CHAPTER 2

Sensory Impacts of Food–Packaging Interactions

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Contents

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Abstract Sensory changes in food products result from intentional or unintentional interactions with packaging materials and from failure of materials to protect product integrity or quality. Resolving sensory issues related to plastic food packaging involves knowledge provided by sensory scientists, materials scientists, packaging manufacturers, food processors, and consumers. Effective communication among scientists and engineers from different disciplines and industries can help scientists understand package–product interactions. Very limited published literature describes sensory perceptions associated with food–package interactions. This article discusses sensory impacts, with emphasis on oxidation reactions, associated with the interaction of food and materials, including taints, scalping, changes in food quality as a function of packaging, and examples of material innovations for smart packaging that can improve sensory quality of foods and beverages. Sensory evaluation is an important tool for improved package selection and development of new materials.

I. INTRODUCTION

Packaging materials are critical components within packaging systems for improving product sensory integrity and quality. There is no known packaging material, not even glass or metal, which does not interact in some way with the product it protects; these interactions can affect the quality of both the food and the package. Sensory evaluation is an important tool in the detection of packaging interactions with food. Changes in food or beverage color and appearance, flavor, odor, and textural characteristics as affected by packaging material chemistry, processing, and characteristics can make or break product success.

Food and beverage packaging functions to contain, protect, communicate, and provide convenience in use of the product (Robertson, 2006). A good packaging system is designed with an appropriate barrier to protect food from external contamination by microorganisms, foreign materials, chemical contaminants, or environmental degradation (Kilcast, 1996; Robertson, 2006). Printed information on the package provides direct communication pertinent to the product in the form of words and graphics, including colors, to the consumer. Indirect communication, whether intentional or unintentional, results when the human sensory response is triggered by unexpected or uncharacteristic product changes as a result of food–packaging interactions (Duncan, 2007). Such changes may noticeably affect product integrity, quality, and shelf-life, resulting in affective (degree of liking or preference) or analytical (recognition of overall or specific product changes) human responses to the contained product.

Flavor, odor, appearance, and texture of foods are not static. Both packaging materials and food products may undergo chemical transformations that alter these food characteristics. Reactions such as oxidation, hydrolysis, and vaporization can lead to the production of off-odors and flavors and changes in texture and visual characteristics (Ayhan *et al.*, 2001). These changes may be caused by the packaging materials themselves, by an interaction between the package and the food, and/or because of poor packaging selection (Huber *et al.*, 2002) and may lead to consumer complaints. New packaging materials or modifications that improve product integrity, quality, and shelf-life are valuable if product improvement is detectable by the consumer or end-user. However, selection of an inappropriate packaging material can result in a negative sensory impression of the contained product by the user, leading to dissatisfaction, decreased use, and communication to the food manufacturer of the product problem. Approximately 50% of all off-odor complaints in one company were due to improper packaging, with major problem sources ranging from degradation of the packaging materials to inadequate selection of packaging material (Frank *et al.*, 2001; Huber *et al.*, 2002). Sweets, cakes, and cookies were the primary foods affected by taints in another food company over a 10-year period, accounting for 50% of the reported cases (Lord, 2003).

Food product manufacturers are at risk of experiencing significant losses in production, sales, and consumer confidence as a result of detectable sensory changes from food–package interactions, potentially leading to a damaged brand image (Huber *et al.*, 2002; Kilcast, 1996; Lord, 2003). Clear communications among technical representatives within the packaging supply line are critical (Fig. 2.1). Food manufacturers bear the highest burden in this line of communication as they have the financial risk of loss of production from defective products as well as the loss of product, which cannot be reworked, and packages, which cannot be reused (Huber *et al.*, 2002).

The challenge of identifying the source of a sensory problem caused by packaging is expensive and time consuming. Communications along the packaging supply line, therefore, should describe the sensory character of the material in its virgin state and after package conversion, with food manufacturers disclosing processing, packaging, and storage conditions and expected duration of contact with the foodstuff (Duncan, 2007). The packaging supply chain includes the materials or resin manufacturer through the packaging supplier/converter to the food processor/manufacturer, each having a vested interest in material and package/product success. Expensive legal litigation resulting from package/product failure is a potential and serious consequence of poor communication. Modern legislation guards against the spoilage of foods by packaging materials by regulating that food packaging materials do not transfer

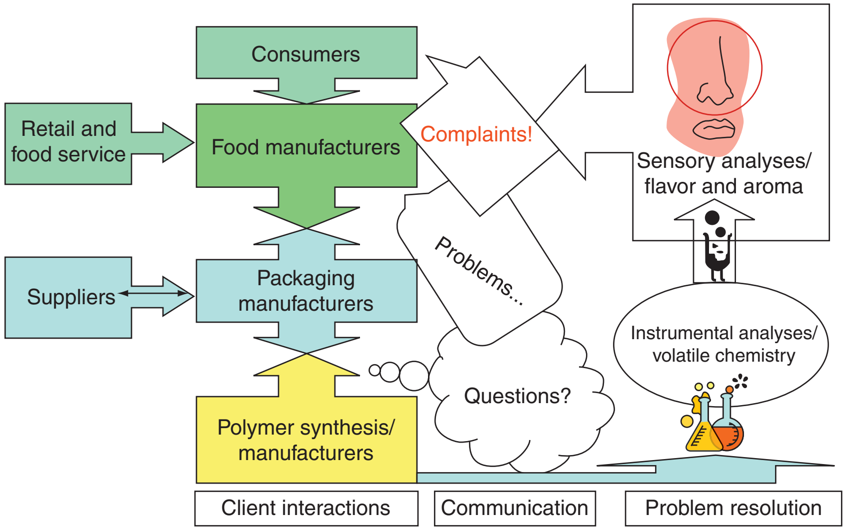

FIGURE 2.1 Clear communications among industry players can help prevent or resolve sensory impacts for food–package interactions.

constituents to foods in sufficient quantities to endanger human health or cause deterioration of the sensory characteristics of foods (Huber *et al.*, 2002; Soderhjelm and Eskelinen, 1985).

Understanding the sensory impacts related to food or beverage interactions with packaging materials may be helpful in preventing or resolving problems as well as in selecting appropriate materials for maintaining product integrity, quality, and shelf-life. The source of the change in sensory quality associated with a food–packaging interaction may occur at any stage of the food manufacturing or supply chain and from different sources at each stage. Preventing the problem from occurring is best but, when a problem does occur, good communications and good detective work are needed to determine the cause of consumer or client complaints (Duncan, 2007).

II. CONSUMER PERCEPTION

Ultimately, the ability of a packaging material to protect food quality depends not on whether an interaction has occurred but on whether or not a consumer can detect that interaction. The repeat purchase of a packaged food product is contingent on many factors, with enjoyment and positive sensory stimulation being among the most important (Kilcast, 1996). Consumer expectations associated with sensory characteristics and quality of a packaged food can be diminished because of unexpected food–packaging interactions. In addition, the perception of contamination caused by unexpected sensory characteristics also raises concerns about safety, even if there is little or no health risk (Anonymous, 1988; Dietrich *et al.*, 2005). However, only a small proportion of consumers purchasing a product exhibiting a food–packaging interaction may call to comment or complain (AFGC, 2007). Therefore, getting sensory observations and qualitative descriptive information from these contacts is very important.

Consumer communication of a sensory problem in a packaged food system may result in a variety of descriptions from different people experiencing the same problem, suggesting that these reports are unreliable. The lack of verbal skills or training in analytical descriptive methods, unfamiliarity with chemical species that may be causing the problem, and bias associated with the conditions under which the sensation was experienced make consumer descriptions of sensory changes difficult to act upon (Kilcast, 1996). It is possible that many sensitive people may experience the sensory problem but only a few may report it. This may be why some incidences of sensory problems associated with food–package interactions seem sporadic, limiting perception of the problem scope and making detection and resolution of the problem challenging (AFGC, 2007). Individuals also perceive flavors at differing concentrations, or threshold levels, and these levels can vary by a factor of a billion from one individual to another. A report of a sensory problem by even one consumer of known high sensitivity may be reason enough to determine the cause (Huber *et al.*, 2002; Kilcast, 1996). Consumers are very important sentinels of quality changes and their comments or complaints may represent the beginning of a major problem.

III. THRESHOLD CONCEPT

The point at which the interaction between the food and package material causes a change in the sensory response of an individual is an important threshold. At this point, the observer is aware that there is something different about the product. Typically, thresholds are discussed in relation to a given chemical compound that contributes a specific odor, flavor, appearance, or textural change. Thresholds for a given compound vary with the medium (food or drink composition) in which it is present, the temperature at which the product is presented, other stimuli contributing to the sensory character of the product, the methodology used in determining the threshold, and individual sensitivity to the stimulus (Kilcast, 1996; Land, 1989; Meilgaard *et al.*, 2007).

If a high proportion of the population is sensitive to the sensory change and the change is negative in character, there is a high potential for consumer complaints about the product. A sensory threshold is the lowest concentration of a compound detectable by a certain proportion, usually 50%, of a given population, indicating that the stimulus is at a level sufficient to create a sensory perception (AFGC, 2007; Kilcast, 1996; Lawless and Heymann, 1998; Meilgaard *et al.*, 2007). Different types of thresholds are recognized. The detection (or absolute) threshold is the lowest physical intensity at which a stimulus is perceptible (Kilcast, 1996; Lawless and Heymann, 1998; Meilgaard *et al.*, 2007); the recognition threshold is the physical intensity at which a stimulus is correctly identified (Kilcast, 1996; Meilgaard *et al.*, 2007). The range in sensitivity of individuals within a population to a given chemical stimulus is typically 2000-fold (AFGC, 2007).

IV. SENSORY EFFECTS

Effects of materials on sensory characteristics and quality of foods and beverages can occur from direct contact, as with a primary package intended for containment, or by indirect means resulting from the environmental conditions (relative humidity, temperature, and air quality) as well as the characteristics of secondary packaging materials. Any material in contact or proximity to a foodstuff may have an effect. This extends to the materials used for water distribution systems, plumbing, gaskets, adhesives, valves, shipping containers, pallets, and other materials, all of which may contribute to perceivable changes in sensory characteristics.

There is a large body of research on the effects of food packaging on flavor and odor chemistry of various foods. However, the focus of such research is often targeted toward identifying the chemicals and relative concentrations that occur as a result of food–package interactions. The relationship between food–package interactions and human sensory response has received relatively little scientific attention.

There are numerous books, review papers, and research publications describing chemical interactions of packaging materials with foods that affect flavor chemistry. Most explain the interactions as a function of changes in analytical flavor chemistry, focusing on migration of substances from the package into the food, absorption of flavor components from the food into the package, and transfer of odors, gases, and light through the polymer package, which then can affect food quality (Ahvenainen, 2000; Barnes *et al.*, 2007; Katan, 1996; Leland, 1997; Piringer and Ruter, 2000; Risch and Ho, 2000). In many research studies, the sensory impact of these reactions is not directly described or is not evaluated, although there may be reference to the impact. Relying only on analytical evaluation of flavor chemistry can be deceiving because these compounds may or may not have an impact on the sensory quality of the food (Piringer and Ruter, 2000; Torri *et al.*, 2008).

Sensory evaluation can help characterize flavors, aromas, appearance effects, and textural changes that might not be able to be determined analytically. Sensory perception is often more sensitive than analytical methods and in some cases is the only way to determine if a change has occurred in a food due to an interaction with its packaging. Human senses can detect changes in volatile chemistry at extremely low concentrations (10^{-6}–10^{-12} mol/ml) for some chemicals (Kilcast, 1996; Lawless and Heymann, 1998; Meilgaard *et al.*, 2007; Reineccius, 2006). However, there are problems with sensory testing that must be kept in mind. These problems include differing perceptions and thresholds for changes in appearance, texture, flavor, and aroma due to the unique physiological and psychological makeup of individual human subjects. The range of human sensitivity, verbal skills for description of the sensation(s), and affective response to the sensation contribute to the challenges associated with identifying the source of a sensory problem in a packaged food system.

The combination of sensory evaluation with analytical approaches is required to identify perceptible changes and to identify the potential chemical changes that may be causing the sensory effect. Low concentrations of compounds responsible for changes in food characteristics may not be detectable by even the most sensitive analytical methods but, in combination with appropriately applied sensory methods, the clues provided by both techniques may help identify the problem, provide indications to the cause, and suggest clues for the source of the problem.

Sensory issues relating to food and packaging interactions may be classified based on the sensory quality changes that occur. Four broad categories that infer the direction (positive/negative) of the quality change include: (1) taints resulting from the packaging material or as a functional limitation of the package; (2) scalping of food constituents; (3) packaging function for protection of sensory properties of the food; and (4) improving flavor and odor quality through food–package interaction (Fig. 2.2).

Taints are defined as a taste or odor foreign to the product (AFGC, 2007; Kilcast, 1996). Taints typically are unpleasant in character and are initiated by or originate from sources external to the food; they are caused by constituents of the packaging material or the near environment migrating into the product. Common sources of taints related to food packaging include packaging materials, inks and dyes, adhesives, and secondary packaging including pallets, shipping containers, and corrugated cardboard materials. Although taints are contaminants of the food

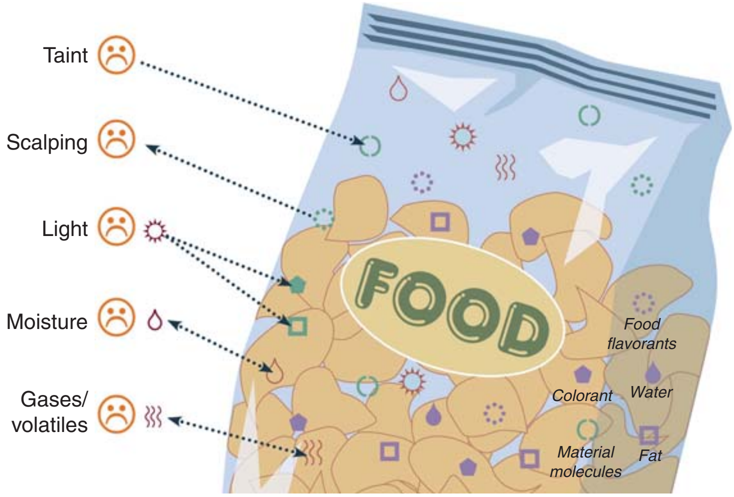

FIGURE 2.2 Negative sensory impacts occur when tainting or scalping occur or ineffective packaging selections are made.

environment, not all contaminants cause taint (AFGC, 2007). To meet legal and consumer expectations, the goal should be zero levels of tainting species (below sensory threshold) so even the most sensitive members of the population cannot detect the taint (Kilcast, 1996). The concentration of the penetrating molecules may be very low and still create a significant sensory response. Tainting molecules in the headspace of a package will influence the sensory response by the consumer when the package is initially opened and perhaps motivate a complaint action (Kilcast, 1996). The threshold for detection in the air above the sample is typically lower than needed to cause a response in the food medium. The majority of published literature associated with sensory issues of food–package interactions is related to taints and flavor scalping.

