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Food Packaging

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11.1 Introduction

Food packaging is defined as a co-ordinated system of preparing food for transport, distribution, storage, retailing, and end-use to satisfy the ultimate consumer with optimal cost (Coles et al., 2003). Food packaging is an essential part of modern society; commercially processed food could not be handled and distributed safely and efficiently without packaging. The World Packaging Organization (WPO) estimates that more than 25% of food is wasted because of poor packaging (WPO, 2009). Thus, it is clear that optimal packaging can reduce the large amount of food waste. Moreover, the current consumer demand for convenient and high-quality food products has increased the impact of food packaging. The purpose of this chapter is to provide background knowledge for those who are interested in or may become involved in the development of food packaging and/or processing.

This chapter consists of four major parts. The development of quality food packaging is impossible if the packaging does not perform its required functions. Therefore, the first part of this chapter discusses the important role packaging plays in maintaining food quality and reducing product waste. The second part is about the properties and forms of food packaging materials and systems to facilitate understanding and appreciation of the major packaging materials, including plastic, paper, metal, and glass, which can affect the quality of food and its shelf life. The third part of the chapter explains aseptic packaging, modified atmosphere packaging and active packaging technologies, which have assumed increasing importance in the food industry in recent years. Finally, the last part of the chapter discusses sustainable food packaging issues, including recycling, biodegradable materials, and package design.

11.2 Functions of food packaging

11.2.1 Containment

The term “containment” means, simply, to contain products to enable them to be moved or stored. It is so basic that it is easily overlooked. However, containment is a key factor for all other packaging functions. All products must be contained for delivery from their point of production to their ultimate destination. Even items that consumers consider as “not a packaged product,” such as bulk produce, must be packaged for transportation. Without packaging, products are likely to be lost or contaminated by the environment. For this reason, we have actually used packaging for millennia. Early packaging such as animal skins, baskets, or leaves from trees were used to contain liquids, powders, grains, etc. The containment function significantly contributes to protecting and preserving products during their distribution.

11.2.2 Protection/preservation

There are two broad types of damage that fresh and processed foods sustain during storage and transportation. One is physical damage such as shock, vibration, compressive forces, etc. The other is environmental damage that occurs due to exposure to water, light, gases, odors, microorganisms, etc. A good packaging system will protect or reduce these types of damage to the package contents. For example, an essential aroma or flavor in coffee or juice may easily be evaporated or oxidized without optimum barrier packaging. A shelf-stable food in a can or pouch may maintain its stability (especially against microorganisms) as long as the package provides protection. However, in the case of fresh food products, the ideal

protection is usually hard to achieve with packaging alone. Since temperature is a major influence on the degradation of food, it is more economical to control temperature through supply chain modification (refrigeration, freezing, etc.). However, packaging can also add a certain level of protection to slow down temperature changes.

11.2.3 Communication

According to the Fair Packaging and Labeling Act (Federal Trade Commission, 1994), food packaging must identify the product, the net quantity of the contents, name/address of business of the manufacturer, packer, or distributor, as well as (usually) nutritional information. The communication function of packaging not only includes the information provided by the written text, but also elements of the packaging design such as package shape, color, recognized symbols or brands. Beyond giving information, the communication function is expected to entice the consumer to purchase the product. Packaging has been regarded as the “silent salesman” (Judd et al., 1989). Consumers may instantly recognize products through appetizing pictures or distinctive brands on packaging, and even simple transparency of the packaging material can attract consumers by allowing them to view the product inside (Selke, 2012).

Another aspect of the communication function is also important. The Universal Product Code (UPC) is widely used to facilitate rapid and accurate checkout in retail stores. Also, most warehouse and distribution centers track and manage their inventory using UPCs. Currently, by using radiofrequency identification (RFID) tags attached to secondary and tertiary packages, manufacturers are able to get better demand signals from customers and markets. An RFID tag can gather data on items automatically without human intervention or data entry. It identifies, categorizes, and manages product and information flow at important inspection and decision points. In addition, RFID tags can be read all at once (e.g. up to 50 per second), while UPC codes can only be read one at a time (Myerson, 2007). RFID technology looks promising in terms of revolutionizing the supply chain. However, it needs to be economical. The cost of individual tags and antenna reading systems is still high. Another problem is the lack of uniformity in global standards in the area of sensor technology. Sensor providers usually provide their own interfaces to communicate with their own tags (Lopez et al., 2011).

11.2.4 Utility

This function of packaging is sometimes termed “convenience.” Consumers demand products that fit into their lifestyles and the packaging industry has had to respond to this. Thus, the utility function encompasses all the packaging attributes that provide added value and convenience to the users of the product and/or package. For example, an important social trend is the growing number of mothers in the workforce and smaller households (people living alone and married couples without children). Unquestionably, food products that offer simplification and convenience have grown in popularity with this group; examples include microwavable entrees, steam-in-pouch vegetables, oven-safe meat pouches, pump-action condiments, and so on.

11.3 Packaging systems

We can categorize packaging systems into four groups: primary packaging, secondary packaging, distribution or tertiary packaging, and unit load.

11.3.1 Primary packaging

The first-level package that directly contacts the product is referred to as the “primary package.” For example, a beverage can or a jar, a paper envelope for a tea bag, an inner bag in a cereal box, and an individual candy wrap in a pouch are primary packages, and their main function is to contain and preserve the product (Soroka, 2008a). Primary packages must be non-toxic and compatible with the food and should not cause any changes in food attributes such as color changes, undesired chemical reactions, flavor, etc.

11.3.2 Secondary packaging

The secondary package contains two or more primary packages and protects the primary packages from damage during shipment and storage. Secondary packages are also used to prevent dirt and contaminants from soiling the primary packages; they also unitize groups of primary packages. A shrink wrap and a plastic ring connector that bundles two or more cans together to enhance ease of handling are examples of secondary packages.

11.3.3 Tertiary package

The tertiary package is the shipping container, which typically contains a number of the primary or secondary

packages. It is also referred to as the “distribution package.” A corrugated box is by far the most common form of tertiary package. Its main function is to protect the product during distribution and to provide for efficient handling.

11.3.4 Unit load

A unit load means a group of tertiary packages assembled into a single unit. If the corrugated boxes are placed on a pallet and stretch wrapped for mechanical handling, shipping and storage, the single unit is referred to as a “unit load.” The objective is to aid in the automated handling of larger amounts of product. A fork-lift truck or similar equipment is used to transport the unit load.

11.3.5 Consumer/industrial packaging

Packaging systems can also be categorized into consumer and industrial packaging. Consumer packaging means a package that will be delivered to the ultimate consumer in the retail store. Usually, primary and secondary packages fit in this category. Industrial packaging means a package for warehousing and distribution to the retail store. Tertiary packages and unit loads fit in this category.

Not all package systems are actually composed of a set of primary, secondary, and tertiary packages. For example, the packaging system for potato chips usually consists only of a flexible barrier bag and a corrugated shipping container before they are palletized, while mayonnaise jars are sold in a club store as a two-pack consisting of plastic bottles, shrink wrap, corrugated boxes, and pallet. Often, the distinction between consumer and industrial packaging is more clear-cut than between primary, secondary, and tertiary packaging.

