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Review

Developments in the active packaging of foods

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Active packaging is one of the innovative food packaging concepts that has been introduced as a response to the continuous changes in current consumer demands and market trends. Major active packaging techniques are concerned with substances that absorb oxygen, ethylene, moisture, carbon dioxide, flavours/odours and those which release carbon dioxide, antimicrobial agents, antioxidants and flavours. The main objectives of this article are to: (1) provide a literature review about the different types of active packaging concepts with respect to mechanism of action, effectiveness and the effects on foods, (2) provide a state of the art about the experimental development and commercialization of active packaging concepts, (3) provide a scope of applications and (4) discuss the obstacles to be overcome in order to make extensive commercial application of active packaging in Europe feasible. © 1999 Elsevier Science Ltd. All rights reserved.

In recent years, many new food packaging concepts have been introduced. Consumers are increasingly demanding mildly preserved convenience foods that have better fresh-like qualities. In addition, changes in retail and distribution practices such as centralization of activities, new trends (e.g. internet-shopping) and internationalization of markets, resulting in increased distribution distances and longer storage times of a set of different products with different temperature requirements, are putting huge demands on the food packaging industry. Traditional packaging concepts are limited in their ability to prolong the shelf-life of food products. Active packaging is an innovative concept that can be defined as a type of packaging that changes the condition of the packaging to extend shelf-life or improve safety or sensory properties while maintaining the quality of the food. This definition of active packaging was chosen for the European FAIR-project CT 98-4170 (see Box 1). Most important active packaging concepts such as O_2 and ethylene scavenging, CO_2-scavengers and -emitters, moisture regulators, antimicrobial packaging concepts, antioxidant release, release or adsorption of flavours and odours are described in detail in this review.

O_2-scavenging technology

In many cases, food deterioration is caused by oxidation of food constituents or spoilage by moulds in the presence of O_2. Although O_2-sensitive foods can be packaged appropriately using modified atmosphere packaging (MAP) or vacuum packaging, these technologies do not always remove O_2 completely. Moreover, the O_2 that permeates through the packaging film cannot be removed by these techniques. By use of an O_2-scavenger, which absorbs the residual O_2 after packaging, quality changes of O_2-sensitive foods can often be minimized. In general, existing O_2-scavenging technologies utilize one or more of the following concepts: iron powder oxidation, ascorbic acid oxidation, photosensitive dye oxidation, enzymatic oxidation (e.g. glucose oxidase and alcohol oxidase), unsaturated fatty acids (e.g. oleic acid or linolenic acid), immobilized yeast on a solid material [1].

The majority of currently commercially available O_2-scavengers are based on the principle of iron oxidation [2]:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$1/2\,O_2 + H_2O + 2e^- \rightarrow 2\,OH^-$$

$$Fe^{2+} + 2\,OH^- \rightarrow Fe(OH)_2$$

$$Fe(OH)_2 + 1/4\,O_2 + 1/2\,H_2O \rightarrow Fe(OH)_3$$

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Box 1. The European FAIR-project CT 98-4170

The European FAIR-project CT 98-4170, which started in January 1999 is being jointly carried out in the framework of the EU FAIR programme by 9 research organisations and 3 industrial companies (Table 1). In various countries active packaging is already successfully applied. In Europe, the development and application of these concepts is limited because of legislative restrictions, fear of consumer resistance and a lack of knowledge about the efficacy of such concepts and their economic and environmental impact. To enable the application of active and intelligent concepts throughout Europe and to establish and implement these concepts in the current relevant regulations for food packaging in Europe, the above European project is under way.

Ageless® (Mitsubishi Gas Chemical Co., Japan) is the most common O_2-scavenging system based on iron oxidation [3]. The sachets are designed to reduce O_2-levels to less than 0.01%. A rule of thumb is that 1g of iron will react with 300 cc of O_2 [4]. When the initial O_2-concentration at the moment of packaging and the O_2-permeability of the packaging material is known, an absorber can be chosen with a higher capacity than the needed calculated capacity. In that way, total absence of O_2 is guaranteed during storage life of the product. However, a potential risk could be accidental ingestion of a large amount of iron, in spite of the label 'Do not Eat' [4]. Other iron-based O_2-absorbent sachets are the ATCO® O_2-absorber (Standa Industrie, France), the Freshilizer® Series (Toppan Printing Co., Japan), Vitalon® (Toagosei Chem. Industry Co., Japan), Sanso-cut (Finetec Co., Japan) and Freshpax® (Multisorb Technologies Inc., USA). The sachets can be found in packages of many foods including fresh and pre-cooked pasta, catering, meat products (e.g. smoked ham and salami), bakery products (e.g. bread, pizza crust, pastries, cookies, cakes), cheese, coffee, nuts and potato chips [1].