Scalping (sorption) is also detrimental to consumer perception of food quality. From a sensory perspective, this type of interaction is different from taints. This phenomenon is associated with key food constituents absorbing into a plastic or other material (Brody, 2002). In this situation, desirable food constituents, such as aroma compounds, acids, lipids, and pigments, are removed from the food or beverage by the packaging materials. This is most commonly described in relation to a decrease in flavor intensity or as an alteration of the flavor profile but could also be associated with color or odor changes. Changes or decreases in quality may be perceived by consumers. The exhibition of reduced sensory quality in many shelf-stable foods in plastic packaging is attributed to scalping (Brody, 2002).

Off-flavors and off-odors, in contrast to tainting or scalping, are related to changes in food chemistry associated with degradative reactions within the food or deteriorative changes of food components (AFGC, 2007; Kilcast, 1996). The character of these changes is typically unpleasant and undesirable in relation to food quality and consumer satisfaction. In addition, changes in pigment chemistry, moisture loss (or gain), or other reactions within the food system may result as a function of improper material selection. Sensory studies on the protective function of packaging (maintaining/improving) on quality primarily exist as supporting information to the assessment of chemistry, microbiology, processing, or engineering of the food–package system. In many cases, these sensory studies are designed to determine if a difference exists because of the experimental variables but detailed, descriptive studies of sensory impacts of the protective function of packaging on food properties is limited.

Novel packaging approaches using active materials or new packaging technologies for a desired sensory effect within the food system, or those that enhance product sensory quality and improve shelf-life, do not fit into any of the prior categories. This area of literature is emerging.

The value in understanding the differences in these sources of subtle changes in sensory quality is associated with distinguishing the cause and possible solutions associated with the problem. There is a wide array of potential contaminants associated with taints and identifying the cause as something originating from external contamination or from internal product change helps narrow the search (Kilcast, 1996). Understanding sensory impacts from food–package interactions will provide greater capacity for improving food–package systems. For example, a piney-spruce taint was observed in a routine quality assurance examination of a packaged ready-to-eat breakfast cereal (Heydanek, 1977). With a careful analytical approach that utilized sensory evaluation in the early stages, the source was traced to the resin bonding paper layers in the glassine liner of the package. With the use of gas chromatography–mass spectroscopy (GC–MS), in combination with additional sensory testing of additional glassine materials, the migrant molecules were identified as major terpenes, fenchyl alcohol, and borneol.

The purpose of this review is to give an overview of the effect that food packaging has on the sensory quality of food. The focus will be on human response and sensory terminology used in describing these interactions in relation to foods and beverages in contact with different materials. Volatile chemistry will be described only as it relates to the sensory effects. It is not the intent of this review to provide detailed information on sensory evaluation methodology. There are numerous text and reference books for developing a basic knowledge of sensory evaluation methods. However, a brief description of nontraditional sensory methods for examining taint and other sensory effects from packaging is provided.

V. METHODS FOR EXAMINING TAINT AND OTHER SENSORY EFFECTS FROM PACKAGING

The selection of an appropriate sensory methodology for examining taints, scalping, off-flavors, or improved product quality is dependent on the project objectives. No single method can answer all questions, such as describing the flavor character and intensity as well as consumer response, so effective communication of the project goal and objectives among the sensory specialist, packaging expert, and project leader is needed (Duncan, 2007). Appropriate selection and training of participants in descriptive evaluation is needed to provide accurate and reliable qualitative and quantitative responses. Descriptive methods, which provide much more information than discrimination or affective methods, are helpful in differentiating how a product–package interaction affects sensory profiles. However, this is a very time intensive effort because of the investment in panel preparation and maintenance. Discrimination testing can be very effective in determining if a difference occurs because of the product–package interaction but these methods do not describe how (change in sensory profile) the product–package interaction affects perception. Such methods require little or no training of panelists but more panelists are needed to increase the power of the test. Untrained panelists representative of the targeted consumer population should be used for estimating affective consumer responses to taints and off-characteristics as well as verifying value-added quality maintenance or improvements of packaged food products. Since a wide range of individual responses can occur in consumer testing, a large number of consumers are needed to verify if the product–package interaction is truly having an impact. For all methods, attention to appropriate environmental, sample, and panelist controls are needed during preparation and presentation. Communication with panelists must be appropriate for instructing panelists in completing the tasks but restricted in details of samples and objectives in order to avoid biases that may affect outcomes or interpretation of the results.

Standard methods that apply to detecting taint from plastic and paperboard materials are described in US ASTM Std E 462-84 (tests for odor and taint transfer from packaging film), ASTM E 619-84 (examination of odors from paper packaging), and German Standard DIN 10 955 (testing of taints transferred by direct contact and also by vapor phase transfer) (Kilcast, 1996). Many of these methods are based on accelerated storage conditions and using food simulants or water or on evaluation of volatile compounds emitted from packaging material (Kim-Kang, 1990; Torri *et al.*, 2008). Sensory methodology books (Lawless and Heymann, 1998; Meilgaard *et al.*, 2007) provide guidance for appropriate design and application of sensory methods. Book chapters with specific reference to packaging (Kilcast, 1996, 2003; Lord, 2003) provide some background and general sensory information in the context of the sensory effects of food packaging. Recent German references assess difficulties in standardizing methods for sensory analysis of packaging materials and quality requirements for colorants and additives used in food and beverage packaging (Anonymous, 2007; Buettner *et al.*, 2007).

VI. TAINTS

Although there are many routes by which taints may occur in foods, one of the greatest risks is from contact of foods with materials that may contain potential migrants (Baigrie, 2003; Kilcast, 1996; Reineccius, 2006). Many materials have molecules that can migrate from the package into the food product. In addition, polymer materials, such as gaskets used in manufacturing processes, containers used for transport, or packaging materials inappropriately used in a process (i.e., irradiation or hot-fill) may cause taints. Water distribution and plumbing materials, flooring materials, and disinfectants or other environmental contaminants on food packaging surfaces also may be sources of tainting molecules. Long-shelf life foods, which are stored in direct contact with packaging materials for a long period of time, are at great risk of developing taint. Beverages, extended shelf-life (ESL) or shelf-stable milk products, and other liquids have a high risk for tainting chemical species to transfer into the food matrix. Water and many ESL dairy products have a low flavor profile so even a low concentration of migrating molecules from the polymer may impact sensory characteristics in these products. A higher fat content within the food product, such as chocolate, contained in the packaging material can cause an increased taint within the food product. Levels of tainting odors and flavors are highest where there is direct contact between the packaging material and foods with a high fat content on the surface. Sensory descriptors associated with tainting chemicals from packaging sources have been reported (Ewender *et al.*, 1995; Lord, 2003).

A. Taints from contact materials

Materials may exhibit a tainting odor from the polymers, monomers, additives, adhesives, or process. Packaging related taints, as reported from the Nestle's Central Packaging Laboratory over a 4-year period (1996–2000) were related to solvents (28%), degraded polyethylene (PE) (24%), styrene (15%), halogenated phenols (15%), degraded paper (3%), and other unknown sources (15%) (Huber *et al.*, 2002). The virgin material should not exhibit an odor; however, that will not guarantee that the material will not impact the sensory profile of the food.

Many materials used for food and beverage packaging have characteristic odors or sensory active compounds (Torri *et al.*, 2008). The intensity and description of the odor may be affected by the number and type of volatile compounds that are released under environmental conditions at the time of evaluation. Chemical composition of the material and polymer morphology may play a role in the sensory characterization. Sensory descriptors do not define a specific chemical compound but may be related to different compounds, a blend of compounds, and even a limited concentration range of a compound or class of compounds. For example, *trans*-2-nonenal in water changes in sensory (taste) description from ''plastic'' (0.2 μg/l) to ''woody'' (0.4–2.0 μg/l), ''fatty'' (8–40 μg/l), and ''cucumber'' (1000 μg/l) (Piringer and Ruter, 2000). Such terms are descriptive of the sensation and perception by human response to the chemical stimuli (Table 2.1).

Sensory active components from packaging may influence the perception of product quality (Piringer and Ruter, 2000). Parameters that may contribute to sensory influence include (Granzer *et al.*, 1986):

- Concentration of the component in the packaging material.
- Solubility of the component in the packaging material (partition gas phase/packaging material).
- Solubility of the component in the food (partition gas phase/food).
- Sensory threshold level of the component.
- Type and intensity of the food aroma.
- Diffusion rate of the component in the packaging material.
- Diffusion rate of the component in food.
- Time and temperature of storage.
- Ratio of the amount of packaging material to the amount of food.

Consideration of these parameters is important when tracking the source of taints and interpreting the relationship between analytical chemistry and sensory impact of the food–package interaction.

Evaluating odor and flavor taints is frequently done with water, fatty food simulants (oil, chocolate, unsalted butter), hydrophilic powders (sugar, cornflour), or combined hydrophilic–hydrophobic matrices (milk or cream, biscuits) (Kilcast, 2003). The Robinson test often is used to evaluate materials for tainting potential. This test places the test material in a sealed container separated from the food simulant or test food at a relative humidity between 53% and 75%. After about 48 h, the test food is evaluated for taint compared to a control, using a discrimination method (Lord, 2003). Chocolate is frequently used as the food simulant for this test. Intensity of the taint may be evaluated using a

TABLE 2.1 Sensory descriptors associated with taint sources (Baner, 2000; Caul, 1961; Huber *et al*., 2002; Piringer and Ruter, 2000; Torri *et al*., 2008)

Taint sources	Material	Sensory descriptors
Packaging materials[a]	Plastics	Acetic acid, acrid, alcohol, adhesive, burnt, burnt wax, candle-like, cat urine, chemical, lube oil, musty, oxidized polyethylene, paint, paraffins, paste, phenolic, plastic, pungent, rancid, soapy, solvent, stale, styrene, stuffy, vinyl, waxy
	Paper/board	Almonds, cardboard, fruity, green grassy, pine, rancid
	Miscellaneous	Jute sack, petrol
Printing/ converting[b]	Solvent based	Aromatic, camphorated, chemical, fruity, solvent, sweet, toluene
	Offset printing	Fat, linseed oil, mineral oil, painty, petrol, rancid, varnish
External contamination[c]	Chemical	Antiseptic, disinfectant, herbicide, hospital, insecticide, medical, metallic, phenolic
	Microbiological	Moldy, mushrooms, musty
	Miscellaneous	Catty, cork, naphthalene, wooden pencil

[a] Material-intrinsic odors
[b] Solvent based includes flexo and gravure printing
[c] Absorption of foreign odor from other materials in contact with packaging during production and storage as well as food–package interactions

5-point rating scale (0 = not perceptible; 4 = strong). The use of the Robinson-style test method, using the rating scale, is effective for quality control of materials intended for food packaging. Understanding the sensory influence of raw and processed materials on food simulants and complex matrices is helpful in reducing taints in packaged foods. Table 2.2 provides a summary of sensory descriptors associated with foods and beverages in contact with packaging materials.

TABLE 2.2 Sensory descriptors associated with some packaging materials containing different foods and beverages

Broad category	Packaging material	Description	Product	Sensory description	References
General	Glass		Milk	Plastic, oxidized, burnt flavor	Karatapanis *et al.* (2006)
	Metal		Beer	Musty flavor	Council AFaG (1997)
			Canned pork products	Catty flavor	Kim-Kang (1990)
	Paper	Board stock	Cakes, biscuits, chocolate confectionary	Off-flavor	Goldenberg and Matheson (1975)
			Chocolate-coated cakes	Off-flavor	Goldenberg and Matheson (1975)
				Mushroom odor	
				Musty, mouldy	Caul (1961)
				Halogen-like odor	Caul (1961)
				Papery, cardboardy	Caul (1961)
				Burnt	Anonymous (1988)
			Breakfast cereal	Piney flavor	Heydanek (1977)
			Milk	Stale, fruity flavor	Karatapanis *et al.* (2006)
				Painty, chalky, fruity, rancid, sulfide, and resinous odor	Anonymous (1988)
		Packing sacks	Cocoa powder	Mouldy odor and disinfectant flavor	Whitfield *et al.* (1984)
			Cocoa beans	Mouldy flavor	Anonymous (1988), Whitfield *et al.* (1984)
		Waxed parchment paper	Butter	Refrigerator/stale	Lozano *et al.* (2007)
	Adhesives	Coatings		Waxy, oily, rancid	Caul (1961)
				Spoiled protein (sulphide)	Caul (1961)
				Resinous	Caul (1961)

		Printing films	Cakes, biscuits, chocolate confectionary, sugar confectionary	Off-flavor	Goldenberg and Matheson (1975)
Plastics	Polyamide/ionomer laminate	Retort pouch	Ham products	Cat urine odor	Piringer and Ruter (2000)
	Polyester, aluminum foil, polyethylene laminate	Retort pouch	Fruit-flavored soft drinks	Off-flavor	Passy (1983)
	Glassine	Liner	Ready-to-eat breakfast cereals	Pine or spruce-like odor	Heydanek (1977)
			Candy wraps	Bitter, burnt, old rubber-like flavor	Kim-Kang (1990)
	Polypropylene		Oats	Stearic, paint, bitter, hay, rancid odor, and flavor grainy	Larsen *et al.* (2005) Heydanek (1978)
			Boiled sweets	Jasmine-like, herbal and floral	Lord (2003)
				"Lube" oil, burnt, phenolic	Caul (1961)
			Orange juice	Musty odor	Feigenbaum *et al.* (1998)
	Polyolefins	Low density polyethylene (LDPE)		Candle-grease, musty, rancid, soapy, pungent, acrid, sickly, astringent, synthetic, metallic, and dry flavor	Linssen and Roozen (1994)
			Water	Musty	Linssen and Roozen (1994)
		High density polyethylene (HDPE)	Milk	Stale, fruity flavor	Karatapanis *et al.* (2006), Moyssiadi *et al.* (2004)
			Corn chips (snack foods)	Plastic odor	Sander *et al.* (2005)
			Water	Tastes: sweet, metallic, stony, pungent, dusty,	Villberg *et al.* (1997)

(*continued*)

TABLE 2.2 (*continued*)

Broad category	Packaging material	Description	Product	Sensory description	References
				stale, plastic, foul, stink bug, candle grease Odors: Sweet, chemical, stale, dirty, foul	
		HDPE water pipes	Water	Earthy-musty flavor	Council AFaG (1997)
				Waxy, plastic, citrus	Heim and Dietrich (2007b), Dietrich (2007)
		Polyethylene (PE)	Wine	Pungent, musty odors	
			Coffee	Rio, medicinal, phenolic, or iodine-like flavor	Council AFaG (1997)
			Wine	Musty cork flavor	Council AFaG (1997)
			Prawns and ocean fish	Iodoform taint	Council AFaG (1997)
				Oxidized oil, waxy, rubbery	Caul (1961)
				Candle-like, stale, stuffy, musty, soapy, rancid odor	Piringer and Ruter (2000)
		PE-coated paperboard	Milk, water, fruit juices	Plastic flavor	Leong *et al.* (1992)
				Wax-like odor	Piringer and Ruter (2000)
		Cross-linked PE Water pipes	Water	Alcohol, sweet chemical, plastic, bitter, mechanical, glue, burning, spicy, fruity, almond,rotten swampy, burning plastic pipe	Durand and Dietrich (2007)

