its shelf life. The product can be protected from processing induced dilution and/or its shelf life extended by the gradual release of encapsulated flavors over time.

Kraft Foods holds a 2002 patent for a system which can retain and release volatile flavor oils and other active compounds (*32*). The technology involves a controlled, prolonged release of a volatile flavor after the initial opening of the package and upon successive re-openings. The system is compatible with commercial methods for filling and sealing containers holding a product, such as instant coffee. New concentrations of flavor are created within the package head space and are available to provide aroma impact upon subsequent opening.

Fragrance additives, either synthetic or natural essential oils, can be used to impart an aroma to a product or to mask undesirable plastic odors. During processing, these compounds are added to thermoplastic resins in pellet or powder form. The fragrance is entrapped within very porous polymers or a thermoset resin matrix when it is added to the melt polymer (*8*). The rate of fragrance release from the package is dependent upon the thickness of the plastic, its surface area-to-volume ratio, the composition, and the amount of active compound included in the plastic.

A Promising Future? It's under Control

The worldwide market for active, controlled, and intelligent packaging of foods and beverages is expected to grow to an estimated $134 billion by 2008 (*1*). As technological packaging innovations progress and material costs decrease, food and beverage manufacturers will begin to implement controlled release technology into their packaging. For example, cyclodextrins have experienced a dramatic drop in production cost in the past thirty years and have reached an acceptable level for even the most raw material price sensitive industries, including the food industry. Advances in controlled release packaging technology allow food and beverage manufacturers to improve flavor and aroma delivery, delay the onset of lipid oxidation, and inhibit pathogenic and spoilage microorganisms in their products. While controlled release active packaging is not currently in wide commercial use, it is poised to improve the safety and enrich the quality of the global food supply.

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