Some O_2-scavengers use an enzyme reactor surface that would react with some substrate to scavenge incoming O_2. Glucose oxidase, a promising O_2-scavenging enzyme is an oxidoreductase that transfers two hydrogens from the –CHOH group of glucose to O_2 with the formation of glucono–delta–lactone and H_2O_2. The lactone then spontaneously reacts with water to form gluconic acid [5]. The reaction is:

$$2G + 2O_2 + 2H_2O \rightarrow 2GO + 2H_2O_2$$

where G is the substrate.

Since H_2O_2 is an objectionable end product, catalase is introduced to break down the peroxide [6]:

$$2H_2O_2 + \text{catalase} \rightarrow 2H_2O + O_2$$

Coupled enzyme systems are very sensitive to changes in pH, a_w, salt content, temperature and various other factors. Additionally, they require the addition of water and, therefore, cannot be effectively used for low-water foodstuffs [7]. One application for glucose oxidase is the elimination of O_2 from bottled beer or wine. The enzymes can either be part of the packaging structure or put in an independent sachet. Both polypropylene (PP) and polyethylene (PE) are good substrates for immobilising enzymes [5]. An unknown factor is the stability over time of the enzyme in the film. Glucose oxidase, bound to a plastic surface (Eupergit C), underwent a 50% drop in activity in 2–3 weeks followed by little loss over the next 4 weeks [8]. Labuza and Breene [5] suggested that a film with bound enzyme which would effectively scavenge O_2 would be in an acceptable price range. A 1998 patent [9] describes a polyolefin structure containing glucose oxidase. A commercially available O_2-removing sachet based on reactions catalysed by food-grade enzymes is the Bioka O_2-absorber (Bioka, Finland). Besides glucose oxidase, other enzymes have potential for O_2-scavenging, including ethanol oxidase which oxidises ethanol to acetaldehyde [5].

Table 1. Participants of the FAIR-project 'Actipak' (CT 98-4170)

Participant	Country
TNO Nutrition and Food Research Institute (coordinator)	The Netherlands
VTT Biotechnology and Food Research	Finland
Universidade de Santiago de Compostela	Spain
ADRIAC (Association pour le Développement de la Recherche dans les Industries agro-alimentaires et de Conditionnement)	France
UNIVERSITEIT GENT (Dapartment of Food Technology and Nutrition)	Belgium
DISTAM (Dipartemento di Scienze e Technologie Alimentari e Microbiologche Sezione Industrie Agrarie)	Italy
PIRA International	United Kingdom
TMI Europe SA	France
Inspectorate for Health Protection, Commodities and Veterinary Public Health	The Netherlands
EASTMAN CHEMICAL BV	The Netherlands
NESTLÉ LTD	Switzerland
DANONE BISCUIT BRANCH	France

An alternative to sachets is the incorporation of the O_2-scavenger into the packaging structure itself. Low molecular weight ingredients may be dissolved or dispersed in a plastic or the plastic may be made from a polymeric scavenger. An example is Oxyguard (Toyo Seikan Kaisha, Japan), an iron-based absorber which can be incorporated into a laminate. The main alternative to dispersal of iron in plastics is organic reactions of plastics themselves. Oxbar™ is a system developed by Carnaud-Metal Box (UK) which involves cobalt-catalysed oxidation of a nylon polymer blended especially in PET-bottles for plastic packaging of wine, beer, sauces and other beverages [10]. Amoco Chemicals (USA) marketed Amosorb®, a polymer-based absorber which can be incorporated in various packaging structures including the sidewall or lid of rigid containers, flexible films, and closure liners [11]. It should be noted that the speed and capacity of O_2-scavenging films are considerably lower compared with iron-based O_2-scavenger sachets [12]. Other recent developments include inserts in the form of flat packets, cards or sheets, as well as O_2-scavenging adhesive labels, like Freshmax® (Multisorb technologies, USA) and the ATCO® labels (Standa Industrie, France).

Ascorbic acid is another O_2-scavenging component which can be used. The basic reaction of Darex O_2-scavenging technology, designed to be incorporated into barrier packaging such as crown caps, plastic or metal closures, is ascorbate oxidizing to dehydroascorbic acid and sulphite to sulphate. The major use is in crown caps to protect beer from oxidation of flavours [13]. The Pillsbury Co. holds a 1994 patent that also utilizes ascorbic acid as reducing agent. A transition metal, preferably copper, is used to catalyse the oxidation reaction. The product, referred to as Oxysorb can be included inside a pouch or may be incorporated into the packaging [7].