		PE + rubber net	Water	Yellowish color, plastic taste/odor	Kontominas *et al.* (2006)
		Polyethylene terephthalate (PETE)		Papery, scorched cloth	Caul (1961)
			Milk	Plastic, oxidized, burnt flavor	Karatapanis *et al.* (2006), Moyssiadi *et al.* (2004)
			Colas	Turpentine-like odor	Kim-Kang (1990)
		PETE + rubber net	Water	Yellowish or opaque color, taste/odor	Kontominas *et al.* (2006)
	Polystyrene		Oat products	Insecticide or plastic flavor	Heydanek (1978)
				Woody, sweet	Caul (1961)
				Plastic-like chemical odor and flavor	Heydanek (1978)
			Coffee creamer and condensed milk	Astringent chemical plastic flavor	Baner (2000)
			Chocolate and lemon cream cookies	Off-flavor and odor	Passy (1983)
	PVC		Fruit drinks	Catty flavor	Kim-Kang (1990)
			Orange and lemon drinks	Off-flavor	Kim-Kang (1990)
			Packed cheese (with PE/PETE lid)	Pungent, chemical pine odor and flavor	Lord (2003)
	Epoxy		Drinking water	Plastic, glue, putty, adhesive, chemical, musty	Heim and Dietrich (2007a), Dietrich (2007)
	Cellophane			Sweet, woody, rubbery	Caul (1961)
	Cellulose film		Sandwiches	Off-flavor	Goldenberg and Matheson (1975)
Other	Environmental odorants			Floral	Caul (1961)
				Woody	Caul (1961)

(*continued*)

TABLE 2.2 (*continued*)

Broad category	Packaging material	Description	Product	Sensory description	References
				Musty, cardboardy, burnt, floral, painty, chalky, fruity, rancid, sulfide, resinous, woody odors	Caul (1961), Anonymous (1988)
	Printing Inks			Off-odor	Caul (1961)
				Musty odor	Anonymous (1988)
				Musty, cardboardy, burnt, painty, chalky, fruity, rancid, sulfide, and resinous odors	Anonymous (1988)
			Oils	Oily, fatty, buttery	Caul (1961)
				Varnishy, painty	Caul (1961)
				Inky, rancid	Caul (1961)
				Garbagey	Caul (1961)
	Rubber hydrochloride (pilofilm)			Sour milk (Casein)	Caul (1961)
				Halogen-like odor	Caul (1961)
	Vinyl	Saran		Aromatic sweet, chlorine, oxidized oil, or solventy	Caul (1961)
		Vinyl chloride		Alcohol, soapy	Caul (1961)
	Glued seams		Cocoa powder	Moldy odor and disinfectant flavor	Anonymous (1988)
	Mixture		Maple syrup	Off-odor	Kim-Kang (1990)
			Granular gelatin	Fish odor	

1. Polystyrene (PS)

Residual styrene monomer from polystyrene production has been associated with tainting problems in different food products (Baner, 2000; Heydanek, 1978; Huber *et al.*, 2002; Piringer and Ruter, 2000). Sensory descriptors for styrene monomer include chemical, insecticide, and plastic (Baner, 2000; Caul, 1961; Heydanek, 1978). Thresholds for styrene monomer are very low in water (taste threshold: 0.022–0.37 mg/kg) and air (odor threshold: 0.050 mg/kg). Thresholds in complex foods and beverages range from 0.2 to 0.3 mg/kg for orange fruit juice drink, a 3% oil-in-water emulsion, and skim milk (0% fat), 1–3 mg/kg for whole milk, oil-in-water emulsions of 15–30% oil, cocoa powder (10–20% fat), and greater than 3 mg/kg for condensed milk (10% fat), butter, and cream (33% fat) (Baner, 2000). PS starts to decompose at very low levels after several hours and at temperatures greater than 240 °C. Ethylbenzene, which is commonly used to dilute solvents during PS polymerization, is another source of these taints (Baner, 2000).

Styrene monomer concentration in foods packaged in 31 different PS-containing food packages and contact materials averaged 224 mg/kg with two products having concentrations between 800 and 1500 mg/kg, well above the sensory threshold limits (Baner, 2000). Strict specifications for styrene monomers as well as for residual solvents, toluene, and odor and taint transfer for supplier materials should be set (Huber *et al.*, 2002).

Polystyrene used for plastic cups has been a source of off-flavors (Huber *et al.*, 2002). Oat products stored in polystyrene containers developed an ''insecticide or plastic'' off-flavor after 6 weeks of storage (Heydanek, 1978). Corn products stored under the same conditions did not develop these taints. Compounds with odors similar to the off-flavor in oats were identified by GC–MS and gas chromatography–olfactometry (GC–O). A similar pattern of volatile peaks were observed in both the PS package and the oat products. The taint was identified as being related to the styrene monomer, which was probably present in the PS feedstock. The level of styrene residual was much greater in oats (~146 mg/kg), at 20 times the styrene odor threshold in air (0.73 mg/kg), than in corn (~1.5 mg/kg). Styrene levels in corn were at twice the odor threshold but were not high enough to cause a taint in the corn product. It is possible the higher fat content of the oats, 11% as compared to 2% for the corn, increased product affinity for the styrene monomer.

Coffee creamers and condensed milk packaged in thermoformed polystyrene single serve (5–10 g product) portion pack containers have demonstrated styrene taint problems (Baner, 2000). These products are typically packaged at ultra-high temperatures (UHT) and, if packaged aseptically, may be stored without refrigeration. The higher storage temperature increases the potential for styrene taint in the product and substantially decreases the potential product shelf-life because of tainting issues. The use of laminate materials, placing PE and ethylene vinyl alcohol (EVOH) on the food contact surface, reduces the migration of styrene monomers from PS to the food. However, even with these laminate barrier materials there still have been styrene taints resulting from the styrene monomer migrating from the PS layer to the inner PE layer when the material was shipped and stored in roll form prior to forming (Baner, 2000). The estimated styrene concentration migrating from the PS into creamers was 23–31 mg/kg, far exceeding the sensory threshold of 0.1–3 mg/kg in cream and potentially creating a sensory impact when the cream is diluted into a food or beverage, such as tea or coffee. The large ratio of package surface to cream volume in these single serve portion packs contributes to this high concentration. The high fat content of cream also increases the transfer rate whereas nonfat milk would have much lower, probably undetectable, styrene taint under the same conditions (Baner, 2000). However, other research suggests that milkfat masks low levels of taint from other materials in whole milk compared to nonfat milk (Leong *et al.*, 1992; van Aardt *et al.*, 2001a).

Storage temperature and changes in product sensory profile with storage also affect the perception of taint from styrene monomer and other tainting compounds. Styrene monomer migration was suggested as a possible contributor to flavor and odor changes of butter packaged in waxed parchment paper during refrigerated storage (Lozano *et al.*, 2007). Butter wrapped in common commercial wrapping foil or wax parchment paper demonstrated different flavor profiles at 6 and 12 months of storage at refrigeration (4 °C) and freezer (−20 °C) temperatures (Lozano *et al.*, 2007). A trained sensory panel ($n = 8$) evaluated intensity (0 (absence); 15 (high)) of selected sensory characteristics (cooked/nutty, milkfat/lactone, refrigerator/stale, and salty taste) representing characteristics of fresh and stored butters. Butters stored for 6 months at refrigeration temperature in waxed parchment paper had detectable ''refrigerator/storage'' flavor (intensity of 1.0–1.1) compared to fresh and foil-wrapped butters but products in both packaging had lower intensities of positive flavor attributes (''cooked/nutty,'' ''milkfat/lactone''). At 12 months, mean intensity values for both parchment and foil wrapped refrigerated products were between 1.6 and 1.9, indicating that this flavor problem had increased and the intensity of ''cooked/nutty'' notes continued to decrease. Frozen products wrapped in parchment exhibited a very low (0.5) intensity of refrigerator/stale flavor after 12 months of storage as compared to no perception of this characteristic in foil-wrapped butter. Frozen storage helped to maintain levels of milkfat/lactone notes and, while cooked/nutty notes decreased slightly more in parchment-wrapped butter than in foil-wrapped, this characteristic still was observed at higher levels in frozen products than in refrigerated products at 12 months.

Styrene monomer migration from the package stored at refrigeration temperatures was detected by GCO but frozen storage can decrease the migration rate (Lozano *et al.*, 2007). Odor threshold levels of styrene, ethylbenzene, and toluene in oil were reported as 3.4, 4.1, and 94.7 mg/kg, respectively, and were higher than the level of these compounds found in all butter samples. Lozano *et al.* (2007) suggested the additive effect of multiple benzene derivative compounds at subthreshold levels, in combination with declining fresh flavor compounds, altered the perception of the refrigerator/stale flavor intensity as the parchment-wrapped product aged. The authors also suggested that differences in matrix between oil (100% lipid) and butter (80% lipid, 20% water) must be considered when relating thresholds from oil to butter. They hypothesized that styrene monomer thresholds in butter would be lower than those reported in oil. This is an important consideration when applying threshold data of compounds in food simulants to the sensory detection of these compounds in complex food products.

Although the common method for assessing thresholds is a 3-sample alternative forced choice method with increasing concentrations, there are some product characteristics that make presentation of more than one sample at a time unsuitable (Lawless and Heymann, 1998). Linssen *et al.* (1991) evaluated PS packaging material taint in chocolate ingredients (chocolate flakes (15% fat), cocoa power (10% and 20% fat), intended for beverages. Chocolate ingredients were mixed with or without (control) PS sheet pieces (0.5 dm^2, 2.0 dm^2), and stored in glass jars for 7 days at 30 °C. Drinks were prepared from chocolate ingredients, water, and sugar for sensory testing. Untrained panelists (n = 48–50) evaluated the drinks compared to a standard (no PS) for a difference comparison as well as for recognition of styrene. A signal detection discrimination method was selected because product stickiness and lingering taste character limited the number of samples that could be presented simultaneously.

Using the signal detection method, panelists responded to each sample with one of four category choices (Linssen *et al.*, 1991). The categories for the difference test and the styrene recognition test were ‘‘(same as the) standard, perhaps standard, perhaps not the standard, not standard’’ and ‘‘styrene recognized, perhaps styrene recognized, perhaps styrene not recognized, styrene not recognized.’’ *R*-indices, used to express the results of signal detection over the characteristic background, represent the probability of correctly distinguishing (chance = 50%; 100% indicates perfect discrimination) between products or correct recognition of styrene by the panelists. There was no difference in taste, based on *R*-indices close to 50%, between test samples and the standard for cocoa drinks and chocolate flakes in contact with low styrene exposure (0.5 dm^2). Higher styrene exposure (2.0 dm^2) in contact with chocolate flakes increased the probability of identifying the difference, with *R*-indices of 64% and 72%

for the plain and milk chocolate flakes, respectively. Milk chocolate has a lower bitter taste intensity than plain chocolate and is more susceptible to styrene taint. Comparisons to a 200 ppb styrene standard in water increased the probability of identifying the styrene taint in chocolate flakes (*R*-indices of 62–88%). Providing a recognition standard increases the probability of discriminating the difference. Increasing the contact area and polymer thickness increased the migration concentration of styrene and increased the chance of taint.

Because the potential for styrene taint to occur is high, any packaging materials containing PS should be evaluated under accelerated migration testing conditions with the intended product (Baner, 2000). The product should be tested using a sensory discrimination test, such as a triangle test, in comparison with a reference product stored under the same conditions but not in contact with the packaging. Accelerated testing conditions must consider food product quality to avoid significant chemical or microbiological spoilage.

2. Polyamides (PA)

Good oxygen barrier properties of a material do not guarantee a good flavor barrier. Polyamides have good oxygen barrier properties but do not provide a good flavor barrier because of their hydrophilic properties (Brody, 2002). Two ham products, cooked and packaged in PA/ionomer laminate films from different film manufacturers, were identified, by consumer complaints, as smelling like cat urine (Piringer and Ruter, 2000). The PA source was different for each manufacturer but the ionomer was traced to one source. Linkage to a specific printing ink on the film was evident and the source was traced to diacetone alcohol (DAA), a chemical precursor of mesityloxide. The cat urine aroma resulted from a reaction by sulfur-containing proteins in the ham that had migrated into the ionomer film with DAA, converting it to mesityloxide (Piringer and Ruter, 2000). Printing inks must be free of mesityloxide and its precursors when used on ionomer-containing laminates or films intended for packaging foods with sulfur-containing proteins (Piringer and Ruter, 2000).

3. Polyolefins

This class of materials includes the family of plastics based on ethylene and propylene (Robertson, 2006). Low, linear, and high density PE and polypropylene (PP) materials are common food packaging materials. The use of polyolefins, such as PE and PE terephthalate (PETE) in contact with foods and beverages is common. However, contact with foods, especially under conditions of heat or long duration, can potentially impact sensory characteristics of the contained product. Packaging should be carefully selected, especially for applications that involve heat treatment at high temperatures while in contact with foods.

Residual solvents from processing of polyolefins and other materials can affect sensory quality of packaged foods. Entrapment of solvents, inks, or other tainting chemicals within layers of newly processed material on a reel increases the risk of taint into food. Frank *et al.* (2001) reported that chocolate wrappers (paper/aluminum low density PE (LDPE)/Surlyn|) with a high odor score (3.0; 4.0 = very strong difference from reference), based on a trained descriptive panel, demonstrated decreasing odor intensity, from the initial odor score 1.3 when aerated for up to 48 h. However, the score (2.6) at 24 h was still above the maximum odor score for acceptable use (2.5 out of 4) as food packaging. Packaging materials are rolled on large reels for shipping and, if not appropriately aerated prior to use, solvents remaining on the inner layers of the roll can cause taint in wrapped chocolate and other foods (Baner, 2000; Frank *et al.*, 2001). Aeration (gassing-off) of unrolled materials enables the packaging supplier to reduce the odor through gassing off of solvents, thus, improving the product quality. Food manufacturers should inquire if adequate aeration time was provided prior to package conversion and require such specifications be met.

The intended use of materials in contact with foods can be a critical parameter in determining material selection. Heating of materials in contact with foods can increase the risk of taint in some circumstances. Plastic nettings, made of plastic-based threads from PE and PETE, are often used for containing raw meats and vegetables. Vegetables, such as potatoes or carrots, are typically washed and often peeled after removal from the package before raw consumption or cooking, thus, reducing the risk of taints. However, some meat products are cooked in these netting materials at temperatures exceeding 100 °C for an hour or more. Migration of molecules from these packaging materials into fatty and aqueous-based food simulants was detected at ranges below and above the European Union established migration limits (60 mg/l) (Kontominas *et al.*, 2006). The impact of migrating molecules was measured by heating different PE or PETE net or threads in potable water for 4 h at 100 °C. A panel of five judges evaluated the taste, odor, and color of the aqueous simulant based on a 5-point intensity scale (0 = no difference between experimental and control sample (water); 4 = very large difference). A preset designation established that a score greater than 1 indicated an unacceptable sensory score and evidence of sensory impact from contact of the material with the aqueous simulant. Only 7 of the 15 materials tested received a score lower than or equal to 1, the sensory acceptability limit. Sensory characteristics that developed in most water samples included a yellowish discoloration or opaque appearance and off-odor and off-taste described as plastic at slight to moderate intensities. Netting materials (PE or PETE) containing rubber and rubber plus cotton resulted in higher sensory impacting characteristics compared to materials consisting of PE or PETE only. Only one sample of PETE thread (no rubber or cotton) produced objectionable plastic taste (score = 2) and slight odor as well as a moderate difference in color (yellowish, dispersion development) compared to the water control sample.