11.4 Materials for food packaging

11.4.1 Plastics

Plastics are a special group of polymers that can be formed into a wide variety of shapes using controlled heat and pressure at relatively low temperatures, compared to metals and glass. Plastics are actually a subcategory of polymers, but in packaging the terms tend to be used interchangeably. There are hundreds of identified “species” of synthetic polymers but in practice, only a few polymers are often used for food packaging. The use of plastics has increased more rapidly than any other

material, and plastic is now the second most used material for packaging. Each plastic has its own unique properties, based on its chemical composition. The performance and interaction with a variety of foods are different for each material. Thus, the plastic material for the packaging of a specific food is selected to function well within the parameters of the application. This subsection focuses on the properties and applications of the plastics that are most commonly used for food packaging.

11.4.1.1 Types of plastics and general properties

11.4.1.1.1 Polyethylene (PE)

Polyethylene, polymerized from ethylene, is the plastic most commonly used for food packaging. PE generally has flexibility, good moisture control, oil and chemical resistance, and good impact strength. PE is also an inexpensive plastic, so for applications where its performance is suitable, this plastic is usually the most economical choice. The simplest form of PE is a completely unbranched structure of $-CH_2-$ units. However, some side branches are always formed during polymerization. If the branches are relatively few and short (2–4 carbon atoms), the structure can fold and pack tightly and yields high-density polyethylene (HDPE). Conversely, if there are many long branches, PE becomes low-density polyethylene (LDPE).

Low-density polyethylene is softer and more flexible, and has lower tensile strength than HDPE. Since it has relatively weak intermolecular forces, LDPE has a low melting temperature, 105–115°C, so it is a useful material for heat sealing. LDPE also has good impact and tear strength. Common applications for LDPE include stretch wraps, shrink wraps, and many types of bags and pouches. LDPE is also used as an adhesive layer for multilayer composite structures, as a coating on paper to provide water protection (such as in milk cartons), in flexible lids for plastic tubs, in squeezable plastic tubes, in soft squeeze bottles, and in a variety of other applications. By far the majority of its use in packaging is in some form of flexible structure, and packaging is the largest market for LDPE.

Like LDPE, HDPE has good oil and grease resistance. It has better barrier properties than LDPE, since permeation occurs almost exclusively through amorphous areas of a polymer, and HDPE has less amorphous area and higher crystallinity than LDPE. It is, therefore, a good water vapor barrier. However, its barrier to oxygen and carbon dioxide, though improved over LDPE, is still very poor. The improved stiffness of HDPE makes it more suitable

than LDPE for rigid or semi-rigid packaging applications, such as bottles, tubs, and trays. In particular, blow-molded bottles for food products are the largest single packaging market for HDPE.

Linear LDPE (LLDPE) is a co-polymer of ethylene and a co-monomer that has short “branches” of a uniform length, distributed randomly in the polymer molecule. The density range of LLDPE is the same as that of LDPE. Compared to LDPE of equal density, because of the structure, LLDPE typically has 50–75% higher tensile strength, 50% or greater elongation, and greater stiffness, along with improved impact strength and puncture resistance. LLDPE is more expensive than LDPE but since the superior performance allows the use of significantly less LLDPE in many applications, switching from LDPE to LLDPE often permits significant economic savings. On the other hand, LLDPE has a higher melting temperature and does not heat seal as well as LDPE so LDPE and LLDPE are often blended to get the best mix of performance and cost. New catalysts allow LLDPE to be produced with the equivalent of long-chain branches, improving its heat seal performance, but with added cost.

11.4.1.1.2 Polypropylene (PP)

Polypropylene is polymerized from propylene gas, which is a relatively low-cost feedstock like ethylene (Soroka, 2008a). As with the PE family, PP has good chemical and grease resistance. Barrier properties of PP are similar to those of HDPE; it is a good water vapor barrier but a poor gas barrier. The polypropylene structure includes methyl groups ($-\text{CH}_3$) attached to every other carbon in the polymer main chain; consequently PP has a lower density and a higher glass transition temperature (the temperature above which a plastic becomes soft and flexible) and higher melting temperature than PE. At freezing temperatures, unmodified PP is very close to its glass transition temperature, and therefore tends to have serious brittleness problems. On the other hand, PP is suitable for use with products that require moderately high temperatures such as hot filling or reheating (but not cooking) in a microwave oven.

One of the main uses of PP in food packaging is in closures (caps). Particularly for threaded caps, while HDPE is deformed too readily and loses sealing force under stress, PP maintains its original stiffness and performs successfully. PP also has outstanding living hinge properties, which is particularly useful for caps where an integral hinge is part of the design. The use of oriented polypropylene (OPP) film has increased rapidly in recent food

packaging applications because a wide range of properties (such as tensile strength, shrinkage rate, transparency, etc.) can be manipulated by the orientation. OPP film has improved mechanical strength and water barrier properties compared to unoriented (cast) film. OPP film, however, is still not suited for gas barrier applications. Biaxial orientation improves clarity because the variation of crystallized layers in PP is reduced across the thickness of the film (less light refraction).

11.4.1.1.3 Polystyrene (PS)

Polystyrene is a linear addition polymer of styrene resulting in a benzene ring attached to every other carbon in the main polymer chain. It is a material that is brittle and clear and has high surface gloss. The use of PS in food packaging is aesthetically appreciated, but the material cannot generally be used when extended shelf life is required because of its poor water vapor and gas barrier properties.

The brittleness of PS limits its use where good impact resistance is required. In order to reduce the tendency to fracture, oriented polystyrene (OPS) is commonly used. Typical applications include produce and meat trays, lids for drink cups, and inexpensive party glasses.

High-impact PS (HIPS) is a PS co-polymer with polybutadiene (synthetic rubber). Adding the synthetic rubber causes HIPS to become opaque but improves the impact resistance significantly. HIPS is commonly used for disposable cutlery, tubs, and other thermoformed containers.

Polystyrene foam incorporates small bubbles within the plastic, which increase the cushioning properties and insulating ability of PS. PS foam is usually called expanded polystyrene (EPS). While it is not uncommon for this material to be called styrofoam, that name is proprietary for Dow Chemical Company's EPS building insulation and should not be used to describe a packaging material. Foamed PS is commonly used for disposable coffee cups, meat and produce trays, egg cartons, etc.

11.4.1.1.4 Polyvinyl alcohol (PVOH)/ethylene vinyl alcohol (EVOH)

Polyvinyl alcohol is produced by hydrolysis of polyvinyl acetate, PVA. Due to the hydrogen bonding (OH) group in the structure, PVOH can provide an excellent gas barrier when it is totally dry. However, PVOH is readily water soluble and loses its gas barrier properties in humid conditions, which greatly limits its usefulness for food packaging. Also, pure PVOH is difficult to process and cannot be thermoformed or extruded. PVOH is

non-toxic and biodegradable once dissolved. This material is generally used in water-soluble pouches such as those for laundry or dishwasher detergent.

Ethylene vinyl alcohol (EVOH) is, in essence, a copolymer of ethylene and vinyl alcohol. Modification with the ethylene groups decreases the water sensitivity of the material (so it no longer is soluble in water) and greatly improves its process ability. EVOH has high mechanical strength and toughness, good clarity, very high resistance to oil and organic solvents, and excellent gas barrier properties. It is the most widely used packaging plastic for an oxygen barrier. EVOH is expensive and susceptible to moisture so it is usually not used alone. Other films that provide a reasonably good water barrier are generally used to surround and protect EVOH from exposure to moisture.