Another O_2-scavenging technique involves sealing of a small coil of an ethyl cellulose film containing a dissolved photosensitive dye and a singlet O_2-acceptor in the headspace of a transparent package. Due to illumination of the film with light of the appropriate wavelength, excited dye molecules sensitize O_2-molecules, which have diffused into the polymer, to the singlet state. These singlet O_2-molecules react with acceptor molecules and are thereby consumed. The photochemical process involved can be presented as follows [14]:

$$\text{photon} + \text{dye} \rightarrow \text{dye}^*$$

$$\text{dye}^* + O_2 \rightarrow \text{dye} + O_2^*$$

$$O_2^* + \text{acceptor} \rightarrow \text{acceptor oxide}$$

$$O_2^* \rightarrow O_2$$

Examples of light-activated scavengers, incorporated in the packaging film, are $\text{Zero}_2^{\text{TM}}$ developed by CSIRO and marketed by Southcorp Packaging (Australia) [12] and OS1000 developed by Cryovac Sealed Air.

The use of an O_2-scavenger can influence different food properties. First of all, O_2-scavenging is effective in preventing growth of moulds and aerobic bacteria. Prevention of mould growth is important for dairy products such as cheese and bakery products. O_2-levels of 0.1% or lower are required to prevent the growth of many moulds [10]. In gas packaged ($40\% N_2/60\% CO_2$) crusty rolls with Ageless®, the headspace O_2-concentration never increased beyond 0.05% and the rolls remained mould-free even after 60 days. A similar mould-free shelf-life was obtained in air or N_2 packaged crusty rolls, both containing Ageless® [15]. The mould-free shelf-life of white bread packaged in PP could be extended from 5 to 45 days at room temperature by introducing an Ageless® sachet. Pizza crust, which becomes mouldy after 2–3 days at 30°C could be kept mould-free for more than 14 days using an appropriate O_2-absorber [3]. However, it is well known that an O_2-free atmosphere can favour the growth of anaerobic pathogens such as *Clostridium botulinum* [4]. O_2-scavengers can also be used to control insect infestation in cereal products during storage. This eliminates the need for chemical means of control [3]. O_2-absorbers can also prevent oxidative damage of a wide range of food constituents such as (1) oils and fats to prevent rancidity, (2) both plant and muscle pigments and flavours to prevent discoloration (e.g. meat) and loss of taste and (3) nutritive elements e.g. vitamins to prevent nutrient loss. Several studies on prevention of oxidative damage by use of O_2-absorbers have been published [16–18].

O_2-scavengers can be used alone or in combination with MAP. Their use alone eliminates the need for MAP machinery and can increase packaging speeds. However, it is usually more common in commercial applications to remove most of the atmospheric O_2 by MAP and then use a relatively small and inexpensive scavenger to remove the residual O_2 within the food package [12]. For an O_2-absorber to be effective, the packaging material needs to have an O_2-barrier of intermediate performance (20 ml/m^2.d.atm), otherwise the scavenger will rapidly become saturated and lose its ability to trap O_2. These cheaper medium-barrier films in combination with an O_2-scavenger could then substitute for the more expensive high-barrier films [2, 10]. More information on the technical aspects of the different types of O_2-scavengers can be obtained from other reviews [5, 10, 19, 20].

Ethylene scavengers

Ethylene (C_2H_4) acts as a plant hormone that has different physiological effects on fresh fruit and vegetables. It accelerates respiration, leading to maturity and senescence, and also softening and ripening of many kinds of fruit. Furthermore, ethylene accumulation can cause yellowing of green vegetables and may be responsible for a number of specific postharvest disorders in fresh fruits and vegetables. Although some effects of ethylene are positive such as degreening of citrus fruit, ethylene is often detrimental to the quality and shelf-life of fruits and vegetables. To prolong shelf-life and maintain an acceptable visual and organoleptic quality, accumulation of ethylene in the packaging should be avoided. A lot of C_2H_4-adsorbing substances are described. Most of these are supplied as sachets or integrated into films. Many of the claims for C_2H_4-adsorbing capacity have been poorly documented; thus the efficacy of the materials is difficult to substantiate [21].