There was no direct relationship between sensory characteristics found in the water migration behavior of molecules in the various netting materials tested (Kontominas *et al.*, 2006). Some samples that exhibited acceptable levels of migration had a moderate or greater intensity of off-flavor, off-odor, or color impact. Not all materials with high migration levels demonstrated sensory impacts in the water. There were samples that had values below the upper limit for migration as well as no real change (less than or equal to 1) in sensory characteristics compared to the control water sample.

Oxidation products of plastics materials may be responsible for off-odor development in heated plastic materials. Relevant sensory compounds are not the alkanes and alkenes, which have high sensory thresholds, but the less concentrated oxygenated compounds, which have low sensory thresholds (Piringer and Ruter, 2000). One-heptene-3-one and 2-nonenal were identified as important tainting compounds from PE-containing packaging materials (Piringer and Ruter, 2000). Kontominas *et al.* (2006) indicated 2-ethyl hexanal, heptanal, octanal, and 2,6-di-*tert* butyl quinone might have been responsible for tainting from the PE and PETE net and threads. PE odor is characterized by a number of sensory descriptors such as candle-like, stale, musty, stuffy, rancid, and soapy (Piringer and Ruter, 2000). Many of these sensory descriptors are used in describing oxidation of foods components.

Heat during polymer processing (polycondensation and melt processing) and package formation can cause formation of low molecular weight acetaldehyde (Robertson, 2006). Dabrowska *et al.* (2003) and Ewender *et al.* (2003) reported that the concentration of acetaldehyde, due to the degradation of the PETE polymer during bottle formation, reaches ~4.5–5.5 ppm when the process is continuous and stable. However, concentrations of more than 50 ppm have been observed even when there was only a short standstill in the bottle production line (Dabrowska *et al.*, 2003). The production of acetaldehyde appears to be initiated when PETE bottles are exposed to ozonated water used for the disinfection and washing of bottles during their manufacture (Dabrowska *et al.*, 2003). Several authors have reported that aldehydes are major oxidation products during ozone disinfection (Weinberg *et al.*, 1993; Richardson, 1998) and Mehta and Bassette (1978) reported high amounts of acetaldehyde production after milk cartons were exposed to ethylene oxide sterilization. However, Song *et al.* (2003) reported that no new compounds were formed in PETE upon exposure to ozonated water. Acetaldehyde migration from PETE can alter flavor profiles of foods and beverages.

Acetaldehyde imparts a fruity, green apple flavor and is found in many food products, including fruits, beverages, and yogurt. The sensory impact of the acetaldehyde taint from packaging is highly dependent on the food system. van Aardt *et al.* (2001a) determined human threshold levels for acetaldehyde in spring water (167 ppb), milk, and chocolate milk using a three-sample alternate forced choice test series with a panel of 25 people. Threshold values for acetaldehyde in milk (whole milk, 4040 ppb; low-fat milk, 4020 ppb; nonfat milk, 3939 ppb) were not affected by fat content. Chocolate milk had a threshold value of 10,048 ppb, which compared well with the results of Bills *et al.* (1972) who looked at the threshold level of acetaldehyde in strawberry milk (11,700 ppb). The higher threshold for chocolate milk, as compared to whole milk, is likely due to the masking effect that chocolate flavoring agents had on acetaldehyde flavor. Several authors have reported an increased acetaldehyde concentration due to exposure to light (Cadwallader and Howard, 1998; Cladman *et al.*, 1998; Jenq *et al.*, 1988; van Aardt *et al.*, 2001b). The combination of these two sources—migration from PETE packaging and exposure to light—could potentially raise the level of acetaldehyde in a food product above threshold levels.

van Aardt *et al.* (2001b) studied the sensory impact of acetaldehyde migration from PETE bottles into milk stored under light. Acetaldehyde concentration in light-exposed milk (3.25% milkfat, 18 days at 4 °C) packaged in clear PETE, clear PETE with UV blocker, amber PETE and high density PE (HDPE) was about the same as milk packaged in glass stored at the same conditions (range for all packaging: 1265–2930 μg/kg). A significant difference in the concentration of acetaldehyde in light-exposed milk as compared to light-protected milk was found. A trained sensory panel ($n = 8$) used a 9-point verbal category scale (1 = not detectable; 9 = very strong) and rated the acetaldehyde intensity around 2 (''trace, not sure'') for both light-exposed and light-protected milk from all packaging. No significant difference in sensory perception of acetaldehyde off-flavor due to either light exposure or bottle type was observed. This lack of a difference, even when significant differences in acetaldehyde concentration were found in light-exposed milk as compared to light-protected milk, is likely due to acetaldehyde concentrations below sensory thresholds for milk. Setting maximum specifications for acetaldehyde concentrations in PETE would protect against sensory impacts in bottled water, which has a very low sensory threshold for this compound.

Studying the sensory impact of materials in contact with water is valuable in understanding the impact of materials use in water distribution and food packaging. The trend for replacing copper piping with polymer-based plumbing materials has created a host of taste and odor problems associated with potable water (AwwaRF, 2002; Dietrich *et al.*, 2005; Rigal 1992, 1995; Rigal and Danjou, 1999; Tomboulian *et al.*, 2004).

Cross-linked polyethylene (PEX) used as home or retail plumbing materials can cause perceptible changes in the odor of tap water (Durand and Dietrich, 2007). A water industry standard flavor profile analysis (Standard Methods 2170B) was used by 10 trained panelists to determine the odor profile of synthetic tap water stored in PEX pipe, manufactured by a silane cross linking procedure. Water, with and without disinfectants (chlorine, chloramine), was stored in PEX pipes for 3–4 days and for three consecutive periods. Odor descriptions generally were summarized as ''burning-solvent, plastic'' odor at the weak to moderate level. A variety of descriptors were used with ''alcohol, plastic, and sweet chemical'' terms common in the first flush period. The addition of disinfectants provided odor characteristics described as ''glue.'' Subsequent flushes changed the odor profile with terms such as fruity, spicy, bitter, almond, rotten swampy, and burning plastic suggesting that the odor was becoming more distinct and perhaps even more objectionable. The chemical 2-ethyoxy-2-methylpropane (ETBE) was identified as a contributor to the odor of PEX pipe.

Marchsan and Morran (2002) found that flavor descriptions varied between chlorinated and nonchlorinated water in contact with PE and PP with stronger tastes frequently found in chlorinated samples. ''Plastic/rubber'' terms were used for chlorinated and nonchlorinated waters stored in PP and PE as well as in nonchlorinated waters from acrylonitrile/butadience/styrene (ABS). ''Plastic/chemical'' descriptors were used for chlorinated and nonchlorinated waters in PP and PE and polyurea materials, and in ABS materials for chlorinated waters only. Polyurethane materials contributed chemical tastes to chlorinated waters and medicinal flavors to nonchlorinated water. The ''chemical'' term also was applied to chlorinated water stored in PP, PE, and ABS and nonchlorinated water stored in ABS. ''Medicinal'' also was used to describe both nonchlorinated and chlorinated waters stored in PP.

Off-flavors in water and milk packaged in PE-coated paperboard cartons have been described by consumers as ''unpleasant plastic'' (Berg, 1980). Leong *et al.* (1992) examined the sensory impact of milk (nonfat (0.05%), lowfat (2%), and whole (3.25%)) packaged in gable-top PE-coated paperboard cartons (half-pint (236 ml), quart (946 ml), and half-gallon (1890 ml). A 10-member panel was selected based on discriminating ability for milk off-flavors and a paired comparison test or a pairwise ranking test was used to evaluate packaging flavor in the samples on days 1, 3, and 6 of storage at 2.2 °C. Control samples initially were packaged in HDPE at the manufacturer but transferred to glass containers within a few hours after transport to the laboratory. Half-pint milk samples (all fat levels) packaged in PE-coated paperboard were clearly distinguishable from milk packaged in glass. The ability to discriminate between milk packaged in PE-coated paperboard and glass increased with decreasing fat content. Packaging flavor seemed to develop most within the first three days of storage. More packaging flavor was found in half-pint packaged milk than in larger containers, probably because of the higher contact surface:volume ratio. Leong *et al.* (1992) documented that heat sealing of the cartons was not the source of the taint. Packaging flavor was found in water samples on day 1 similar to the results for low fat milk. Packaged flavor in milk stored in PE-coated paperboard develops within 24 h and is more easily detected with decreasing fat content, possibly because milk fat appears to mask or dilute this flavor defect (Leong *et al.*, 1992). This conflicts with most evidence that as fat content in a food product increases, so does that of the migration of volatile compounds from the packaging material to the food product and so does the presence of off-odors and flavors. However, nonfat milk has even less flavor character than lowfat and whole milk, which may be one reason that the package flavor is more evident. The most common packaging material for milk is now HDPE.

Many dairy processors blow mold HDPE containers for milk, juice, and water in the processing plant. Without proper specifications for sensory quality of the granules, taints may be readily noticeable in these products. HDPE pellets were reported to have low concentrations of odor-producing compounds but the sensory impact of these compounds, as determined by GCO was strong (Villberg *et al.*, 1997). Leachate water from high quality HDPE was described as having a sweet, metallic, stony, and pungent taste and sweet, chemical, stale, dirty, and foul odor. Some HDPE pellets contributed negative taste (dusty, stale, plastic, foul, stink bug, and candle grease descriptors) and odors (stale, dirty, foul). The majority of odor compounds were carbonyl compounds. 2-octenal, which gives a mushroom odor, and butylacrylate, which gives a glue-like odor, were the strongest, while moderate odors were imparted by 2-propanal (glue-like odor) and methyl hexanal (green, pungent) and were found only in the poor quality pellets. Other compounds found to leach into water from poor quality HDPE were 2,4-heptadienal, nonanal, and undecadienal. Ethyl propanate leached out in extremely small amounts but gave a very strong odor, which smelled like glue (Villberg *et al.*, 1997).

HDPE and epoxy, frequently used in home plumbing, were implicated in having the greatest impact on odors in tap water (Dietrich, 2007). A trained sensory panel, using the water industry standard flavor profile analysis method, evaluated six different plumbing materials for odor intensity. In order of increased odors in tap water (simulated) as a function of material indicated chlorinated polyvinyl chloride (cPVC) as having the least increase in odors, with cross-linked PE (PEX)-a, copper, and PEX-b having increasing levels of odors. Increased odors can cause sensory annoyance. Water stored in HDPE was characterized as having a ''waxy, plastic, citrus'' odor at moderate levels (Heim and Dietrich, 2007b). Odor intensity increased in the presence of chlorine and ''chemical, plastic'' descriptors were used; chloramine disinfectants also caused an increase in odor intensity described as ''waxy-crayon, plastic.''

Piagentini *et al.* (2002) studied the effects of citric acid, ascorbic acid, and type of packaging film on the sensory characteristics, chlorophyll retention, and weight loss of fresh cut spinach in refrigerated storage. Spinach was packaged in either mono-oriented PP bags or in LDPE bags and stored at refrigeration temperatures for 14 days. A trained sensory panel evaluated off-odor, appearance, wilting, and color using a 10 mm unstructured line scale. Storage time significantly (< 0.001) affected sensory attributes, while the type of packaging film only influenced off-odor development ($p < 0.001$). Off-odor development was greater for oriented PP than for LDPE. The type of packaging film had no effect ($p > 0.05$) on visual sensory characteristics. The intensity of off-odor packaged in LDPE reached an average of 7.3 after 14 days (9 = none, 0 = severe). The oriented PP had an average sensory value of 5 after 14 days. Di Pentima *et al.* (1995) found similar results with broccoli, whole spinach, and asparagus packaged in different plastic films stored at 4 °C.

4. Polyvinyl chloride (PVC) and chlorinated PVC (cPVC)

PVC and cPVC can have a metallic odor and taste due to accidental contamination by antimony (Tamboulian *et al.*, 2002). Phenolic and acetone odors are attributed to *m*-chlorophenol and cyclohexanone, respectively. Threshold levels for these compounds in water are 0.005 ppm for *m*-chlorophenol and 0.12 ppm for cyclohexanone. PVC pipes and polymer coatings have been found to have an organosulfur odor that is attributed to ethyl-2-mercaptoacetate. This compound arises from the interaction between low molecular weight alcohols with synthetic organic compounds added to PVC as a heat stabilizing agent (Sides *et al.*, 2001). Heim and Dietrich (2007b) did not find a significant odor in synthetic tap water stored in cPVC pipes compared to water stored in glass control pipes.

5. Epoxy

Epoxy is used as a lining for water reservoirs, water mains, and home plumbing systems (Heim and Dietrich, 2007a). These applications can impact sensory quality of tap water in food manufacturing, food service operations, and residential homes. This effect may be most noticeable in water but residual aroma and flavor compounds may cause a taint in foods prepared with these water sources. An odor assessment, using a water industry standard flavor profile analysis method, identified a strong relationship between water (simulated tap water, pH 7.7–7.9) stored in epoxy-lined copper pipes for 3–4 days and an odor described as ''plastic, adhesive, putty.'' In addition, a noticeable decrease in chlorine and chloramine disinfectant odors were identified (Heim and Dietrich, 2007a).

B. Taints from additives or noncontacting materials

The primary chemicals associated with taints are solvents or inks, aliphatic aldehydes and ketones, phenols or halogenated phenols, and anisoles (Lord, 2003).

1. Printing inks, varnishes

Color, graphics and labels on primary and secondary packages are used to inform, advertise, attract attention, and promote the product within. Printing (or packaging) inks and varnishes contain colorants, binders, solvents, and additives. Most of the off-odor related consumer complaints linked to packaging at Nestle were attributed to residual solvents from inadequate printing or converting processes or the use of low-quality promotional items (Huber *et al.*, 2002). These systems may be characterized as solvent-based, water-based, oleo-resinous, or UV- or electron beam (energy) curing (Aurela and Soderhjelm, 2007). Although these materials are applied to the external surface of the packaging material, low molecular weight compounds will easily migrate through the packaging material, with the exception of glass and aluminum foils, into the food. Some of these compounds have a noticeable smell and can contribute to taint of the food product. Oxidized aromas in the foods may be partially related to oxidation of vegetable oils used in offset printing or alkyd resins, used as binders in inks. Aldehydes and ketones resulting from the oxidation process can unexpectedly modify the flavor and odor of food within the package, creating a negative, even repulsive, sensory response (Soderhjelm and Eskelinen, 1985). Mineral oils may contain aromatic compounds, which can diffuse readily through fibrous or plastic packaging materials. Toluene and xylene, which are aromatic compounds, should be avoided in printing of food packages (Aurela and Soderhjelm, 2007). Hydrocarbon compounds in lithographic inks have been sources of taints (Kilcast, 1996). Low odor inks and varnishes should be chosen. At the minimum, adequate time for airing for solvent or UV-cured systems, which may produce taints from trace residues of acrylate monomers and from benzophene photoinitiators, before packaging should be allowed (Aurela and Soderhjelm, 2007; Kilcast, 1996). Printed and varnished paperboards containing residual solvents may be one of the main sources of taints in foods (Soderhjelm and Eskelinen, 1985).