11.4.1.1.5 Polyester (PET)

Polyethylene terephthalate (PET) is commonly produced by the reaction of ethylene glycol and terephthalic acid and has been one of the fastest growing food packaging plastics for the last several years. While PET is only one member of the general polyester family, the name “polyester” is generally regarded as PET, as it is the most commonly used plastic of the family. The properties of PET are attractive as a food packaging material; it has very high mechanical strength, good chemical resistance, light weight, excellent clarity, and reasonably high barrier properties. PET is also stable over a wide range of temperatures (-60°C to 220°C). Thus, under some circumstances PET can be used for “boil-in-the-bag” products which are stored frozen before reheating or in dual-ovenable containers, since it has resistance to higher temperatures than many other plastics. PET is mostly oriented biaxially to improve its mechanical strength and gas barrier properties.

Polyethylene terephthalate recently took over from HDPE as the most widely used plastic in bottles of all types (HDPE still predominates in the overall container category). Its first large-scale use was in bottles for carbonated soft drinks. Its barrier properties and mechanical strength are much higher than those of HDPE, with excellent transparency. It is more expensive than HDPE but offers improved performance, and its cost has decreased as production has increased.

One disadvantage of PET is its low melt strength (the ability to maintain its general shape in molten status). PET flows like a liquid (rather than like a viscous plastic) at its melting temperature, and has a narrow melting

temperature range. These characteristics make forming and sealing difficult. Thus, careful control of processing temperatures is important for PET. In order to increase the melt strength of PET, PET co-polymers can be used. The most widely used co-polymer is glycol-modified PET (PETG). This has greatly reduced crystallinity and reasonably good melt strength, which allows it to be thermoformed or extrusion blow molded into clear bottles.

11.4.1.1.6 Polyvinyl chloride (PVC)

Polyvinyl chloride is produced from vinyl chloride monomers. PVC has high toughness and strength, good dimensional stability, good clarity, excellent oil barrier properties, and good heat sealability. Even though it has many beneficial properties, PVC is easily degraded at high temperature. It decomposes and gives off hydrogen chloride (HCl) around its melting temperature. Thus, unmodified PVC is almost impossible to process due to thermal degradation. Most PVC used in packaging is mixed with a large amount of plasticizer to decrease its melting point and hence reduce thermal degradation. Since the incorporation of plasticizer reduces the attractions between neighboring polymer molecules and reduces the melting point, it also has significant impacts on all the material's properties. For example, highly plasticized PVC films have excellent stretch properties and unique “cling,” making them ideal for hand wrapping fresh meats, but the films have poor barrier properties. One of the most widespread uses of PVC is in various blister packages (e.g. medical tablets, toothbrushes, etc.) and clamshells (e.g. USB memory cards, batteries, etc.). Due to the ease of thermoforming, excellent transparency, and relatively low cost, PVC is an attractive material for these types of packages.

The high plasticizer content and the presence of residual vinyl chloride monomer have been a concern for use of PVC as a food packaging material. The levels of vinyl chloride monomer (VCM) in PVC food packaging are currently extremely low. The Food and Drug Administration (FDA) proposed limiting the VCM level to between 5 and 10 parts per billion (ppb) (FDA, 2002). So far, no evidence has been presented that PVC itself is a carcinogen, though VCM is known to be one. However, in recent years, many PVC packages, such as water and vegetable oil bottles, have been replaced by PET. PET is rapidly replacing PVC in thermoformed blister packages and clamshells for food products, as well. However, PVC film is still widely used for the stretch wrapping of trays containing fresh red meat and produce.

11.4.1.1.7 Polyvinylidene chloride (PVDC)

Polyvinylidene chloride has one more chlorine atom per monomer unit than PVC. Like PVC, PVDC is also a very heat-sensitive material. It is decomposed and generates HCl at only a few degrees above its melting temperature. PVDC can be modified with various co-monomers, typically in amounts between 6% and 28%. Properties of PVDC depend on the type as well as the amount of the co-monomer. The most noticeable benefit of this plastic is its excellent barrier properties against water vapor, odors/flavors, and gases. Thus, PVDC plastic is commonly used in food and pharmaceuticals as a barrier packaging material. Since it is a relatively expensive material, PVDC is rarely used alone in packaging containers. It is usually used as a component in multilayer structures or applied as a coating layer. One common use of PVDC coating is as a combination oxygen and moisture barrier and heat-seal layer on cellophane. PVDC is also used in co-extruded structures such as plastic cans, for its excellent barrier properties. PVDC co-polymer film is frequently used as a household wrap or a shrink film.

11.4.1.1.8 Polyamides (PA or nylon)

Nylons, or polyamides (PA), are a whole family of synthetic polymers. The term “nylon,” formerly a DuPont trade name, is more frequently used in the US. It is formed by condensation polymerization of a diamine and a dibasic acid or by polymerization of certain amino acids. Various chemical structures can be produced but the amide ($-\text{CONH}-$) functional group is always present in the main structure and is largely responsible for the mechanical strength and barrier properties.

Based on their polymerization method, two categories of PA can be identified. One family is made by polymerizing a mixture of diamines and diacids. These can be named using the number of carbons in the straight-chain diacids and straight-chain diamines they are made from. Thus nylon 6,6 is formed from a 6-carbon amine plus a 6-carbon acid. The other family of PAs is formed from only one type of monomer, an amino acid, and is identified by the number of carbons in that amino acid. Nylon 6, for example, is formed from a 6-carbon amino acid. These two types of PA have similar physical and chemical properties. The number of carbons in the structure affects the properties of PA. Longer carbon chains (more CH_2 groups) result in plastics with a lower melting point and increased resistance to water vapor.

A semi-crystalline polyamide, MXD6, was introduced in the 1980s. It is formed by condensing metaxylene diamine and adipic acid (a straight-chain 6-carbon carboxylic acid). MXD6 provides much higher water barrier properties than conventional PAs.

Polyamides in general provide excellent optical clarity, oil and chemical resistance, and mechanical strength over a wide range of temperatures. In packaging applications, the use of PA is often found in the form of film for high-temperature sterilization or hot-filling applications. PAs also act as flavor and gas barriers, but have poor water vapor barrier properties. Thus, for most applications PAs are combined with other materials, such as LDPE and ionomer, to add water vapor barrier and heat sealability properties. These types of materials are used in the vacuum packaging of meats and cheeses.

11.4.1.1.9 Polycarbonate (PC)

Polycarbonate is made from carbonic acid and bisphenol A. The proper name for PC is polybisphenol-A carbonate (as is the case for “polyester,” the generic name has come to mean this most used member of the family). The material is a very tough and rigid plastic with excellent clarity. However, it has a relatively high permeability to both water vapor and gases. Thus, it must be coated if good barrier properties are required. Its main packaging uses are large refillable water bottles and refillable milk jugs. PC is also used to a very limited extent in food packaging as a component of multilayer structures to provide transparency and in high strength containers (with high barrier materials). For example, multilayer beer or beverage bottles, containing PC and a thin barrier layer such as EVOH or PVDC, can be used to extend shelf life while still providing transparency (Hernandez, 1997). However, the application is limited by the relatively high cost of PC.