Many suppliers offer C_2H_4-scavengers based on potassium permanganate ($KMnO_4$), which oxidizes ethylene to acetate and ethanol. In this process, colour changes from purple to brown indicating the remaining C_2H_4-scavenging capacity. Products based on $KMnO_4$ cannot be integrated into food-contact materials, but are only supplied in the form of sachets because $KMnO_4$ is toxic and has a purple colour. Typically, such products contain 4 to 6% $KMnO_4$ on an inert substrate with a large surface area such as perlite, alumina, silica gel, vermiculite, activated carbon or celite [21]. Rengo Co. (Japan) developed 'Green Pack', a sachet of $KMnO_4$ embedded in silica. The silica adsorbs the ethylene and the permanganate oxidizes it to acetate and ethanol [5]. The technology of C_2H_4-scrubbing has also been transferred to household refrigerators. Systems containing a zeolite coated with $KMnO_4$ are now available and are meant to be used in consumer refrigerators. Two examples are Mrs Green's Extra Life cartridges from Dennis Green (USA) and Fridge Friend™ sachets from Ethylene Control (US patent 5278112).

Another type of C_2H_4-scavenging concept is based on the adsorption and subsequent breakdown of ethylene on activated carbon. Charcoal containing PdCl as a metal catalyst was effective at 20°C in preventing the accumulation of ethylene, in reducing the rate of softening in minimal processed kiwifruits and bananas and in reducing chlorophyll loss in spinach leaves but not in broccoli [22].

Other C_2H_4-adsorbing technologies are based on inclusion of finely dispersed minerals such as zeolites, clays and Japanese oya into packaging films [21]. Most of these packaging films, however, are opaque and not capable of adsorbing C_2H_4 sufficiently [23]. Although the incorporated minerals may adsorb ethylene, they also alter the permeability of the films: C_2H_4 and CO_2 will diffuse much more rapidly and O_2 will enter more readily than through pure PE. These effects can improve shelf-life and reduce headspace C_2H_4-concentrations independently of any C_2H_4-adsorption. In fact, any powdered material can be used to reach such effects. Furthermore, the adsorbing capacity is often lost when incorporating these minerals into a polymer matrix [21]. Commercially available examples of these mineral containing materials are the Orega plastic film (Cho Yang Heung San Co., Korea) [24], Evert-Fresh (Evert-Fresh Co., USA), Peakfresh™ (Peakfresh Products, Australia), BO film (Odja Shoji Co., Japan) and Profresh™ (Europe). Peakfresh™ is a mineral impregnated film that is FDA approved and complies with current EU directives.

C_2H_4-scavengers are not yet very successful, probably because of insufficient adsorbing capacity. A large proportion of the fresh fruits and vegetables harvested each year are lost due to fungal contamination and physiological damage [25]. The C_2H_4-adsorbing packaging concepts could possibly contribute to an increase in the export of fresh produce.

CO_2-scavengers and emitters

CO_2 is formed in some foods due to deterioration and respiration reactions. The produced CO_2 has to be removed from the package to avoid food deterioration and/or package destruction [1]. CO_2-absorbers might therefore be useful. Coffee, when roasted, can contain up to 15 atm dissolved CO_2 due to the Strecker degradation reaction between sugars and amines [5]. The O_2- and CO_2-scavenging sachet FreshLock® or Ageless® E is used in coffee to delay oxidative flavour changes and absorb the occluded CO_2 which if not removed would cause the package to burst [19]. The active compound $Ca(OH)_2$ of FreshLock® reacts at sufficiently high humidity with the CO_2 to produce $CaCO_3$ [26]. Multiform Desiccants patented (US 5322701) a CO_2-absorbent sachet including a porous envelope containing CaO and a hydrating agent such as silica gel on which water is adsorbed. The following reactions occur [27]:

$$CaO + H_2O \rightarrow Ca(OH)_2$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

In some cases, however, high CO_2-levels (10–80%) are desirable for foods such as meat and poultry because these high levels inhibit surface microbial growth and thereby extend shelf-life [28]. Fresh meat, poultry, fish and cheese can benefit from packaging in a high CO_2-atmosphere [1]. Removal of O_2 from a package by use of O_2-absorbers creates a partial vacuum which may result in a collapse of flexible packagings. Also, when a package is flushed with a mixture of gases including CO_2, the CO_2 dissolves partly in the product and creates a partial vacuum. In such cases, the simultaneous release of CO_2 from inserted sachets which consume O_2 is desirable. Such systems are based on either ferrous carbonate or a mixture of ascorbic acid and sodium bicarbonate [10]. The O_2-absorbers/CO_2-

generators are mainly used in products where package volume and package appearance are critical e.g. peanuts or potato crisps [19]. The main CO_2-generators/absorbers are listed in Table 2.