Placing printed premiums (coupons) within a food package is common but these materials also may be sources of taints. Premiums intended for packaged dry mix beverages were tested for their contribution of odors prior to inclusion (Apostolopoulos, 1998). Overwrapped (PE) and unwrapped premiums were placed in Mason jars, sealed, and heated at 49 °C for 1 h and cooled. An odor evaluation panel ($n = 4$), familiar with solvent odors associated with the packaging industry, rated odor intensity on a scale of 0–10 (0 = no odor; 8–10 = excessive odor), described the odor, and also indicated if the odor was objectionable or not. The solvent odor was attributed to the PE resin or the paint used with the premiums. Cyclohexane concentration, as determined by GC/MS was 16 times higher in unwrapped premiums than attributed to the overwrapped premiums; toluene, 2-methyl heptane, and 3-methyl hexane also were detected. The sensory panel identified no odor associated with the overwrapped premiums but identified a very strong (rating of 9), solvent-like, objectionable odor for the unwrapped premiums. The PE overwrap contributed no distinct odor and effectively contained the premium odor. The paint used in the manufacturing and printing of the premiums was implicated. However, unsealed or punctured overwrap would not provide appropriate protection, potentially leading to taints in the beverage powders.

2. Coloring agents

Coloring agents are often used in materials to provide protection from visible and ultraviolet light, and should be considered as a potential source of taints. Heinio and Ahvenainen (2002) studied the odor of packaging materials as a function of different coloring agents. However, there was no direct indication, based on odor, that the coloring agent was the source of taint in the packaged food. They recommended that odor testing should only be regarded as an indicator.

3. Antioxidants

Tomboulian *et al.* (2002) has reported that butylated hydroxytoluene (BHT) can impart a ‘‘burnt plastic’’ odor and is an additive in HDPE pipes. Quinone may be derived from BHT due to interactions with residual chlorine in pipes (Anselme *et al.*, 1985). Yam *et al.* (1996) reported that antioxidants, such as vitamin E, Irganox 1010, and BHT, contributed to off-flavors in water. Vitamin E yielded less off-flavor, possibly due to lower aldehyde and ketone concentrations. Extrusion temperatures over 280 °C and exposure time for melt contributed to more oxidation of LDPE films and higher intensities of off-flavors in water in contact with LDPE with different antioxidants (Andersson *et al.*, 2005).

C. Taints from recycled materials

Recycled materials may contain absorbed odorous or flavorful molecules from earlier use that, when introduced into a new packaging material, may cause taint (Franz and Welle, 2003; Kilcast, 1996). Analytical detection limits of instrumentation may be higher than sensory thresholds from some flavor compounds so, while the recycled material may appear to have low or nondetectable concentrations of volatile contaminants, there may be sufficient levels for sensory detection (Franz and Welle, 2003).

Limonene, for example, is readily absorbed from citrus juices into packaging materials. Analysis of recycled PETE after exposure to model compounds showed average and maximum values of 18.6 and 86 ppb for acetaldehyde and 2.8 and 20 ppb for limonene. Analysis of contaminants such as solvents in recycled plastics showed extremely low levels ranging from 1.4 to 2.7 ppb and resulted from only 0.03% to 0.04% of the recollected PETE bottles (Franz *et al.*, 2004). Recycled HDPE, PP, PS, and PETE polymers demonstrated sensory properties characteristic of the virgin polymers but also additional odor notes (Huber and Franz, 1997). A sensory panel readily identified the recycled polymer from virgin polymers based on these additional odor notes. Recycled HDPE was most different from the virgin material whereas recycled PETE had the lowest odor deviation. Recycled PS and PP had more odor notes than the matched virgin material but did not have as great a difference as was found for HDPE. Use of recycled materials should be considered on a case by case basis, using appropriate sensory testing to verify sensory intertness of recycled PETE or any other materials (Franz and Welle, 2003). If the contained product is bland in odor and flavor, the impact of these molecules may be even more evident (Kilcast, 1996). Recycled materials would not be appropriate for water or milk packaging.

With the continuing desire to recycle and reuse plastic packaging materials to reduce their environmental impact, the absorption of compounds into the packaging material will become increasingly important. It has been reported that the recycling process used for plastics are not completely efficient in their ability to eliminate absorbed compounds. These compounds can then desorb into the new product upon reuse of the plastic (Safa and Bourelle, 1999). Deep cleaning, or supercleaning, technologies for recycled polymers are safe and produce bottles with very low levels of contamination, positively influencing sensory properties of the recycled materials (Franz and Welle, 2003; Franz *et al.*, 2004).

VII. SCALPING/SORPTION

Sorption of flavor compounds, or more colloquially "scalping," is considered a major factor in the degradation of food quality (Arora *et al.*, 1991; Ayhan *et al.*, 2001; Charara *et al.*, 1992; Fukamachi *et al.*, 1996). The term sorption encompasses the properties of absorption, adsorption, and cluster formation and describes the penetration and movement of a chemical compound into a polymer (Robertson, 2006). Aroma and flavor perception often involves the interplay of many compounds in a specific proportion. Therefore, any disturbance of this balance due to sorption can change the sensory characteristics of the product and reduce its acceptability (Arora *et al.*, 1991; Sajilata *et al.*, 2007). All plastic materials have some sorption capacity for flavor molecules (Gremli, 1996), which can result in a sensory impact. Higher storage temperatures will accelerate the sorption of volatiles. Volatiles associated with flavor of a given food product may be decreased by as much as 20% by sorption (Gremli, 1996).

Absorption of flavor molecules into the package may be affected by a number of parameters associated with the material and the food (van Willige, 2002). Crystallinity, morphology, and polarity of polymers can influence the rate of absorption. Size, concentration, copermeants, and polarity of flavor molecules within the food system also affect absorption. Storage temperature and time exposed to the food matrix affect polymer and food matrices, creating additional challenges in determining effects of materials in contacts with foods.

Not only can absorption alter the aroma and flavor of a product, it can also change the mechanical properties of the polymer. Swelling and gas permeability are factors that effect the physical properties of a polymer (Robertson, 2006; Sadler and Braddock, 1991; Safa and Bourelle, 1999). Swelling occurs when compounds are absorbed into the polymer and distort the shape of the package. As absorption increases there is also a subsequent increase in gas permeability. This increase in gas permeability can affect the shelf-life and sensory quality of a food by, for example, increasing oxidation. In very severe cases, absorption can affect package integrity.

Color and appearance of a food are important quality aspects on which consumers base many initial purchase and consumption decisions. Nylon-6 polyamides may scalp dye materials from foods, altering the food color intensity. Liquids and moist foods (high water content) in direct contact with the polymer have the greatest potential for changes or loss of color. Migration of food colorants into packaging material can alter the package and product appearance or cause staining of food contact surfaces on household items. Such problems increase consumer complaints and lead to decreased sales (Oehrl *et al.*, 1991). However, there is very little published research that directly considers color and appearance changes as a function of interaction of materials and colorants.

There are a number of studies that look at the absorption of flavor compounds into different polymer packaging materials (Arora *et al.*, 1991; Ayhan *et al.*, 2001; Charara *et al.*, 1992; Fukamachi *et al.*, 1996; Hernandez-Munoz *et al.*, 2001; Imai *et al.*, 1990; Konczal *et al.*, 1992; Letinski and Halek, 1992; Moshonas and Shaw, 1989; Nielsen *et al.*, 1992; Sadler and Braddock, 1991; Safa and Bourelle, 1999; van Willige *et al.*, 2000, 2002, 2003). There are fewer studies looking at the effect that this absorption has on the sensory quality of the food. The few sensory studies that have been done to date are contradictory and more research into this area is imperative (Ayhan *et al.*, 2001; Durr *et al.*, 1981; Kwapong and Hotchkiss, 1987; Mannheim *et al.*, 1987; Moshonas and Shaw, 1989; Pieper *et al.*, 1992; Sadler et al, 1995; Sharma *et al.*, 1990).

Several studies found that scalping of flavor volatiles by polymers did not affect the sensory quality of juices. Sharma *et al.* (1990) found that fruit squashes and tropical fruit beverages stored with PP and PE had no differences detected using triangle testing. Pieper *et al.* (1992) reported that a 50% decrease in limonene concentration, along with a small decrease in alcohol and aldehyde concentration, did not affect the sensory quality of orange juice. Sadler *et al.* (1995) tested the effect of volatile compound absorption from orange juice into LDPE, PETE, and EVOH stored at 4.5 °C for 3 weeks on the sensory characteristics of the juice and observed no change. van Willage (2002) reported that a sensory panel ($n = 27$) could not find a significant difference in flavor of reconstituted orange juice packaged in LDPE, PET, or polycarbonate (PC) although analytical flavor chemistry documented a large decrease in flavor constituents.

Other investigators, however, found that the absorption of flavor compounds by polymer packaging material did affect the perception of odor and flavor (Ayhan *et al.*, 2001; Kwapong and Hotchkiss, 1987; Mannheim *et al.*, 1987; Moshonas and Shaw, 1989). A sensory panel found no significant difference in color in orange juice processed by pulsed electric field stored in glass, PETE, HDPE, and LDPE, even though there were significant analytical differences (Ayhan *et al.*, 2001). A significant difference in flavor was found in juice stored in LDPE after 56 days compared to the other packaging materials but no significant differences were found in flavor after 112 days in glass, PETE, and HDPE. Overall, the retention of all flavor compounds was significantly higher in glass and PETE than HDPE and LDPE. An increase in storage temperature had adverse effects on flavor and color. There was more loss of aldehydes and esters in all packages after 2 weeks than hydrocarbons, and flavor loss was more advanced in HDPE and LDPE than in PETE and glass. These results can be explained by both the absorption of flavor compounds and by the acceleration of the production of degradation products due to oxygen permeability and increased storage temperature (Ayhan *et al.*, 2001).

VIII. PROTECTION OF SENSORY QUALITY BY FOOD PACKAGING

Packaging materials can significantly increase the shelf-life of a food by reducing or slowing the degradation of the food. Package characteristics such as decreased oxygen and light permeability, for example, are responsible for the increased shelf-life. The proper choice of packaging, while at times difficult to do, is extremely important for protecting and maintaining sensory quality.

Saint-Eve *et al.* (2008) identified that packaging choice affected the sensory quality, specifically aroma, of flavored stirred yogurts with 0% or 4% fat content. A trained sensory panel (n = 8–15) evaluated yogurt packaged in glass, PS, or PP over a 28-day refrigerated storage period. Evaluations, using an unstructured line scale with ''weak'' and ''very intense'' as the anchors, reflected 10 odor, 15 aroma, 2 taste, and 3 texture-in-mouth characteristics. While aroma intensity and profile changed for yogurts packaged in all materials over time, glass provided the best protection for aroma and flavor intensity as it had the best barrier properties. A time effect was evident with relation to sensory perception and scalping of aroma compounds. Loss of some aroma compounds was greater in yogurts stored in PP than in PS but the flavor chemistry stabilized before the 28th day of storage for yogurt packaged in PP. The kinetics of aroma compound sorption were slower in PS than in PP, perhaps because of the differences in crystallinity between the two materials at 4 °C. Nonfat yogurts packaged in glass and PS developed similar sensory odor and aroma changes over the 28-day storage. Fruity notes were better retained in PS-packaged products compared to PP-packaging but more acids were also noted. The authors also suggested that higher fat content (4%) product may lose less volatiles into packaging by absorption because of the lipophilic nature of many aroma compounds, thereby reducing the interaction with packaging materials. Fewer or less intense flavor and odor defect characteristics were identified in 4% yogurts packaged in PS at the end of shelf-life than for yogurt packaged in glass or PP.

A. Protection against light

One major reason for nutrient loss and off-flavor development today is due to extended exposure to fluorescent light in food retail display cases. Many foods and beverages are susceptible to light-induced reactions, especially those with photo-sensitizers. Natural pigments found in foods that commonly act as photochemical initiators are flavonoids, riboflavin (vitamin B_2), chlorophyll, heme, and vitamin K.

The chemical effects of photo-oxidation on food components results in off-flavor development or changes in pigmentation or appearance. Dairy products, which are very susceptible to photo-oxidation, develop a distinct, unpleasant flavor described as ''cardboard'' or ''burnt feathers'' (Bodyfelt *et al.*, 1988). Sunstruck flavor of beer is also a noteworthy flavor defect caused by light. Fruits, vegetables, pigmented beverages, candies, and other colored food systems may demonstrate color change from photo-oxidation of pigments. Ingredients, such as powdered milk, flavorings, and colorants, will develop off-flavors, off-odors, or color changes as a function of light exposure. The use of packaging materials to protect food systems from the effects of light is common. However, the most effective solutions for protection of product and ingredient sensory quality is to provide a complete light block, which is not always the most effective method for marketing a product to consumers.

The primary plastic packaging materials used for refrigerated milk products are HDPE and PETE (Anonymous, 2002). Clear glass, olefin-coated fiberboard, blow molded PE, and high-density PC or PE also are used. Glass allows 91% light transmission, HDPE allows 57%, while fiberboard allows 4% light transmission. Fiberboard containers were found to protect milk from light oxidation for up to 48 h whereas milk in plastic or glass containers developed light oxidized flavor within 12 h of exposure to 100–200 ft-c fluorescent light. Milk in clear PE pouches showed off-flavor development in 6 h after exposure to 100 ft-c and 3 h at 200 ft-c.

Many investigators have found that packaging materials that protect milk and dairy products from photo-oxidation are important to sensory quality (Christy *et al.*, 1981; Cladman *et al.*, 1998; Dimick, 1973; Gorgern, 2003; Papachristou *et al.*, 2006a,b; Rysstad *et al.*, 1998; Simon and Hansen, 2001; van Aardt *et al.*, 2001b; Zygoura *et al.*, 2004). Zygoura *et al.* (2004) found that both clear and pigmented (2% TiO_2) PETE had significantly higher lipid oxidation than paperboard and 3-layer pigmented coextruded HDPE and monolayer pigmented HDPE between days 3 and 7 (end of test). Oxygen permeability of the packaging material did not affect oxidation, but this could have been due to the large headspace of the packages used. Sensory evaluation, using a trained panel and a flavor and intensity rating scale (0 = unfit for consumption, 5 = very good), showed that milk packaged in clear bottles had a much lower acceptability score than milk packaged in pigmented bottles.