11.4.1.1.10 Ionomers

Ionomers have an unusual structure compared to other plastics. These plastics contain ionic as well as covalent bonds, while other packaging plastics have only covalent bonds in their structure. The plastic is manufactured by neutralization of ethylene-based co-polymers containing acid groups with a base containing a metal (such as sodium, zinc, lithium, etc.). The result is positively charged metal ions and negatively charged ions in the base polymer chain, creating random cross-link like ionic bonds between the polymer chains. This combination of ionic and covalent bonds creates a polymer with excellent

toughness as well as transparency. Ionomers also have excellent adhesion properties so they are commonly used in composite structures with film, paper, or aluminum foil to provide an inner layer with excellent heat sealability. They are especially useful in applications where the sealing layer may become contaminated, making it difficult to provide strong heat seals, such as in packaging of processed meats. The excellent impact and puncture resistance of ionomers, even at low temperatures, is also useful for skin packaging of sharp items such as meat cuts containing bone (as well as for inherently sharp products such as knives). Another advantage is ionomers' high infrared absorption, which allows faster heat shrink packaging processes. On the other hand, ionomers are relatively high-cost materials and have relatively poor gas barrier properties.

11.4.1.2 Additives

Additives are auxiliary ingredients intended to modify or enhance a plastic's properties without recognizably changing its chemical structure. Nearly all commercial resins are blended with additives before or during processing into their finished forms. In food packaging, all additives used must comply with the regulations of the appropriate food regulatory authority. For example, the maximum allowable migration of an additive from a packaging material is generally controlled by FDA regulations (FDA, 2005a).

Stabilizers are one of the most common ingredients in plastic resins. Plastics are susceptible to chemical changes during processing, as a result of their exposure to heat, mechanical force (shear), and usually oxygen. Stabilizers minimize the thermal oxidation or other reactions undergone by the polymer.

Plasticizers perform a lubricating function within the plastic material and make it more flexible. They also lower the glass transition and melting temperatures (as discussed in sections 11.4.1.1.6 and 11.4.1.1.7).

Colorants alter the color of plastic materials. Usually pigments (or sometimes dyes) are blended into the plastic as master batch color concentrates at the forming machine. It is possible to obtain virtually any desired color from most plastics, with the appropriate selection of colorants.

Nucleating agents encourage the formation of crystallinity in the polymer. The agents are often used to improve the clarity of PP. By adding a nucleating agent, the crystallite size in the PP can be minimized without any overall decrease in crystallinity, resulting in improved clarity without loss of other performance properties.

There are also additives designed to modify the surface of the plastic. These include slip agents, antislip agents, antiblocking agents, lubricants, mold release agents, anti-fogging agents, and antistatic agents.

11.4.1.3 Processing and converting of plastics

11.4.1.3.1 Extrusion

Most plastic forming processes begin with melting the plastic in an extruder, except for compression molding and solvent casting techniques. In the extruder, thermoplastics are mixed and softened, which enables shaping into some desired form when they reach an optimum temperature and pressure. Extrusion is used to convert plastic resin into a sheet, film, or tube. There are two main sources of the heat that melts the plastic resin. One is external heating, usually electric heater bands, and the other is friction within the extruder, as the plastic is conveyed. When the melted plastic exits the extruder, it is sent through a die of a desired shape.

In order to convert the molten plastic into film, two processes are commonly used: the cast film process (also called the flat film process) and the blown film process (also called the tubular process). For cast film, the molten plastic is extruded through a slit die, and then it is cooled on a chilled roller (or sometimes in a quenching water bath), as shown in Figure 11.1. Due to the rapid cooling, cast film generally has better clarity than blown film, and the process also results in more uniform thickness. For blown film, the molten plastic is extruded through an annular die. The plastic exits the extruder in the shape of a hollow tube, which is expanded with internal air pressure. As is shown in Figure 11.2, the film is stretched in the longitudinal and circumferential directions during the process which results in biaxial orientation of the film. The blown film process is usually more economical than the cast film process for long runs, and the mechanical

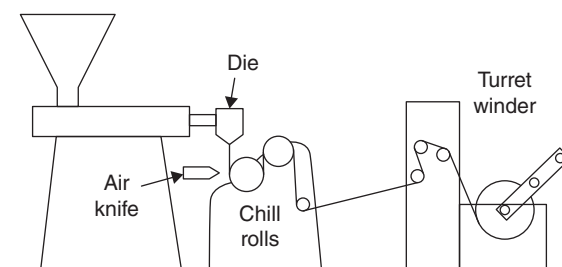


Figure 11.1 Cast film process (from Selke et al., 2004).

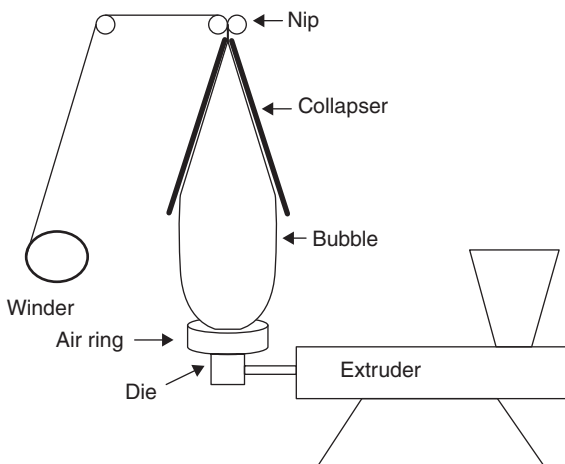


Figure 11.2 Blown film process (from Selke et al., 2004).

properties are often better than cast film, due to the biaxial orientation. Plastic resins for the blown film process must have good melt strength. Thus, not all polymer films can be produced by the blown film process. Blown film tends to have more variation in thickness and less clarity than cast film. Most plastic bags are made using the blown film process.

11.4.1.3.2 Thermoforming

In thermoforming, a plastic sheet heated to its optimum temperature (near its melting temperature) is placed over a mold, and pressure is applied to stretch it into a designed shape. The forming pressure (the pressure used to stretch the sheet) is obtained by pneumatic and/or mechanical means. In the simplest system, a vacuum is drawn through the mold and the forming pressure comes simply from atmospheric pressure pushing the plastic into the mold. In order to get good results from thermoforming, it is best if the plastic sheet is relatively easy to form and the molded shape is relatively simple. Typical thermoplastics used for thermoforming include HIPS, PVC, PP, PA, and PET. Packages made by thermoforming include clamshells, blister packages, and some tubs.

11.4.1.3.3 Injection molding

In an injection molding operation, the molten plastic (from the extruder) is injected into a mold with the desired shape, cooled, and ejected from the mold. Injection molding is widely used for making threaded closures

(caps), tubs, and jars, and for making the initial shapes (preforms) used for injection blow-molded bottles. Injection molding can provide accurate and sophisticated forms as well as a high production rate. However, it is a relatively expensive process and short production runs are not economical. Resins that are commonly used for injection molding include LDPE, HDPE, PP, and PET.

11.4.1.3.4 Blow molding

In the blow molding process, an initial shape (called a parison) is surrounded by a mold with the desired shape, and air is blown into the parison to force it to expand against the wall of the mold. The mold is then opened and the solidified product is ejected. There are two major categories of blow molding: extrusion blow molding and injection blow molding.