Moisture regulators

Foods susceptible to moisture damage need to be packaged in a high humidity barrier material. A certain amount of moisture, however, can be trapped in the packaging or develop during distribution. If not removed, this moisture will be absorbed by the product or condensate will be formed, causing microbial spoilage and/or low consumer appeal. Excessively high levels of water causes softening of dry crispy products such as biscuits and crackers, caking of milk powder and instant coffee or moistening of hygroscopic products such as sweets and candies. On the other hand, excessive water evaporation through the packaging material might result in desiccation of the packed foodstuff or it may favour lipid oxidation. To prevent this and establish the desired relative humidity in the package headspace, food manufacturers can use a film with the appropriate water vapour permeability or use a desiccating film or a moisture controlling sachet or pad. Desiccants are successfully being used for a wide range of foods, such as cheeses, meats, chips, nuts, popcorn, candies, gums and spices [29]. The main purpose of moisture control is to lower a_w, thereby reducing the growth of moulds, yeast and spoilage bacteria on foods with high a_w, such as ready-to-eat meals. The shelf-life of packaged tomatoes at 20°C was extended from 5 to 15–17 days with a pouch containing NaCl, mainly by retardation of surface mould growth [30]. Another application is in the removal of melting water from frozen fish, meat or other frozen foods and blood or tissue fluid from meat to make the package more attractive to the consumer. A third reason for moisture control is to prevent condensation when fresh horticultural produce respires.

Drip-absorbent sheets such as Thermarite® (Australia), Toppan™ (Japan) or Peaksorb® (Peakfresh Products, Australia) for liquid water control in high a_w, foods such as meat, fish, poultry, fruits and vegetables, basically consist of a superabsorbent polymer in between two layers. Large sheets are also used for absorption of melted ice in packages of seafood during air transportation. The preferred polymers for absorbing water are polyacrylate salts and graft copolymers of starch [10]. Another approach to control excess moisture is to intercept the moisture in the vapour phase. This is done by placing humectants between two layers of a plastic film which is highly permeable to water vapour or by using a moisture absorbent sachet [13]. Pichit™ (Showa Denko, Japan) is a film composed of two sheets of polyvinylalcohol between which is a layer of the humectant propylene glycol [5]. Pichit™ is marketed for home use for wrapping meat or fish to reduce the a_w proximate to the food. There is, however, a lack of experimental verification of the significance of this effect [10]. For dried food applications, desiccants such as silica gel, molecular sieves, CaO and natural clays (e.g. montmorillonite) are often contained within Tyvek™ sachets [12]. Examples where these compounds are used include the sachets MINIPAX® and STRIPPAX® and the moisture absorbing label DesiMax® (United Desiccants, USA) and the sachets Desipak®, Sorb-it®, Tri-sorb® and 2-in-1™ (Multisorb technologies, USA).

Antimicrobial packaging concepts

To control undesirable micro-organisms on foods, antimicrobial substances can be incorporated in or coated onto food packaging materials [5]. The principle action of antimicrobial films is based on the release of antimicrobial entities, some of which could pose a safety risk to consumers if the release is not tightly controlled by some mechanisms within the packaging material [31]. The major potential food applications for antimicrobial films include meat, fish, poultry, bread, cheese, fruits and vegetables [5].

In Japan Ag-substituted zeolite is the most common antimicrobial agent incorporated into plastics. Ag-ions which inhibit a range of metabolic enzymes, have strong antimicrobial activity. The unique feature of Ag–zeolites is their broad antimicrobial spectrum. As Ag–zeolite is expensive, it is laminated as a thin layer (3–6 μm) containing Ag–zeolite. The normal incorporation level varies from 1 to 3% [32]. Only a few descriptions of the effectiveness of this material have appeared and the regulatory status on the addition of Ag to foods has not been clarified in the US or Europe [33].