Simon and Hansen (2001), using an untrained panel and a ''difference from control'' test, found that milk packaged in oxygen barrier board (EVOH and foil) deteriorated much more slowly than milk packaged in standard or juice boards. The foil-lined board had the added benefit of a light block. Inhibition of oxygen permeation into a package does not solely protect against degradation. Milk packaged in HDPE with a carbon black layer (light barrier) and no oxygen barrier was shown to have better protection against light oxidation than HDPE with an EVOH oxygen barrier but no light barrier (Gorgern 2003; Moyssiadi *et al.*, 2004).

PETE has an advantage over high-density poly(ethylene) (HDPE), the polymer currently used for the larger sizes of milk packaging, since the oxygen transmission rate at 4 °C, 50% relative humidity, and 21% oxygen of a commercial one-pint PETE bottle is 19 μl/day compared to 390–460 μl/day for a commercial one-pint HDPE bottle (van Aardt *et al.*, 2001b). However, translucent HDPE has an advantage over clear PETE in that it blocks approximately 40% light between 300 and 700 nm, whereas clear PETE only blocks ~20% light in the same range (van Aardt *et al.*, 2001b).

The efficacy of film over-wraps, made from single and multilayers of iridescent film, to reduce the production of light oxidation in milk and for effectiveness in controlling light oxidized flavor in milk was tested (Webster, 2006; Webster *et al.*, 2007). A balanced incomplete block multisample difference test using a ranking system and a trained panel was used for the evaluation of light oxidation flavor intensity. Packaging overwraps limited the production of light oxidation flavor in milk over time but not to the same degree as the complete light block. Blocking all visible riboflavin excitation wavelengths was better at reducing light oxidation flavor than blocking only a single visible excitation wavelength. However, blocking transmission of all riboflavin excitation wavelengths at the levels suggested by the International Dairy Federation (IDF) was not sufficient to completely protect against the production of light oxidation flavor, suggesting the presence of a photosensitizer other than riboflavin in the milk.

Bray *et al.* (1977) found that 73% of 2000 consumers preferred nonexposed milk to light exposed milk.

B. Preventing moisture loss

Protection of color and texture, as well as odor and flavor, of food products also is an important consideration when choosing the appropriate food packaging material. Nylon-LDPE plastics helped protect vacuum-packaged burnt coconut meat and coconut water from color and texture changes over a 28-day storage compared to a PVC film (Jangchud *et al.*, 2007). Burnt aromatic coconut water and meat were stored at 5 °C and 80–90% relative humidity in two package treatments with an unwrapped treatment as the control and evaluated over a 28-day shelf-life. Packaging treatments included: (1) PVC film (thickness: 11 μm; water vapor transmission rate (WVTR): 210 g/(m^{2}d); OGTR: 8133 cc/(m^{2}d bar)); and (2) under conditions of vacuum in a Nylon: linear LDPE plastic bag (15 μm, 120 μm thickness each, respectively; WVTR: 5.1 g/(m^{2}d); OGTR: 73 cc/(m^{2}d bar)). Sensory evaluation of color (water: yellow, transparency; meat: white), texture (hardness), as well as several odor and flavor characteristics were assessed on a 15-cm unstructured line scale (0 = "weak"; 15 = "strong") by 12 experienced/trained panelists. Vacuum packaging effectively ESL of the burnt coconut by limiting color alteration in the coconut water and meat and maintaining hardness of the coconut meat. Panelists rated the coconut packaged in Nylon: linear LDPE with high acceptability after 28 days whereas the PVC-film wrapped treatment had declined in quality, partially as a result of increased microbial growth, by 14–18 days. The barrier properties of the Nylon: linear LDPE film maintained the desired vacuum storage of the product, which contributed to the improved product quality.

IX. USING PACKAGING TO IMPROVE SENSORY QUALITY

Smart packaging, referring to value-added packaging features that enhance the functionality of a product, encompasses active packaging as well as other developments that improve product safety and efficiency (Robertson, 2006). Examples of active packaging systems include oxygen and ethylene scavengers, carbon dioxide scavengers and emitters, preservative releasers, ethanol emitters, moisture absorbers, and flavor/odor adsorbers. Innovative technologies for these systems may have intended impact on sensory characteristics of foods through control of microbial growth, oxidation reactions, moisture migration, and absorbance of undesirable odor-impacting molecules. While there is a large body of literature in the area of smart (active, intelligent, other) packaging materials and systems, the relationship to sensory impact on humans is secondary to the chemical or microbiological impacts, including analytical flavor chemistry, that are primarily studied. We have illustrated the potential for sensory impacts of some packaging innovations with a few examples.

A. Sensory impact of novel antimicrobial ingredients in packaging systems

Controlling microbial degradation of food systems is paramount in maintaining sensory quality. Inclusion of antimicrobial agents from naturally derived sources within the polymer reduces the risk from a consumer perspective (Suppakul *et al.*, 2008). Extracts of clove, grapefruit seeds, huanglian, rhubarb, and basil have been embedded in LDPE to test for antimicrobial effects (Suppakul *et al.*, 2008). Linalool and methylchavicol, antimicrobial compounds from basil were embedded in LDPE and demonstrated inhibitory effects on microbial growth in naturally contaminated cheddar cheese samples. These materials (control LDPE film, linalool-LDPE, and methylchavicol-LDPE) also were tested for sensory impacts on wrapped, cubed cheddar cheese over 6 weeks of storage at 4 °C. The materials and the cheese were both sterilized by ultraviolet light prior to contact. Using a triangle test method, a panel of 10 members evaluated the cheese for basil taint. Linalool-embedded LDPE did not impact flavor of the cheddar cheese over the 6-week storage as panelists could not detect the difference between cheese stored in LDPE or linalool-embedded LDPE. However, methylchavicol-embedded film caused a taint in the cheese as early as 7 days. This sensory impact was detectable again only in the fourth week of the study. Methylchavicol was reported to have a more distinct flavor than linalool and was more evident in the cheese. While the microbial shelf-life of cheese was improved with use of methylchavicol-embedded LDPE as compared to linalool-LDPE and LDPE control materials, sensory effects were noticeable with use of this compound, illustrating the potential for reducing the commercial success of the antimicrobial material (Suppakul *et al.*, 2008). Selection of naturally occurring antimicrobial agents or other active additives should be based on both intended efficacy as well as potential for protecting the sensory integrity of the product.

B. Flavor and odor absorbers for improved flavor

Some food processing methods impose negative sensory quality parameters on food systems. UHT processing of fluid milk and citrus juices, for example, increases the perception of cooked or stale flavor and odor notes because of thermal degradation of macro- and micronutrients within the system. An increase in low molecular weight aldehydes and ketones has been identified as primary contributors to these negative sensory characteristics in heat processed beverages (Suloff, 2001). Milk, soymilk, and water are bland, having low flavor and odor profiles, and low concentrations of migrating molecules from PETE or other materials can influence sensory quality (Norton, 2003; van Aardt *et al.*, 2001a,b). Odor-adsorbing materials were synthesized from cyclodextrin, d-sorbitol, and nylon MXD6 blended with PETE for removal of aroma compounds associated with lipid oxidation (Suloff *et al.*, 2003) and identified that selective adsorption of low molecular weight aldehydes, compared to larger aldehydes, occurred with partition coefficients of three to six times higher magnitude. Cooperatively, Norton (2003) demonstrated the human sensory impact by evaluating the sensory threshold for targeted compounds and the efficacy of the odor-absorbing compounds in spring water, milk, and UHT procesed ESL soymilk.

Norton (2003) initially established the sensory impact of selected molecules to establish if absorption by the scavenging compounds would be at efficacious levels. Low molecular weight aldehydes and ketones (hexanal, 2-heptenal, 2-pentanone, and 2,4-nonadienal) in spring water, pasteurized milk (2% milkfat), and ESL soymilk were selected as representative compounds of oxidation and high temperature processing notes. Human thresholds, based on 12 panelists, were determined, in ascending order of concentration using a series of 3-sample alternate forced choice tests, by both logistic regression and the geometric mean approach. Testing was done under controlled conditions in individual sensory booths. Untrained panelists initially were provided a reference sample of the selected compound at supratheshold concentration in the testing medium. Thresholds calculated using logistic regression were consistently higher than those calculated using the geometric mean approach, but both methods found thresholds of hexanal, 2-heptenal, 2-pentanone, and 2,4-nonadienal to vary significantly when comparing the three media. Hexanal and 2,4-nonadienal had lower thresholds than 2-heptenal and 2-pentanone. Odor detection thresholds of 2-heptenal, 2-pentanone, and 2,4-nonadienal were lowest in water, followed by milk, then soymilk at product temperatures of 4 °C.

Triangle tests ($n = 36$ panelists, α 0.05) verified that five combinations of absorber addition in volatile-spiked spring water, milk and soymilk altered the aroma of the product. Addition of β-cyclodextrin in both hexanal-spiked spring water and milk significantly influenced odor. Panelists also found a significant difference ($p < 0.05$) in 2-pentanone spiked milk with the addition of both β-cyclodextrin and d-sorbitol and in 2-heptenal spiked soymilk with the addition of d-sorbitol. Because of its ability to adsorb odors caused by lipid oxidation, β-cyclodextrin may be a good scavenger in packaging systems for milk and soymilk. However, since β-cyclodextrin is very reactive with low molecular weight compounds, there is a possibility that desirable aromas could also be scavenged. d-sorbitol also was somewhat effective as a scavenger for aroma compounds, particularly in milk. The authors did not report on efficacy of these active components in absorbing volatiles when imbedded into the material.

C. Controlling oxidation through timed release of antioxidants

Active packages can be designed that contain compounds, such as antioxidants, which can migrate into the food and improve sensory quality by reducing oxidation, increasing shelf-life, and increasing nutritive quality. Additives are commonly used in polymer processing to inhibit oxidative reactions (Robertson, 2006). Excess addition of antioxidants, such as butylated hydroxyanisole (BHA) or BHT, has been effective in controlling oxidized flavor in dry breakfast cereals and crackers and other dry products (Hoojjat *et al.*, 1987; Jadhav *et al.*, 1996; Miltz *et al.*, 1995).

van Aardt *et al.* (2005a,b, 2007) studied the effect of antioxidant addition into milk and poly(lactide-co-glycolide) (PLGA) films to determine if timed release of antioxidant addition from packaging might be effective in limiting photo-oxidation of fluid milk and milk powders. Similarity testing, using triangle test methods, identified that levels of added antioxidants (0.05% α-tocopherol or 0.025% α-tocopherol or 0.025% ascorbic acid) to reduced fat milk (2% milkfat) were not significantly perceptible by panelists ($n = 30$). Subsequently, milk was spiked with and without antioxidants and exposed to light (1100–1300 lx) for 10 h at 4 °C. A sensory panel ($n = 24$) compared the samples for difference, using the triangle test method. Milk with tocopherol/ascorbic acid addition was different from the light-exposed control and had a fresher milk flavor, indicating that antioxidant addition had controlled photo-oxidation. However, tocopherol alone did not provide any benefit. A timed addition of antioxidants from packaging was studied by the direct addition of antioxidants to milk over a 6-week period under lighted refrigeration conditions (van Aardt *et al.*, 2005b). The timed effect did reduce concentrations of some odor-active compounds associated with light-induced oxidation, as determined by GCO evaluations by a trained panel ($n = 3$). A combination of BHA and BHT significantly reduced the concentrations of heptanal and 1-octene-3-ol, which are common light oxidation off-flavor compounds in light-exposed milk (van Aardt *et al.*, 2005b). The single, initial addition of a combination of α-tocopherol and ascorbyl palmitate significantly reduced hexanal production for the first 4 weeks of the study but not thereafter. In a separate study, antioxidants were incorporated into PLGA films; films were stored in milk powders and water and oil food simulants in the presence and absence of light (van Aardt *et al.*, 2007). Milkfat was stabilized to a degree, based on GC analysis of volatiles, against photo-oxidation of milk powders in the presence of antioxidant-loaded PLGA but sensory analysis was not used as confirmation. Although the sensory studies completed (van Aardt *et al.*, 2005a,b) document the potential benefit for timed-release of antioxidants, there is no direct evidence that the change in flavor chemistry from the PLGA films resulted in a sensory impact of the milk powders or food simulants.

The potential for smart packaging for improvement of food quality and safety is very high. Although sensory evaluation is essential in the early stages of development, there is an important role for sensory evaluation simultaneously with analytical assessments of new materials in contact with food systems. New materials or novel applications of materials may deliver value in improved sensory quality or create unexpected sensory impact that may not be interpreted from analytical chemical or physical methods of assessment.

X. CONCLUSIONS

Sensory impacts from food–packaging interactions are probably more prevalent than acknowledged. Studies that have included controlled sensory analysis concurrently with analytical methods for studying the effects of materials on foods have demonstrated that human assessment is needed. All sectors of the food packaging supply line are important in controlling the risk of taints and avoiding quality degradation from scalping of valuable volatiles and pigments. Commitment to understanding sensory impacts from interaction of food and packaging materials can lead to innovations for improved quality and shelf-life of food systems.

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REFERENCES

Ahvenainen, R. (ed.) (2000). ''Novel Food Packaging Techniques.'' Woodhead, CRC Press, Boca Raton, FL. 590pp.

Andersson, T., Holmgren, M. H., Nielsen, T., and Wesslen, B. (2005). Degradation of low density polyethylene during extrusion. IV. Off-flavor compounds in extruded films of stabilized LDPE. *J. Appl. Polym. Sci.* **95**, 583–595.

Anonymous. (1988). Migration of toxicants, flavors, and odor-active substances from flexible packaging materials to foods. *Food Technol.* **42**, 95–102.

Anonymous. (2002). Packaging opportunities for fluid milk. *Dairy Foods* **5**, A–H.

Anonymous. (2007). Free from off odour and off flavour. Colorants and additives in food and beverage packaging. *Verpackungs-Rundschau* **58**(12), 49–50.

Anselme, C., Nguyen, K., Bruchet, A., and Mallevialle, J. (1985). Can polyethylene pipes impart odors in drinking-water. *Environ. Technol. Lett.* **6**, 477–488.

Apostolopoulos, D. (1998). Identification of the source of an off-odor in premiums intended for use with dry mix beverages. *In* ''Food Flavors: Formation, Analysis and Packaging Influences'' (E. T. Contis, C. T. Ho, C. J. Mussinan, T. H. Parliament, F. Shahidi, and A. M. Spanier, eds.), pp. 753–757. Elsevier Science BV, Amsterdam, The Netherlands (*In* Sajilata, M. G., Savitha, K., Singhal, R. S., and Kanetkar, V. R. (2007). Scalping of flavors in packaged foods. *Comp. Rev. Food Sci. and Food Safety* **6**, 17–35).

Arora, D. K., Hansen, A. P., and Armagost, M. S. (1991). Sorption of flavor compounds by low density polyethylene film. *J. Food Sci.* **56**, 1421–1423.

Aurela, B., and Soderhjelm, L. (2007). Food packaging inks and varnishes and chemical migration into food. Ch. 13. *In* ''Chemical Migration and Food Contact Materials'' (K. A. Barnes, C. R. Sinclair, and D. H. Watson, eds.), pp. 302–319. Woodhead, Cambridge, England.

Australian Food and Grocery Council (AFGC). (2007). ''Organohalogen Taints in Foods.'' AFGC, Canberra, Australia. 16pp. (http://www.afgc.org.au).