Extrusion blow molding is the most used blow molding process. The parison is continuously extruded as a hollow tube. When the parison reaches the proper length, the open halves of the mold are closed around the parison. This tube is usually extruded in a downward direction, and air pressure inflates the hollow tube into the shape of the container. The tubular parison is cut off at the top and pinched shut at the bottom before blowing. Thus, all containers produced by extrusion blow molding have a pinch-off line across the bottom and mold parting lines on the sides. This is a fast and inexpensive process. Extrusion blow molding is commonly used for HDPE 1/2 gallon and 1 gallon milk and water bottles where high barrier properties (against gas and flavors) are not required. The plastic for extrusion blow molding must have sufficient melt strength to maintain that hollow tube shape and permit it to be formed further. Another limitation is rather limited control over the distribution of wall thickness.

Injection blow molding starts with injection molding of a preform. The preform usually has a test tube-like shape and is nearly the same length as the height of the bottle. After injection molding, the hot preform is placed into the container mold and air pressure is used to stretch it into the mold shape. Sometimes, the preform is produced earlier, cooled, and then reheated before the blowing process. After cooling, the mold is opened and the finished container is ejected. This process provides better dimensional accuracy, including uniform wall thickness and a high-quality neck finish (threaded area). Another advantage of this process is that it produces less scrap than extrusion blow molding.

Injection stretch blow molding is similar to injection blow molding but the length of the preform is considerably

shorter than the height of the bottle. During the blow molding process, the preform is stretched in both the longitudinal and transverse directions, so the container is biaxially oriented. The finished product has better mechanical strength, better gas and water vapor barrier properties, and better transparency due to the orientation. Careful control over the temperature profile in the parison is extremely important for successful stretch blow molding. Injection stretch blow molding is used to produce PET bottles for carbonated beverages, sports drinks, juices or other bottles, including those used in hot-fill and aseptic processing.

11.4.1.4 Plastic permeability

While glass and metal have almost perfect barrier properties, plastics are permeable in various degrees to gases, water vapor, organic vapors, or other low molecular weight compounds. When the gas or vapor compounds pass through the plastic, they must solubilize at first, diffuse through the material, and finally desorb on the other side. Such vapor or gas mass transfer (or permeability) has a significant impact on the shelf life, quality, and safety of foods. For example, the expected loss of moisture from juice or of CO₂ from carbonated beverages, depending on storage conditions, can be estimated through quantitative evaluation of the package permeability. Similarly, the time required to reach certain atmospheric conditions in the package that favor the growth of aerobic or anaerobic pathogens can also be estimated through calculation of the permeability. These are just two of many examples that could be cited. This section only provides a general theoretical background for permeability and discussion of factors affecting the permeability of gases/vapors through materials.

11.4.1.4.1 Basic theory of permeability

Under steady-state conditions, the permeability coefficient of a non-porous plastic is described by the following equation (Crank, 1975):

$$P = D \times S \quad (11.1)$$

where P is the permeability coefficient, D is the diffusion coefficient, which is a measure of how fast the permeant compounds are moving through the plastic polymer, and S is the solubility coefficient that shows how much permeant is contained within the plastic.

Calculation of permeability of plastics is based on Fick's first law of diffusion. A gas or vapor will diffuse through a

plastic film at a constant rate if a constant pressure difference is maintained across the plastic:

$$F = -D \frac{\partial c}{\partial x} \quad (11.2)$$

where F is the flux (vapor mass transfer), D is the diffusion coefficient, c is concentration of permeant in the plastic and x is the distance across the plastic (or thickness). If the flow and diffusion rate are constant, the above equation gives the following equation:

$$F = -D \frac{c_2 - c_1}{L} \quad (11.3)$$

where c₁ and c₂ are the concentrations of the diffusing compound on the two sides of the plastic film. L refers to the thickness of the film. The flux (F) can be defined as the amount of permeant (Q) passing through a surface of unit area (A) in time (t). Thus, the above equation can be rewritten as follows:

$$F = \frac{Q}{At} \quad (11.4)$$

$$Q = D \frac{(c_1 - c_2)At}{L} \quad (11.5)$$

In the case of gas permeation, it is easier to measure the equilibrium vapor pressure (p) rather than the actual concentrations of the permeant in the film. Using Henry's law, the concentrations of the permeants (c) can be expressed as:

$$c = Sp \quad (11.6)$$

where p is the partial pressure and S is the solubility coefficient. Then, by combining Equations 11.5 and 11.6, the following equation is formed:

$$Q = DS \frac{(p_1 - p_2)At}{L} \quad (11.7)$$

The DS can be replaced with P, the permeability coefficient, based on Equation 11.1. Finally, the permeability coefficient (P) can be rewritten as:

$$P = \frac{QL}{At(p_1 - p_2)} \quad \text{or} \quad \frac{QL}{At\Delta p} \quad (11.8)$$

The permeation of compounds through a plastic is described by a diffusing model, using Henry's and Fick's

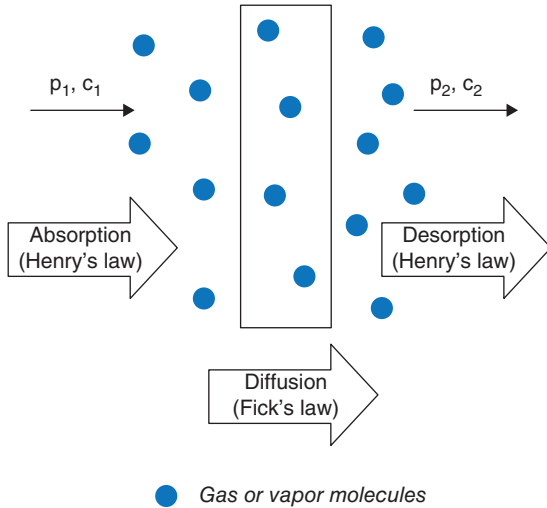


Figure 11.3 General mechanism of mass permeation through a plastic film.

laws to obtain the expression above. The mechanism is shown in Figure 11.3.

The permeability coefficient (P) can be used to estimate the shelf life of a product or to determine an appropriate package to provide the desired shelf life. There are various units available to express P . In the SI system, common units for P are:

$$P = \frac{\text{Quantity of permeant} \times \text{thickness}}{\text{area} \times \text{time} \times \text{partial vapor pressure}} = \frac{\text{cm}^3 \times \text{cm}}{\text{cm}^2 \times \text{s} \times \text{Pa}}$$

Instead of the permeability coefficient, the quantity of permeant flowing per unit area per unit time, such as the oxygen transmission rate (OTR) or water vapor transmission rate (WVTR), is frequently used to express the barrier characteristics of plastic materials. For example, OTR is related to P as follows:

$$P = \frac{QL}{At\Delta p} = \text{OTR} \frac{L}{\Delta p} \quad (11.9)$$

Example 11.1 The oxygen transmission rate of PET film with 0.1 cm thickness is $0.41 \text{ cm}^3 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. The partial pressure difference (Δp) through the film is 21278 Pa. What is the oxygen permeability coefficient of the film?