Table 2. Commercial CO_2-scavengers or -generators with possible O_2-scavenging capacity [19]

Trade name	Company	Substances and actions
Freshlock or Ageless E	Mitsubishi Gas Chemical (Japan)	CO_2-scavenging ($Ca(OH_2)$/O_2-scavenging (iron powder)
Ageless G	Mitsubishi Gas Chemical (Japan)	CO_2-generating (ascorbic acid)/O_2-scavenging
Freshilizer CV	Toppan Printing Co (Japan)	CO_2– and O_2-scavenging (non-ferrous metal)
Freshilizer C and CW	Toppan Printing Co (Japan)	CO_2-generating/O_2-scavenging
Freshpax M	Multisorb technologies (USA)	CO_2-generating/O_2-scavenging
Verifrais	S.A.R.L. Codimer (France)	CO_2-generating
Vitalon G	Toagosei Chem. Ind. Co. (Japan)	CO_2-generating/O_2-scavenging

Several other compounds have been proposed and/or tested for antimicrobial activity in food packaging including organic acids such as sorbate, propionate and benzoate [34] or their respective acid anhydrides [35], bacteriocins e.g. nisin and pediocin [36], enzymes such as lysozyme [37], metals [32] and fungicides such as benomyl [38] and imazalil [39]. At the IFT Annual Meeting (1998) a film was presented which contains a natural antimicrobial compound derived from grapefruit seed [40]. A rarely mentioned possibility for manufacturing antimicrobial films is to incorporate radiation-emitting materials into films. However, little direct evidence for the efficiency of this technology has been published in the scientific literature [33]. Many of the incorporated antimicrobials are not yet permitted for food use [33]. The choice of the antimicrobial is often limited by the incompatibility of the component with the packaging material or by the heat lability of the component during extrusion [34, 41]. One per cent potassium sorbate in a LDPE film inhibited the growth of yeast on agar plates. The LDPE resin and potassium sorbate powder can be mixed, extruded and pelletized to produce a masterbatch. These pellets can be added to LDPE resin. The masterbatch should be produced at low temperature to prevent heat decomposition of the potassium sorbate [34]. Another study [41], however, found the relatively polar sorbate, benzoate and propionate to be incompatible with the apolar LDPE. Acid anhydrides were thought to be more compatible than free acids and their salts because of their lower polarity. Two commercial biocidal films are currently marketed. One is composed of a chlorinated phenoxy compound and the other consists of chlorine dioxide. A commercial antifungal coating containing chitosan is also sold as a shelf-life extender for fresh fruit [37]. Specific trade names or effectiveness of these commercial products were not mentioned. An interesting commercial development is the recent marketing of food-contact approved Microban® (Microban Products Co., USA) kitchen products such as chopping boards, dish cloths,... which contain triclosan, an antimicrobial aromatic chloro-organic compound, which is also used in soaps, shampoos, etc. [16]. In EU countries, however, the use of triclosan for food-contact applications is not allowed and the SCF (Scientific Committee for Food) has currently major objections against the use of triclosan in food contact materials.

CSIRO (Australia) is developing systems which gradually release SO_2 to control mould growth in some fruits. However, excessive release of SO_2 from pads of sodium metabisulphite incorporated microporous material has been shown to cause partial bleaching problems in grapes. The accumulation or absorption of the excess SO_2 by foods could cause toxicological problems. Knowledge about the diffusion rate of SO_2 to the food is essential to address toxicological issues and ensure safety in SO_2-releasing active packaging systems [31].

In contrast to conventional antimicrobial films, some functional groups that have antimicrobial activity have been immobilized on the surface of polymer films [31]. Recently, the use of 193 nm UV irradiation was investigated using an UV excimer laser to convert amide groups on the surface of nylon to amines having antimicrobial activity [42].

Another compound that exhibits antimicrobial effects is ethanol. Spraying ethanol onto foods prior to packaging can be applied, but another option is to use sachets generating ethanol vapour. Ethicap® or Antimold® (Europe) from Freund Industrial Co. (Japan) consists of a 55%/10% ethanol/water mixture adsorbed onto silicon dioxide powder (35%), contained in a sachet of a laminate of paper/ethyl vinyl acetate copolymer. Ethicap® acts by absorbing moisture from the food and releasing ethanol vapour [19]. Apple turnovers, with a_w 0.93 had a limited shelf-life of 14 days at ambient temperatures when packaged in air or a CO_2/N_2 (60%/40%) gas mixture due to the growth of and CO_2-production from *Saccharomyces cerevisiae*. Using Ethicap®, yeast growth was suppressed completely in all packages during 21 days at 25°C [43]. A second ethanol releasing sachet from Freund Industrial Co. is Negamold®, which scavenges O_2 as well as generating ethanol vapour. Other ethanol generators are Oitech™ (Nippon Kayaku, Japan), Ageless® type SE (Mitsubishi Gas Chemical Co.) and ET Pack (Ueno Seiyaku, Japan) [19]. Ethanol vapour generators are widespread in Japan and are mainly used for high moisture bakery goods, fish products and cheese. Studies which report considerable shelf-life extensions for a number of foods are reviewed [19]. For example, a 5 to 20-fold extension in mould-free shelf-life has been observed for cakes with high water content depending on the size of Ethicap® used. A major disadvantage of ethanol vapour is its absorption by the food product. In some cases the ethanol concentration in the product might cause regulatory problems. If the product is heated prior to consumption the accumulated ethanol may evaporate. Another drawback is the cost of the sachets, which limits their use to products with higher profit margins [19].