Ayhan, Z., Yeom, H. W., Zhang, Q. H., and Min, D. B. (2001). Flavor, color, and vitamin C retention of pulsed electric field processed orange juice in different packaging materials. *J. Agric. Food Chem.* **49**, 669–674.

Baigrie, B. (ed.) (2003). ''Taints and Off-Flavours in Food.'' Woodhead, CRC Press, Boca Raton, FL. 203pp.

Baner, A. L. (2000). Case study: Styrene monomer migration into dairy products in single serve portion packs. *In* ''Plastic Packaging Materials for Food: Barrier Function, Mass Transport, Quality Assurance, and Legislation'' (O.-G. Piringer, and A. L. Baner, eds.), pp. 427–443. Weinheim (Feberal Republic of Germany), Wiley-VCH.

Barnes, K. A., Sinclair, C. R., and Watson, D. H. (eds.) (2007). ''Chemical Migration and Food Contact Materials,'' 464pp. Woodhead, CRC Press, Boca Raton, FL.

Berg, N. (1980). Sensoric and instrumental analysis of off-flavour giving compounds from polyethylene. Presented at 3rd *Int. Symp. Migration*, Hamburg, Germany, October 22–24. Unilever Forschungsgesellschaft mbH, Hamburg, Germany. In Leong, C. M. O., Harte, B. R., Partridge, J. A., Ott, D. B., and Downes, T. W. (1992). Off-flavor development in milk packaged in polyethylene-coated paperboard cartons. *J. Dairy Sci.* **75**, 2105–2111.

Berg, H. W., Filipello, F., Hinreiner, E., and Webb, A. D. (1955). Evaluation of threshold and minimum difference concentrations for various constituents in wines. *Food Technol.* **9**, 23–26.

Bills, D. D., Yang, C. S., Morgan, M. E., and Bodyfelt, F. W. (1972). Effect of sucrose on the production of acetaldehyde and acids by yogurt culture bacteria. *J. Dairy Sci.* **55**, 1570–1573.

Bodyfelt, F. W., Tobias, J., and Trout, G. M. (1988). ''The Sensory Evaluation of Dairy Products.'' Van Nostrand Reinhold, New York, NY. 598pp.

Bray, S. L., Duthie, A. H., and Rogers, R. P. (1977). Consumers can detect light-induced flavor in milk. *J. Food Prot.* **40**, 586–587.

Brody, A. L. (2002). Flavor scalping: Quality loss due to packaging. *Food Technol.* **56**(6), 124–125.

Buettner, A., Strube, A., and Welle, F. (2007). Can sensory analysis of packaging materials be standardized? *Verpackungs-Rundshau* **58**(6), 97–99.

Cadwallader, K. R., and Howard, C. L. (1998). Analysis of aroma-active components of light activated milk. *In* ''Flavor Analysis: Developments in Isolation and Characterization'' (C. J. Mussinan, and M. J. Morello, eds.), pp. 343–358. ACS, Washington, DC.

Caul, J. F. (1961). The American approach to odour in the packaging of food. *World's Paper Trade Rev.* 2325–2337.

Charara, Z. N., Williams, J. W., Schmidt, R. H., and Marshall, M. R. (1992). Orange flavor absorption into various polymeric packaging materials. *J. Food Sci.* **57**, 963–972.

Christy, G. E., Amantea, G. F., and Irwin, R. E. T. (1981). Evaluation of effectiveness of polyethylene over-wraps in preventing light-induced oxidation of milk in pouches. *Can. Inst. Food Sci. Technol. J.* **14**, 135–138.

Cladman, W., Scheffer, S., Goodrich, N., and Griffiths, M. W. (1998). Shelf-life of milk packaged in plastic containers with and without treatment to reduce light transmission. *Int. Dairy J.* **8**, 629–636.

Council AFaG. (1997). Organohalogen taints in foods. *Food Australia* **59**(3), S1–S16.

Dabrowska, A., Borcz, A., and Nawrocki, J. (2003). Adehyde contamination of mineral water stored in PET bottles. *Food Addit. Contam.* **20**, 1170–1177.

Dietrich, A. M. (2007). Sensory impacts from polymer pipes interacting with drinking water oxidants. Abstract POLY 684. Am. Chem. Soc. Annual Meeting, Boston, MA.

Dietrich, A., Cuppett, J., Edwards, M., Powers, K., Duncan, S., Bosch, D., and Kleczyk, E. (2005). Corrosion of copper plumbing and its effects on consumer health and economics. Proceedings of the 2005 NSF DMII Grantees Conference, Phoenix, Arizona, p. 14.

Dimick, P. S. (1973). Effect of fluorescent light on the flavor and select nutrients of homogenized milk held in conventional containers. *J. Milk Food Technol.* **36**, 383–387.

Di Pentima, J., Rios, J., Clemente, A., and Olias, J. (1995). Biogenesis of off-odor in broccoli storage under low-oxygen atmosphere. *J. Agric. Food Chem.* **43**, 1310–1313.

Duncan, S. E. (2007). Flavor and aroma of food and package interaction: Perception and communication. Abstract POLY 686. Am. Chem. Soc. Annual Meeting, Boston, MA.

Durand, M. L., and Dietrich, A. M. (2007). Contributions of silane cross-linked PEX pipe to chemical/solvent odours in drinking water. *Water Sci. Technol.* **55**(5), 153–160.

Durr, P., Schobinger, U., and Waldvogel, W. (1981). Aroma quality of orange juice after filling and storage in soft packages and glass bottles. *Alimenta* **20**, 91–93. (*In* Linssen, J. P. H., van Willige, R. W. G., and Dekker, M. (2003). Packaging-flavour interactions. Ch. 8. *In* ''Novel Food Packaging Techniques'' (R. Ahvenainen, ed.), pp. 144–171. Woodhead, CRC Press, Boca Raton, FL).

Ewender, J., Lindner-Steinert, A., Ruter, M., and Piringer, O. (1995). Sensory problems caused by food and packaging interactions: Overview and treatment of recent case studies. *In* ''Foods and Packaging Materials—Chemical Interactions'' (P. Ackermann, M. Jagerstad, and T. Ohlsson, eds.), 12pp. Royal Society of Chemistry, Cambridge, England.

Ewender, J., Franz, R., Mauer, A., and Welle, R. (2003). Determination of the migration of acetaldehyde from PET bottles into non-carbonated and carbonated mineral water. *Deutsche Lebensmittel-Rundschau* **6**, 215–221.

Feigenbaum, A., Lebosse, R., and Ducruet, V. (1998). Polypropylene as active packaging material for aroma sorption from model organge juice. *In* ''Food Flavors: Formation, Analysis and Packaging Influences'' (E. T. Contis, C.-T. Ho, C. J. Mussinan, T. H. Parliment, F. Shahidi, and A. M. Spanier, eds.), pp. 743–751. Elsevier Science BV, Amsterdam.

Frank, M., Ulmer, H., Ruiz, J., Visani, P., and Weimar, U. (2001). Complementary analytical measurements based upon gas chromatography–mass spectrometry, sensory system and human sensory panel: A case study dealing with packaging materials. *Anal. Chim. Acta* **431**, 11–29.

Franz, R., Mauer, A., and Welle, F. (2004). European survey on post-consumer poly(ethylene terephthalate) (PET) materials to determine contamination levels and maximum consumer exposure from food packages made from recycled PET. *Food Addit. Contam.* **21**, 265–286.

Franz, R. and Welle, F. (2003). Recycling packaging materials. Ch. 23. *In* ''Novel Food Packaging Techniques'' (R. Ahvenainen, ed.), pp. 497–518. CRC Press, Boca Raton, FL.

Fukamachi, M., Matsui, T., Shimoda, M., and Osajima, Y. (1996). Cross-linking treatment of EVA film to improve flavor preservation. *J. Agric. Food Chem.* **42**, 1989–1992.

Goldenberg, N., and Matheson, H. R. (1975). ''Off-flavours'' in foods, a summary of experience: 1948–1974. *Chem. Ind.* 551–557.

Gorgern, M. (2003). Influence of bottle wall structure on the preservation of the organoleptic properties of milk. *In* ''Proceedings of the 13th International Conference on Polyester Containers for Food and Beverages,'' p. 357. Schotland Business Research, Skillman, NJ.

Granzer, R., Koszinowski, J., Robinson-Mand, L., and Piringer, O. (1986). Verpack-Rundsch. 37, techn.-wis-sensch. Beilage, 53–58. (*In* Piringer, O. and Ruter, M. (2000). Sensory problems caused by food and packaging interactions. Ch. 13. *In* ''Plastic Packaging Materials for Food: Barrier Function, Mass Transport, Quality Assurance, and Legislation'' (O.-G. Piringer and A. L. Baner, eds.), pp. 407–426. Wiley-VCH, Weinheim (Federal Republic of Germany)).

Gremli, H. (1996). Flavor changes in plastic containers. A literature review. *Perfum. Flav.* **21**, 1–8.

Heim, T. H., and Dietrich, A. M. (2007a). Sensory aspects of drinking water in contact with epoxy-lined copper pipe. *Water Sci. Technol.* **55**(5), 161–168.

Heim, T. H., and Dietrich, A. M. (2007b). Sensory aspects and water quality impacts of chlorinated and chloraminated drinking water in contact with HDPE and cPVC pipe. *Water Res.* **41**, 757–764.

Heinio, R. L. and Ahvenainen, R. (2002). Monitoring of taints related to printed solid boards with an electronic nose. *Food Addit. Contam.* **19**, 209–220.

Hernandez-Munoz, P., Catala, R., and Gavara, R. (2001). Food aroma partition between packaging materials and fatty food simulants. *Food Addit. Contam.* **18**, 673–682.

Heydanek, M. G. (1977). Tracing the origin of off-flavors in a breakfast cereal. *Ann. Chem.* **49**, 901A.

Heydanek, M. G. (1978). How to spot a stinker—Predicting flavor effects of packaging materials. *Food Prod. Dev.* **12**(5), 17–18.

Hoojjat, P., Harte, B. R., Hernandez, R. J., Giacin, J. R., and Miltz, J. (1987). Mass transfer of BHT from high density polyethylene film and its influence on product stability. *J. Packaging Technol.* **22**, 78–81.

Huber, M., and Franz, R. (1997). Studies on contamination of post-consumer plastics from controlled resources for recycling into food packaging applications. *Deutsche lebensmittel-Rundschan* **93**(10), 328–331. (*In* Franz, R., and Welle, F. (2003). Recycling packaging materials. Ch. 23. *In* ''Novel Food Packaging Techniques'' (R. Ahvenainen, ed.), pp. 497–518. Woodhead, CRC Press, Boca Raton, FL).

Huber, M., Ruiz, J., and Chastellain, F. (2002). Off-flavour release from packaging materials and its prevention: A foods company's approach. *Food Addit. Contam.* **19**(Suppl.), 221–228.

Imai, T., Harte, B. R., and Giaicin, J. R. (1990). Partition distribution of aroma volatiles from orange juice into selected polymeric sealant films. *J. Food Sci.* **55**, 158–161.

Jadhav, S. J., Nimbalkar, S. S., Kulkarni, A. D., and Madhavi, D. L. (1996). Lipid oxidation in biological food systems. *In* ''Food Antioxidants: Technological, Toxicological, and Health Perspectives'' (D. L. Madhavi, S. S. Deshpande, and D. K. Salunkhe, eds.), pp. 5–64. Marcel Dekker, New York, NY.

Jangchud, K., Puchakawimol, P., and Jangchud, A. (2007). Quality changes of burnt aromatic coconut during 28-day storage in different packages. *LWT* **40**, 1232–1239.

Jenq, W. R., Bassette, R., and Crang, R. E. (1988). Effects of light and copper ions on volatile aldehydes of milk and milk fractions. *J. Dairy Sci.* **71**, 2366–2372.

Karatapanis, A. E., Badeka, A. V., Riganakos, K. A., Savvaidis, I. N., and Kontominas, M. G. (2006). Changes in flavour volatiles of whole pasteurized milk as affected by packaging material and storage time. *Int. Dairy J.* **16**, 750–761.

Katan, L. L. (ed.) (1996). ''Migration from Food Contact Materials.'' Blackie Academic and Professional, New York, NY. 303pp.

Khiari, D., Barrett, S., Chinn, R., Bruchet, A., Piriou, P., Matia, L., Ventura, F., (Mel) Suffet, I., Gittelman, T., Leutweiler, P., and AwwaRF. (2002). ''Distribution Generated Taste-and-Odor Phenomena.'' AwwaRF, Denver, CO.

Kilcast, D. (1996). Organoleptic assessment. Ch. 4. *In* ''Migration from Food Contact Materials'' (L. L. Katan, ed.), pp. 51–76. Blackie Academic and Professional, New York, NY.

Kilcast, D. (2003). Sensory analytical methods in detecting taints and off-flavours in food. Ch. 2. *In* ''Taints and Off-Flavours in Foods'' (B. Baigrie, ed.), pp. 5–30. CRC Press, New York, NY.

Kim-Kang, H. (1990). Volatiles in packaging materials. *J. Food Sci. Nutr.* **29**(4), 255–271.

Konczal, J. B., Harte, B. R., Hoojjat, P., Tanaka, Y., and Osajima, Y. (1992). Apple juice flavor compound sorption by sealant films. *J. Food Sci.* **57**(4), 967–969.

Kontominas, M. G., Goulas, A. E., Badeka, A. V., and Nerantzaki, A. (2006). Migration and sensory properties of plastics-based nets used as food-contacting materials under ambient and high temperature heating conditions. *Food Addit. Contam.* **23**(6), 634–641.

Kwapong, O. Y., and Hotchkiss, J. H. (1987). Comparative sorption of aroma compounds by polyethylene and ionomer food-contact plastics. *J. Food Sci.* **52**, 761–763. (see also p. 785).

Land, D. G. (1989). Taints—Causes and prevention. Ch. 2. *In* ''Distilled Beverage Flavour—Recent Developments'' (J. R. Piggott and A. Paterson, eds.), Ellis Horwood, Chichester. (*In* (2007). ''Organohalogen Taints in Foods.'' AFGC, Canberra, Australia. 16pp. http://www.afgc.org.au).

Larsen, H., Lea, P., and Rodbotten, M. (2005). Sensory changes in extruded oat stored under different packaging, light and temperature conditions. *Food Qual. Pref.* **16**, 573–584.

Lawless, H. T., and Heymann, H. (1998). ''Sensory Evaluation of Food.'' Chapman and Hall, New York, NY. 819pp.

Leland, J. V. (1997). Flavor interactions: The greater whole. *Food Technol.* **51**, 75–76. (see also pp. 78–80).

Leong, C. M. O., Harte, B. R., Partridge, J. A., Ott, D. B., and Downes, T. W. (1992). Off-flavor development in milk packaged in polyethylene-coated paperboard cartons. *J. Dairy Sci.* **75**, 2105–2111.

Letinski, J., and Halek, G. W. (1992). Interaction of citrus flavor compounds with polypropylene films of varying crystallinities. *J. Food Sci.* **57**, 481–484.