Using Equation 11.9:

$$\begin{aligned} \text{OTR} \frac{L}{\Delta p} &= \frac{0.41 \text{ cm}^3}{\text{cm}^2 \times \text{s}} \times \frac{0.1 \text{ cm}}{21278 \text{ Pa}} \\ &= 1.926 \times 10^{-6} \text{ cm}^3 \cdot \text{cm} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1} \end{aligned}$$

Example 11.2 A food stored in a PET jar with a wall thickness of 0.1 cm and a surface area of 400 cm^2 becomes rancid if it absorbs 3 cm^3 of oxygen. The O_2 permeability coefficient of PET is $1.2 \times 10^{-15} \text{ cm}^3 \cdot \text{cm} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{pa}^{-1}$. The oxygen vapor pressure inside the container (P_i) was 0 Pa and outside the container (P_o) was 21278 Pa. What is the shelf life of this product?

Using Equation 11.9:

$$P = \frac{QL}{At\Delta p}$$

The t in Equation 11.9 is the shelf life of the product if Q is the maximum allowable amount of gas inside the package. Thus, the expression can be rewritten as:

$$\begin{aligned} t &= \frac{QL}{AP\Delta p} \\ &= \frac{3(\text{cm}^3) \times 0.1(\text{cm})}{400(\text{cm}^2) \times 1.2 \times 10^{-15}(\text{cm}^3 \cdot \text{cm} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{pa}^{-1}) \times 21278(\text{pa})} \\ &= 29373061 \text{ s} = 400 \text{ day} \end{aligned}$$

Thus, the shelf life of the product in the PET package is 400 days.

11.4.2 Paper and paper-based materials

Paper and paperboard are the most commonly used packaging materials in the world. In the US, over 50% of all packaging is paper based, including food packaging. Paper is produced from plant fibers. More than 95% of paper is made from wood, and the remaining sources are mainly agricultural by-products, such as straw (of wheat, rye, barley, and rice), sugar cane bagasse, cotton, flax, bamboo, corn husks, and so on. Making pulp is the initial stage in making paper or paperboard, and the quality of the paper is closely related to the quality of the pulp. Pulping can be done using mechanical, chemical, or a combination process. Mechanical pulping produces papers that are characterized by relatively high bulk and low strength as well as relatively low cost. Their use in packaging is very limited. Chemical pulping produces stronger and higher quality paper and is also more expensive. Combination processes are intermediate in cost and properties. The pulp produced may be unbleached or bleached to various degrees, and various sizing agents and other additives are used to control functions and appearance.

11.4.2.1 Types of paper and their applications

Different varieties of papers are used in packaging applications. This section will give a brief overview of the major type of papers used for food packaging.

11.4.2.1.1 Kraft paper

Kraft paper is the most used packaging paper and has excellent strength. It is made using the sulfate (kraft) chemical pulping process, and is usually produced from soft wood. Unbleached kraft is the strongest and most economical type of paper. It is used in uncoated form for bags and in the production of corrugated board for boxes, as well as for drums, cans, and other applications. It can be coated or laminated for improved barrier properties and additional strength, or creped for cushioning.

11.4.2.1.2 Bleached paper

Bleached paper is produced using bleached pulps that are relatively white, bright, and soft. Its whiteness enhances print quality and aesthetic appeal. It is generally more expensive and weaker than unbleached paper. This type of paper is used uncoated for fancy bags, envelopes, and labels. However, it is often clay coated for overwraps and labels.

11.4.2.1.3 Greaseproof and glassine

Greaseproof is a dense, opaque, non-porous paper made from highly refined bleached kraft pulp. The prolonged beating during processing results in short fibers. Glassine derives its name from its glassy smooth surface. After the initial paper making process, it is passed through an additional set of calendars (supercalendared) in the presence of steam. The result is a glossy, transparent sheet with good grease and oil resistance (it does not have complete oil barrier but is still fairly resistant to oil). These papers are often used for packaging butter and other fatty foods.

11.4.2.1.4 Waxed paper

Waxed paper is produced by adding paraffin wax to one or both sides of the paper during drying. Many base papers are suitable for waxing, including greaseproof and glassine. The major types are dry waxed, wet waxed, and wax laminated. Dry-waxed paper is produced using a heated roller to allow the wax to soak into the paper. The paper does not have a waxy feel and does not have a

continuous wax film on the surface. Wet-waxed paper is produced when the wax is cooled quickly after it is applied, so that the wax remains on the surface of the paper. Wax-laminated paper is bonded with a continuous film of wax which acts as an adhesive, so that it can provide both moisture barrier and a heat-sealable layer.

11.4.2.1.5 Vegetable parchment

Vegetable parchment is produced by adding concentrated sulfuric acid to the surface of the paper to swell and partially dissolve the cellulose fibers. It produces a grease-resistant paper with good wet strength (meaning that it maintains its strength well when it is wet). Vegetable parchment is odorless, tasteless, boilable, and has a fiber-free surface. Labels and inserts on products with high oil or grease content are frequently made from parchment. Parchment can also be treated with mold inhibitors and used to wrap foods such as cheese (Robertson, 2007).

11.4.2.2 Paperboards and their applications

Paper and paperboard can be distinguished by thickness (caliper) and weight of the material. Material is generally termed “paperboard” when its thickness is more than 300 μm and/or its weight exceeds 250 g/m^{-2} (Hanlon et al., 1998). Various types of paperboard are manufactured but paperboard for food packaging generally includes whiteboard, linerboard, foodboard, cartonboard, chipboard, and corrugated board.

11.4.2.2.1 Whiteboard

Whiteboard is made with a bleached pulp liner on one or both sides to improve appearance and printability, and the remaining part is filled with low-grade mechanical pulp. Whiteboard is suitable for contact with food and is often coated with polyethylene or wax for heat sealability. It is used for ice cream, chocolate, and frozen food cartons.

11.4.2.2.2 Linerboard

Linerboard is usually made from softwood kraft paper and is used for the solid faces of corrugated board. Linerboard may have multiple plies. Increasingly, linerboards containing recycled fiber are being used in packaging. The higher quality layer is always placed on top.

11.4.2.2.3 Foodboard

Foodboard is used to produce cartons that are suitable for direct food contact. It is normally made using 100% virgin pulp but recently recycled pulp using an innovative barrier coating with a sustainable coating material is also being used. Foodboard is a sanitary, coated, and water-resistant paperboard. It should be designed to protect against migration of outside contaminants (such as ink or oil) into packaged food. Foodboard can be used for all types of foods, particularly frozen and baked foods.

11.4.2.2.4 Cartonboard (boxboard)

Cartonboard is used to make folding cartons and other types of boxes. Most often, this is a multilayer material made of more than one type of pulp, and often incorporating recycled fibers. To improve its appearance, it may be clay coated or may have a ply of virgin fibers on one or both surfaces.

11.4.2.2.5 Chipboard

Chipboard is the lowest quality and lowest cost paperboard, made from 100% recycled fiber, and is not used in direct contact with foods. Outer cartons for tea and breakfast cereals are some examples. It is also commonly lined with whiteboard to produce a multi-ply board such as cartonboard.

11.4.2.2.6 Corrugated board

Corrugated board has an outer and inner lining of kraft paper with a central corrugating (fluted) material. Corrugated boards resist impact, abrasion, and compression forces so they are commonly used in shipping containers.