Antioxidant release

Antioxidants are widely used as food additives to improve oxidation stability of lipids and to prolong shelf-life, mainly for dried products and O_2-sensitive foods. Antioxidants can also be incorporated into plastic films for polymer stabilization in order to protect the films from degradation. It is well established that antioxidant concentrations in polymeric films decrease during storage due to oxidation but also because of diffusion through the bulk of the polymer towards its surface followed by evaporation [44]. In the US cereal industry waxed paper has sometimes been used as a reservoir for antioxidant release [5]. This type of active packaging is still at the experimental stage and few commercial applications are known. Oatmeal cereals, packaged in high-level (0.32%) BHT-impregnated HDPE, had an extended shelf-life compared with cereals packaged in low-level (0.022%) BHT-impregnated HDPE. After six weeks, the HDPE film was free of BHT and 19% of that originally present in the film remained in the cereal. The oat flakes packaged in the film with 0.32% BHT, showed less oxidation than the control (0.022% BHT). A considerable amount of the BHT was lost by outward migration. However, these outward losses can be controlled by the use of an extra layer with a low permeability for the antioxidant [44]. There has been some concern regarding the physiological effects of consuming BHT due to its tendency to accumulate in human adipose tissue. The use of BHT in contact with foods has, therefore, been questioned. It is therefore desirable to find natural and harmless antioxidants [45]. Recently, vitamins E and C have been suggested for integration in polymer films to exert their antioxidative effects. Vitamin E has proved to be very stable under processing conditions and has an excellent solubility in polyolefins. It is confirmed, however, that vitamin E is a less mobile antioxidant in LDPE than BHT, as vitamin E is a larger molecule. Since vitamin E migrated from the film to the fatty food simulant to a lesser extent than BHT, the success of the vitamin E releasing active packaging concept is difficult to assess [45].

Release or absorption of flavours and odours

Flavour scalping i.e. sorption of food flavours by polymeric packaging materials, may result in loss of flavour and taste intensities and changes in the organoleptic profile of foods [46]. Generally, flavour scalping is detrimental to food quality, but it could be used in a positive way to selectively absorb unwanted odours or flavours. An active packaging concept to reduce bitterness in grapefruit juices has been described [47, 48]. The causes of the bitter taste are the glycosidic flavanone naringin and the triterpenoid lactone limonin. Naringin is the bitter component found in most fresh citrus fruits and therefore in freshly processed citrus juices. Limonin is formed as a result of heat treatment of the juice during processing, as well as a chemical action in the acidic juice medium. To counteract this, an active thin cellulose acetate (CA) layer for application on the inside of the packaging has been developed. This layer contains the fungal-derived enzyme naringinase, consisting of α-rhamnosidase and β-glucosidase, which hydrolyses naringin to naringenin and prunin, both non-bitter compounds. Food-contact approved CA films, which contained immobilized naringinase showed a 60% naringin hydrolysis in grapefruit juice in 15 days at 7°C and a reduction in the limonine content due to adsorption on the CA film [48].

Two other types of taints that could be removed by active packaging are amines and aldehydes. Malodorous amines, resulting from protein breakdown in fish muscle, include strongly alkaline compounds [10]. A Japanese patent based on the interactions between acidic compounds (e.g. citric acid) incorporated in polymers, and the off-odours claimed amine-removing capabilities [49]. Another approach to remove amine odours has been provided by the Anico Co. (Japan). The Anico bags made from a film containing ferrous salt and an organic acid such as citric or ascorbic acid are claimed to oxidize the amine or other oxidizable odour-causing compounds as they are absorbed by the polymer [10]. Aldehydes, formed from the breakdown of peroxides resulting from the initial stages of autooxidation of fats and oils, can make a wide variety of fat-containing foods, such as potato crisps, biscuits and cereal products, organoleptically unacceptable. Removal of aldehydes such as hexanal and heptanal from package headspaces by means of the layer Bynel IXP101 which is a HDPE masterbatch is claimed by Dupont Polymers [10].