Linssen, J. P. H., Janssens, J. L. G. M., Reitsma, J. C. E., and Roozen, J. P. (1991). Sensory analysis of polystyrene packaging material taint in cocoa powder for drinks and chocolate flakes. *Food Addit. Contam.* **8**(1), 1–7.

Linssen, J. P. H., and Roozen, J. P. (1994). Food flavour and packaging interactions. *In* ''Food Packaging and Preservation'' (M. Mathlouthi, ed.), pp. 48–61. Blackie Academic and Professional, Glasgow.

Lord, T. (2003). Packaging materials as a source of taints. *In* ''Taints and Off-Flavours in Food'' (B. Baigrie, ed.), pp. 64–111. Woodhead, CRC Press, Boca Raton, FL.

Lozano, P. R., Miracle, E. R., Krause, A. J., Drake, M., and Cadwallader, K. R. (2007). Effect of cold storage and packaging material on the major aroma components of sweet cream butter. *J. Agric. Food Chem.* **55**, 7840–7846.

Mannheim, C. H., Miltz, J., and Letzter, A. (1987). Interaction between polyethylene laminated cartons and aseptically packed citrus juices. *J. Food Sci.* **52**, 737–740.

Marchsan, M. and Morran, J. (2002). Tastes associated with products in contact with drinking water. Abstract from the Sixth IWA Symposium on Off-Flavours in the Aquatic Environment. Barcelona, Spain, October 7–10.

Mehta, R. S. and Bassette, R. (1978). Organoleptic, chemical and microbiolgical changes in ultra-high-temperature sterilized milk stored at room temperature. *J. Food Prot.* **41**, 806–810.

Meilgaard, M. C., Civille, G. V., and Carr, B. T. (2007). ''Sensory Evaluation Techniques.'' CRC Press, Boca Raton, FL. 448pp.

Miltz, J., Passy, N., and Mannheim, C. H. (1995). Trends and applications of active packaging systems. *In* ''Foods and Packaging Materials—Chemical Interactions'' (P. Ackermann, M. Jagerstad, and T. Ohlsson, eds.), pp. 201–210. The Royal Society of Chemistry, Cambridge, England.

Moshonas, M. G. and Shaw, P. E. (1989). Flavor evaluation and volatile flavor constituents of stored aseptically packaged orange juice. *J. Food Sci.* **54**, 82–85.

Moyssiadi, T., Badeka, A., Kondyli, E., Vakirtzi, T., Savvaidis, I., and Kontominas, M. G. (2004). Effect of light transmittance and oxygen permeability of various packaging materials on keeping quality of low fat pastuerized milk: Chemical and sensorial aspects. *Int. Dairy J.* **14**, 429–436.

Nielsen, T. J., Jagerstad, I. M., and Oste, R. E. (1992). Study of factors affecting the absorption of aroma compounds into low-density polyethylene. *J. Sci. Food Agric.* **60**, 377–381.

Norton, J. (2003). Efficacy of odor scavengers in reducing odor compounds in water, milk and soymilk. M.S. Thesis, Virginia Tech, Blacksburg.

Oehrl, L. L., Malone, C. P., and Keown, R. W. (1991). Interactions of food, drug and cosmetic dyes with nylon and other polyamides. Ch. 4. *In* ''Food and Packaging Interactions II'' (S. J. Risch, and J. H. Hotchkiss, eds.), pp. 37–52. ACS Symposium Series 473, ACS, Washington, DC.

Papachristou, C., Badeka, A., Chouliara, I., Kondyli, E., Kourtis, L., and Kontominas, M. G. (2006a). Evaluation of polyethylene terephthalate as a packaging material for premium quality whole pasteurized milk in Greece. Part II. Storage under fluorescent light. *Eur. Food Res. Technol.* **224**, 237–247.

Papachristou, C., Badeka, A., Chouliara, I., Kondyli, E., Athanasoulas, A., and Kontominas, M. G. (2006b). Evaluation of polyethylene terephthalate as a packaging material for premium quality whole pasteurized milk in Greece. Part I. Storage in the dark. *Eur. Food Res. Technol.* **223**, 711–718.

Passy, N. (1983). Off-flavors from packaging materials in food products—Some case studies. *In* ''Instrumental Analysis of Foods: Recent Progress,'' p. 413. Academic Press, New York.

Piagentini, A. M., Guemes, D. R., and Pirovani, M. E. (2002). Sensory characteristics of fresh-cut spinach preserved by combinated factors methodology. *J. Food Sci.* **67**, 1544–1549.

Pieper, G., Borgudd, L., Ackermann, P., and Fellers, P. (1992). Absorption of aroma volatiles of orange juice into laminated carton packages did not affect sensory quality. *J. Food Sci.* **57**, 1408–1411.

Piringer, O.-G. and Ruter, M. (2000). Sensory problems caused by food and packaging interactions. Ch. 13. *In* ''Plastic Packaging Materials for Food: Barrier Function, Mass Transport, Quality Assurance, and Legislation'' (O.-G. Piringer, and A. L. Baner, eds.), pp. 407–426. Wiley-VCH, Weinheim (Federal Republic of Germany).

Reineccius, G. (2006). ''Flavor Chemistry and Technology.'' 2nd ed., Taylor and Francis Group, CRC, New York, NY. 489pp.

Richardson, S. D. (1998). Drinking water disinfetion by-products. *In* ''Encyclopedia of Environmental Analysis and Remediation'' (R. A. Mayers, ed.), pp. 1398–1421. Wiley, New York.

Rigal, S. (1992). The use of organoleptic investigations to evaluate the quality of materials in contact with drinking water. *Water Sci. Technol.* **4**(25), 41–48.

Rigal, S. (1995). Odour and flavour in waters: Quantitative method for a new European standard. *Water Sci. Technol.* **31**(11), 237–242.

Rigal, S. and Danjou, J. (1999). Tastes and odors in drinking water distribution systems related to the use of synthetic materials. *Water Sci. Technol.* **40**, 203–208.

Risch, S. J. and Ho, C.-T. (2000). ''Flavor Chemistry: Industrial and Academic Research.'' ACS Symposium Series 756. American Chemical Society, Washington, DC. 180pp.

Robertson, G. L. (2006). ''Food Packaging Principles and Practice.'' 2nd Ed., CRC Press, Boca Raton, FL. 550pp.

Rysstad, G., Ebbesen, A., and Eggestad, J. (1998). Sensory and chemical quality of UHT-milk stored in paperboard cartons with different oxygen and light barriers. *Food Addit. Contam.* **15**, 112–122.

Sadler, G. D. and Braddock, R. J. (1991). Absorption of citrus flavor volatiles by low density polyethylene. *J. Food Sci.* **56**, 35–38.

Sadler, G., Parish, M., Davis, J., and van Clief, D. (1995). Flavor–package interaction. *In* ''Fruit Flavors'' (R. L. Fourseff, and M. M. Leahy, eds.), pp. 202–210. American Chemical Society, Washington, DC. (*In* Linssen, J. P. H., van Willige, R. W. G., and Dekker, M. (2003). Packaging-flavour interactions. Ch. 8. *In* ''Novel Food Packaging Techniques'' (R. Ahvenainen, ed.), Woodhead Publishing Ltd., CRC Press, Boca Raton, pp. 144–171).

Safa, H. L. and Bourelle, F. (1999). Sorption-desorption of aromas on multi-use PET bottles. A test procedure. *Packaging Technol. Sci.* **12**, 37–44.

Saint-Eve, A., Levy, C., le Moigne, M., Ducruet, V., and Souchon, I. (2008). Quality changes in yogurt during storage in different packaging materials. *Food Chem.* **110**, 285–293.

Sajilata, M. G., Savitha, K., Singhal, R. S., and Kanetkar, V. R. (2007). Scalping of flavors in packaged foods. *Comp. Rev. Food Sci. Food Saf.* **6**, 17–35.

Sander, R. A., Zyzak, D. V., Morsch, T. R., Zimmerman, S. P., Searles, P. M., Strothers, M. A., Eberhart, B. L., and Woo, A. K. (2005). Identification of 8-nonenal as an important contributor to ''plastic'' off-odor in polyethylene packaging. *J. Agric. Food Chem.* **53**, 1713–1716.

Sharma, G. K., Madhura, C. V., and Arya, S. S. (1990). Interaction of plastic films with foods. I. Effect of polypropylene and polyethylene films on fruit squash quality. *J. Food Sci. Technol.* **27**, 127–132. (*In* Linssen, J. P. H., van Willige, R. W. G., and Dekker, M.(2003). Packaging-flavour interactions. Ch. 8. *In* ''Novel Food Packaging Techniques'' (R. Ahvenainen, ed.), Woodhead Publishing Ltd., CRC Press, Boca Raton, pp. 144–171).

Sides, S. L., Polowy, K. B., Thornquest, A. D., Jr., and Burinsky, D. J. (2001). Identification of a pharmaceutical packaging off-odor using solid phase microextraction gas chromatography/mass spectrometry. *J. Pharm. Biomed. Anal.* **25**, 379–386.

Simon, M., and Hansen, A. P. (2001). Effect of various dairy packaging materials on the shelf life and flavor of ultrapasteurized milk. *J. Dairy Sci.* **84**, 784–791.

Soderhjelm, L. and Eskelinen, S. (1985). Characterization of packaging materials with respect to taint and odour. *Appita* **38**(3), 205–209.

Song, Y. S., Al-Taher, F., and Sadler, G. (2003). Migration of volatile degradation products into ozonated water from plastic packaging materials. *Food Addit. Contam.* **20**, 985–994.

Suloff, E. C. (2001). Modeling the adsorption of aldehydes and ketones to novel poly(ethylene terephthalate) blends by inverse gas chromatography to develop an improved polymer for food packaging. Ph.D. Dissertation, Virginia Tech, Blacksburg.

Suloff, E. C., Marcy, J. E., Blakistone, B. A., Duncan, S. E., Long, T. E., and O'Keefe, S. F. (2003). Sorption behavior of selected aldehyde-scavenging agents in poly(ethylene terephthalate) blends. *J. Food Sci.* **68**(6), 2024–2033.

Suppakul, P., Sonneveld, K., Bigger, S. W., and Miltz, J. (2008). Efficacy of polyethylene-based antimicrobial films containing principal constituents of basil. *Food Sci. Techol.* **41**(5), 779–788.

Tomboulian, P., Schweitzer, L., Mullin, K., Wilson, J., and Khiari, D. (2002). Materials used in distribution systems—Contributions to taste-and-odor. *Water Sci. Technol.* **49**(Pt. 2), 219–226.

Tomboulian, P., Schweitzer, L., Mullin, K., Wilson, J., and Khiari, D. (2004). Materials used in drinking water distribution systems: Contribution to taste and odor. *Water Sci. Technol.* **49**, 219–226.

Torri, L., Piergoiovanni, L., and Caldiroli, E. (2008). Odour investigation of granular polyolefins for flexible food packaging using a sensory panel and an electronic nose. *Food Addit. Contam.* **25**(4), 490–502.

van Aardt, M., Duncan, S. E., Bourne, D., Marcy, J. E., Long, T. E., Hackney, C. R., and Heisey, C. (2001a). Flavor threshold for acetaldehyde in milk, chocolate milk, and spring water using solid phase micro-extraction gas chromatography (SPME-GC) for quantification. *J. Agric. Food Chem.* **49**, 1377–1381.

van Aardt, M., Duncan, S. E., Marcy, J. E., Long, T. E., and Hackney, C. R. (2001b). Effectiveness of poly(ethylene terephthalate) and high density poly(ethylene) in protection of milk flavor. *J. Dairy Sci.* **84**(6), 1341–1347.

van Aardt, M., Duncan, S. E., Marcy, J. E., Long, T. E., O'Keefe, S. F., and Nielsen-Sims, S. R. (2005a). Aroma analysis of light-exposed milk stored with and without natural and synthetic antioxidants. *J. Dairy Sci.* **88**, 881–890.

van Aardt, M., Duncan, S. E., Marcy, J. E., Long, T. E., O'Keefe, S. F., and Nielsen-Sims, S. R. (2005b). Effect of antioxidant (α-tocopherol and ascorbic acid) fortification on light-induced flavor of milk. *J. Dairy Sci.* **88**, 872–880.

van Aardt, M., Duncan, S. E., Marcy, J. E., Long, T. E., O'Keefe, S. F., and Sims, S. R. (2007). Release of antioxidants from poly(lactide-*co*-glycolide) films into dry milk products and food simulating liquids. *Int. J. Food Sci. Technol.* **42**, 1327–1337.

van Willige, R. W. G. (2002). Effects of flavour absorption of foods and their packaging materials. Ph.D. thesis. Wageningen University, The Netherlands. (*In* Linssen, J.P.H., van Willige, R. W. G., and Dekker, M. Packaging-flavour interactions. Ch. 8. *In* ''Novel Food Packaging Techniques'' (R. Ahvenainen, ed.). Woodhead Publishing Ltd., CRC Press, Boca Raton, FL. pp. 144–171).

van Willige, R., Linssen, J., and Voragen, A. (2000). Influence of food matrix on absorption of flavour compounds by low-density polyethylene: Oil and real food products. *J. Sci. Food Agric.* **80**, 1790–1797.

van Willige, R. W. G., Linssen, J. P. H., Legger-Huysman, A., and Voragen, A. G. J. (2003). Influence of flavour absorption by food-packaging materials (low-density polyethylene, polycarbonate and polyethylene terephthalate) on taste perception of a model solution and orange juice. *Food Addit. Contam.* **20**(1), 84–91.

Villberg, K., Veijanen, A., Gustafsson, I., and Wickstrom, K. (1997). Analysis of odour and taste problems in high-density polyethene. *J. Chromatogr.* **791**, 213–219.

Webster, J. B. (2006). Changes in aromatic chemistry and sensory quality of milk due to light wavelength. Ph.D. Dissertation. Virginia Tech, Blacksburg, VA.

Webster, J. B., Duncan, S. E., Marcy, J. E., O'Keefe, S. F., and Sims, S. N. (2007). Packaging solutions for sensory degradation in foods and beverages due to photooxidation. Abstract POLY 685. *Am. Chem. Soc.* Annual Meeting, Boston, MA.

Weinberg, H. S., Glaze, W. H., Krasner, S. W., and Sclimenti, M. J. (1993). Formation and removal of aldehydes in plants that use ozonation. *J. AWWA* **85**, 72–85.

Whitfield, F. B., Tindale, C. R., Shaw, K. J., and Stanley, G. (1984). Contamination of cocoa powder by chlorophenols and chloroanisoles adsorbed form packaging materials. *Chem. Ind.* 772–774.

Yam, K. L., Yo, Y. C., Young, S. S., and Zambetti, P. F. (1996). Effect of resin types and antioxidants on release of off-flavor from HDPE bottles. *Polym. Plastics Technol. Eng.* **35**(5), 727–755.

Zygoura, P., Moyssiadi, T., Badeka, A., Kondyli, E., Savvaidis, I., and Kontominas, M. G. (2004). Shelf life of whole pasteurized milk in Greece: Effect of packaging material. *Food Chem.* **87**, 1–9.