11.4.2.3 Paperboard cartons and other containers for food packaging

Folding cartons are made of paperboard, typically between 300 and 1100 μm in thickness. They are creased, scored, cut, and folded into the desired shape. The cartons usually are shipped flat to the product manufacturer (or carton assembler). Paperboard can be coated or laminated when improved function is desired. For example, wax lamination provides moisture resistance, glassine lamination provides oil/grease resistance, and PE lamination provides heat sealing and moisture resistance. Clay and

mineral coatings on the exterior provide improved appearance and printing quality.

Molded pulp containers are produced by placing aqueous slurry of cellulosic fibers into a screened mold. Since molded pulp containers are regarded as a sustainable packaging material, they are gaining popularity. Typical applications in food packaging include egg cartons, food trays, and other tray type containers for fruits. Molded pulp containers can be laminated with thermally resistant plastics such as PET to provide functionality as dual-ovenable containers (suitable for use in conventional ovens as well as microwaves).

11.4.3 Metals

11.4.3.1 Types of metal and general properties

Metal is used in packaging in a variety of applications, from rack systems to tuna cans. For food packaging, four types of metal are commonly used: steel, aluminum, tin, and chromium.

Steel and aluminum are commonly used in production of food cans, and are the primary materials for metal packaging. Food cans are most often made of steel, and beverage cans are usually produced from aluminum. Steel tends to oxidize when it is exposed to moisture and oxygen, producing rust. Therefore, tin and chromium are used as protective layers for steel. Tinplate is a composite of tin and steel made by electrolytic coating of bare steel with a thin layer of tin to minimize corrosion. If chromium is used to provide corrosion protection instead of tin, the resulting material is called electrolytic chromium-coated steel (ECCS) or tin-free steel (TFS). ECCS is less resistant to corrosion than tinplate but has better heat resistance and is less expensive.

11.4.3.2 Can forming process

There are two basic styles of cans: three-piece and two-piece. As the name indicates, a three-piece can is made from three pieces (a body blank and two ends), and a two-piece can is made from two pieces (one body and one end).

11.4.3.2.1 Three-piece cans

Hermetically sealed three-piece cans consist of a can body and two endpieces. The process for making three-piece cans starts with rolling steel into a rectangular strip (about 1.8 mm thick). Next, coating is applied, depending on the

requirements of the food. Generally, more acidic food has a higher coating weight on the inner side of the strip. Additional coating is applied to improve the surface brightness, to resist corrosion, and to prevent interaction with foods. More details about coating are provided in section 11.4.3.4. In order to make the can body, the steel sheet is cut into a rectangular piece and formed into a cylindrical shape, and its side is seamed. For food packaging, most three-piece cans are made using welded side seams. Soldering was the original method, but has been mostly discontinued due to concerns about lead contamination. Lead solder is no longer permitted for packaging of products sold in the US as well as in many other countries. Next, the body is flanged, and one end of the can is attached using a double seaming process. The double seam forms a hermetic seal by interlocking the end cover and body of the can with a rubbery sealing compound between them. After filling, the second end is attached in the same manner. The structure and main components of a double seam are shown in Figure 11.4.

Cans for food packaging are often subjected to external and internal pressure during processing and storage. The can body may be rippled or beaded to increase its strength.

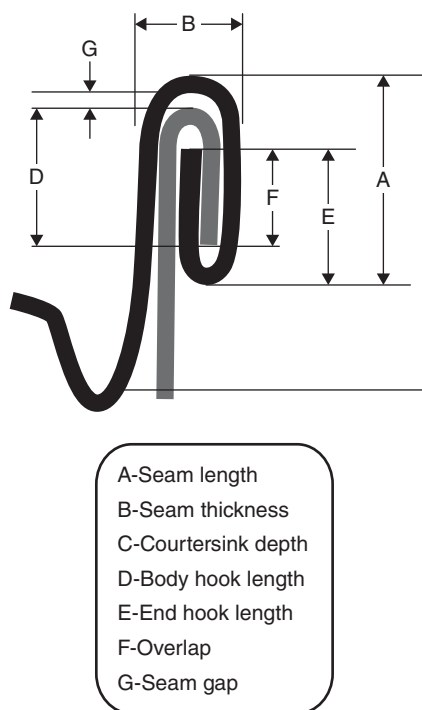


Figure 11.4 Structure and main components for double seaming.

11.4.3.2 Two-piece can

A two-piece can does not have a side seam. It is composed of the body and one cover for the top. There are two main methods of producing two-piece cans: draw and iron (DI) and draw and redraw (DRD). In the DRD process, a metal blank is punched into a die (drawn) to form a shallow can shape. The diameter of the cup produced in the initial draw is then further reduced by a similar redraw process. Some very short cans do not require this second draw so are not really DRD cans – these are referred to as shallow draw cans. The wall and base thickness, as well as the surface area, are the same as those of the original blank. The DRD process is commonly used for TFS cans. After the body is shaped, the can is trimmed, often beaded, and after filling the end is double seamed onto the can body.

In the DI process, typical for aluminum beverage cans, a circular disk shape blank is cut and drawn to a shallow cup. The cup is usually redrawn once, and then is passed through a series of ironing dies that extend and thin the walls. Thus, the base of the can ends up thicker than the walls. DI cans are usually used for carbonated beverages. The ends of DI cans are often necked (narrowed) to reduce the size of the end, as this improves the ability to stack the cans, and lowers the overall cost (by saving metal).

11.4.3.3 Metal foil and containers

Aluminum foil is the most commonly produced metal foil. It is manufactured by passing aluminum sheet between a series of rollers under pressure. Pure aluminum (purity >99.4%) is passed through rollers to reduce the thickness to less than 150 μm and then annealed to provide dead-folding properties. Foil is widely used for wraps (9 μm), bottle caps (50 μm), and trays for ready-to-eat meals (50–100 μm). Aluminum foil has excellent barrier properties against gases and water vapor. Thus, it is also used as the barrier material in laminated films for packages, such as those in retort pouches.

Collapsible aluminum tubes can be used for the packaging of viscous products. The collapsible tube allows the user to apply precise amounts of the products when required because the tubes permanently collapse as they are squeezed and prevent air being drawn into the container again. These types of tube applications for foods are rare in the US but more common in Europe. Typical applications include condiments packages such as mustard, mayonnaise, and ketchup.

Metallized films are also used in food packaging applications for their excellent barrier properties. The principle

of metallization is to use a vapor deposition process to deposit an extremely thin layer of metal on another substrate (film). The typical thickness of the aluminum layer in metallized film is 400–500 Å. Oriented polypropylene (OPP) is the material most often used for metallized film applications. Nylon and PET are also common film substrates.

11.4.3.4 Coating

One of the major problems associated with metal packaging is corrosion. The inside of a can is normally coated to prevent interaction between the can and its contents. The outside of a can is generally also coated to provide protection from the environment. Coatings used in cans need to provide an inert barrier (must not impart flavor to the product), must usually resist physical deformation during fabrication, be flexible, spread evenly and completely cover the surface of the metal, and the coating must adhere well to the metal and be non-toxic (for food packaging).

Two methods are used for the application of protective coatings to metal containers: roller coating and spraying. The roller coating process is used for external coating of cylindrical can bodies and spraying is used if physical contact is difficult, such as for the inside surface of can bodies. Typical can coatings are polymers applied in a liquid state and then dried after application by solvent removal, oxidation or heat-induced polymerization. The commonly used coating materials for food packaging include the following (Robertson, 2007).