Some commercialized odour-absorbing sachets e.g. MINIPAX® and STRIPPAX® (Multisorb technologies, USA) absorb the odours developing in certain packaged foods during distribution due to the formation of mercaptans and H_2S. 2-in-1™ from United Desiccants (USA) is a combination of silica gel and activated carbon packaged together for use in controlling moisture, gas and odour within packaged products. Profresh® is claimed to be a freshness-keeping and malodour control masterbatch to PE and PS. The active component ADI50 (composition not revealed) is claimed to absorb ethylene, ethyl alcohol, ethyl acetate and H_2S.

Flavour incorporation in packaging material might be used to minimize flavour scalping. Flavour release might also provide a means to mask off-odours coming from the food or the packaging. Further applications of flavour-enriched packaging materials include the possibility to improve the organoleptic quality of the product by emitting desirable flavours into the food and to encapsulate pleasant aromas, that are released upon opening. It is of importance that the aforementioned technologies are not misused to mask the development of microbial off-odours thereby concealing the marketing of products that are below standard or even dangerous for the consumer [46].

Scope of applications

Applications of active packaging are numerous and growing. O_2-scavengers and antioxidant releasing systems can be used with most O_2-sensitive products to extend their shelf-life. Desiccants have been used extensively with dried and mould-sensitive foods. C_2H_4-scavengers

Table 3. Current and future applications of active packaging [1]

Concept	Food groups						
	Dry	**High fat**	**Minimally processed**	**Meat and dairy**	**Frozen**	**Bakery**	**Beverages**
O_2-scavenger	Roasted nuts, coffee, dried fish, cerals, species	Potato chips, chocolate	Fresh, pre-cooked pasta	Cheese, salami, smoked meats, fish, sausages	Fish, vegetables	Pizza crust, bread, cakes, cookies, pastries	Beer, fruit juice, ready-to-drink tea, tomato-based products, wine
CO_2-scavenger	Coffee		Fruit	Cheese, beef jerkey, poultry products			
CO_2-emitter	Nuts	Potato crisps, peanuts	Produce	Fresh meat and fish		Sponge cake	
C_2H_4-emitter				Climacteric produce			
C_2H_4-scavenger			Climacteric produce				
Moisture scavenger	All		Fresh pasta, produce	Meat, fish, cheese	Seafood, meat, fish	Bread, biscuites	
Ethanol emitter	Semi-dry fish			Cheese	Fish	Sweet bread, high moisture bakery products	
Antimicrobial release			Fruit	Cheese, meat		Bread, cakes	
Antioxidant release	Breakfast cereal						Bag-in-box wine
Flavour releasing film					Ice-cream		Orange juice
Flavour absorption				Fish			Fruit juicess

are finding their way into the horticultural produce industry, and antimicrobial release systems can be used with bakery foods, cheese and other products [1]. Table 3 provides a synopsis of current and future applications of active packaging technologies.

The future

In the USA, Japan and Australia, active packaging concepts are already being successfully applied. In Europe, the development and application of active packaging is limited because of legislative restrictions, fear of consumer resistance, lack of knowledge about effectiveness, economic and environmental impact of concepts. No specific regulations exist on the use of active packaging in Europe. Active packaging is subjected to traditional packaging legislation, which requires that compounds are registered on positive lists and that the overall and specific migration limits are respected. This is more or less contradictory to the concept of some active packaging systems in which packaging releases substances to extend shelf-life or improve quality. The food industry's main concern about introducing active components to packaging seems to be that consumers may consider the components harmful and may not accept them [50]. In Finland a consumer survey conducted in order to determine consumer attitudes towards O_2-absorbers revealed that the new concepts would be accepted if consumers are well informed by using reliable information channels [50]. More information is needed about the chemical, microbiological and physiological effects of various active concepts on the packaged food i.e. in regard to its quality and safety. So far research has mainly concentrated on development of various methods and their testing in a model system, but not so much on functioning in food preservation with real food products [51]. Furthermore, the benefits of active packaging need to be considered in a holistic approach to environmental impact assessment. The environmental effect of plastics-based active packaging will vary with the nature of the product/package combination. The additional ingredients need to be evaluated for their environmental impact [10]. Active packaging is an emerging and exciting area of food technology which can confer many preservation benefits on a wide range of foods [12]. As more companies become aware of the economic advantages [19] of using absorbent technology, and consumers accept this approach, the technology will likely emerge as the preservation technology of the twenty first century [52].

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