- **Epoxy-phenolic compounds:** these are used for all types of steel and cans. They are resistant to acids and have good heat resistance and flexibility. They are used for beer, soft drinks, meat, fish, fruits, vegetables, and so on. They are especially suitable for acidic products and have excellent properties as a basecoat under acrylic and vinyl enamels.
- **Vinyl compounds:** vinyl compounds have good adhesion and flexibility, and are resistant to acid and alkaline products. However, they are not suitable for high-temperature processes such as retorting of food. They are used for canned beers, wines, fruit juices and carbonated beverages and as clear exterior coatings.
- **Phenolic lacquers:** phenolic compounds are inexpensive and resistant to acid and sulfide compounds. They are used for acid fruits, fish, meats, soups, and vegetables.
- **Polybutadiene lacquers:** polybutadiene compounds have good adhesion, chemical resistance, and high heat resistance. They are used for beer and soft drinks, soups, and vegetables (if zinc oxide is added to the coating).

- **Acrylic lacquers:** acrylic lacquers are expensive coating materials. They take heat processing well and provide an excellent white coat. They are used both internally and externally for fruits and vegetables.

- **Epoxy amine lacquers:** epoxy amine lacquers are also expensive. They have excellent adhesion, heat and abrasion resistance, and flexibility, and no off-flavor. They are used for beer and soft drinks, dairy products, and fish.

- **Alkyd lacquers:** alkyd lacquers are low cost and used mostly as an exterior varnish over inks (due to flavor and color problems inside the can).

11.4.4 Glass

Glass is defined as “an amorphous inorganic product of fusion that has been cooled to a rigid condition without crystallizing” (ASTM, 2003). For food packaging, bottles or jars are the types of glass packaging most often used, bottles being the primary use. In the US, 75% of all glass food containers are bottles.

Glass is made primarily of silica, derived from sand or sandstone. For most glass, silica is combined with other raw materials in various proportions. For example, soda-lime glass, the glass typically used for food packaging, contains silica (68–73%), limestone (10–13%), soda ash (12–15%), and alumina (1.5–2%). Glass is inert to a wide variety of food and non-food products, very rigid and strong against pressure, transparent, and non-permeable (excellent barrier properties). However, glass has disadvantages due to its heavy weight and fragility. For food packaging, the fragility has caused some safety concerns such as the possibility of the presence of chipped glass in food products. Glass for food packaging has declined over the last three decades, with glass losing market share to metal cans and, increasingly, to plastics. However, it still plays an important role in packaging.

11.4.4.1 Forming of glass

The glass making process begins with weighing out and mixing of the raw materials and introduction of the raw material to the glass melting furnace, which is maintained at approximately 1500 °C. Cullet, broken or recycled glass, is also an important ingredient in glass production. In the melting furnace, the solid materials are converted to liquid, homogenized, and refined (getting the bubbles out). At the end of the furnace, a lump of molten glass, called a “gob,” is transferred to the glass forming process.

For food packaging, glass can be formed using the blow-and-blow process, wide-mouth-press-and-blow process,

or narrow-neck-press-and-blow process. In the blow-and-blow process, compressed air blows the gob into the blank mold of the forming machine and creates the shape of the parison. Then, the completed parison is transferred into the blow mold where air blows the parison to form a final shape. In the wide-mouth-press-and-blow process, a metal plunger is used to form the gob into the parison shape, instead of using air blowing. As in the blow-and-blow process, the compressed air blows the container into its final shape. In the narrow-neck-press-and-blow process, the overall process is similar to the wide-mouth-press but a much smaller metal plunger is used to make the parison shape. Less than 38 mm of finish diameter is regarded as narrow mouth and over 38 mm is called wide mouth. (Glass Packaging Institute, 2012). The press-and-blow process provides increased productivity, less weight, and more uniform wall thickness compared to the blow-and-blow process. Beer or beverage bottles are common applications for the narrow-neck-press-and-blow process.

Once the finished container is formed, it is transferred to a large oven known as a *lehr* for the annealing process. The function of annealing is to reheat and gradually cool the container in order to relieve the residual thermal stress. Surface coatings are often applied to the glass container for strengthening and lubricating the surface. Hot-end coatings are applied before the container enters the annealing oven (when the glass is still hot due to the previous forming process). Hot end coatings consist of tin chloride (which reacts to form tin oxide) or organo-tin. These compounds are applied in vapor form and leave a rough high-friction surface on the glass container, which provides a good adhesive surface for the cold-end coatings. They also supply hardness, fill in minor cracks, and compress the glass surface. After the glass containers are cooled, a cold-end coating is applied to increase lubricity and minimize the scratching of surfaces. These coatings typically consist of lubricants such as waxes, polyethylene, polyvinyl alcohol, and silicone. Since cold-end coatings make the glass surface more slippery, it is important to check the compatibility of the cold-end treatment with adhesives used in labeling.

11.5 Other packaging types

11.5.1 Aseptic packaging

Aseptic packaging is the filling of a commercially sterilized product into a sterilized container under aseptic conditions and then sealing it hermetically to prevent

contamination. Therefore, the sterility can be maintained throughout the handling and distribution process. The aseptic packaging permits shorter heat exposure for the food than typical thermal sterilization processes such as canning and retorting; therefore it generally results in superior food quality compared to typical thermal sterilization. Because of the separate package and food product sterilization, the selection of material and container design can be more flexible than in traditional thermal sterilization.

The required microbial count reduction (referred as log reduction) for the sterilization of a food contact packaging material is determined by the type of product. For non-sterile acidic products (pH <4.5), a minimum 4-log reduction in bacterial spores is required. For sterile, neutral, low-acid products (pH >4.5), a 6-log reduction is required. In addition, if sterility against *Clostridium botulinum* endospores is required, a 12-log reduction is required, and the process is called commercial sterilization. The sterilization methods for aseptic packaging materials include irradiation (such as ultraviolet rays, infrared rays, and ionizing radiation), heat (such as saturated steam, superheated steam, hot air, hot air and steam), and chemical treatment (such as hydrogen peroxide, ethylene oxide, peracetic acid). These processes can be used either individually or in combination.

The type of aseptic packaging material used is influenced by the nature of the product, the cost of both product and packaging, and the preference of consumers. The most widely used aseptic package is the paperboard laminated carton. The typical structure of this material consists of unbleached or bleached paperboard, polyethylene, and aluminum foil. The laminated structure is impermeable to liquid, gas, and light. The detailed structure of a typical paperboard carton (which is produced by Tetra Pak) is shown in Figure 11.5.

Aseptic packages can also be in the form of cans, bottles, pouches, trays, or cups. Can type aseptic packages are the same basic types of metal cans as in the regular canning process: tinplate, ECCS, and aluminum. Under an aseptic packaging process, the heating time for sterilization and food quality are the same for both large and small containers, while the traditional canning process has longer heating times for larger containers. Bottle type aseptic packages are produced from plastics as an economical alternative to glass for non-returnable containers. HDPE, PP, and PET are the most commonly used materials for this type of package. Pouch type aseptic packages are made from similar laminated paperboard structures. Also, multilayer films containing LLDPE and

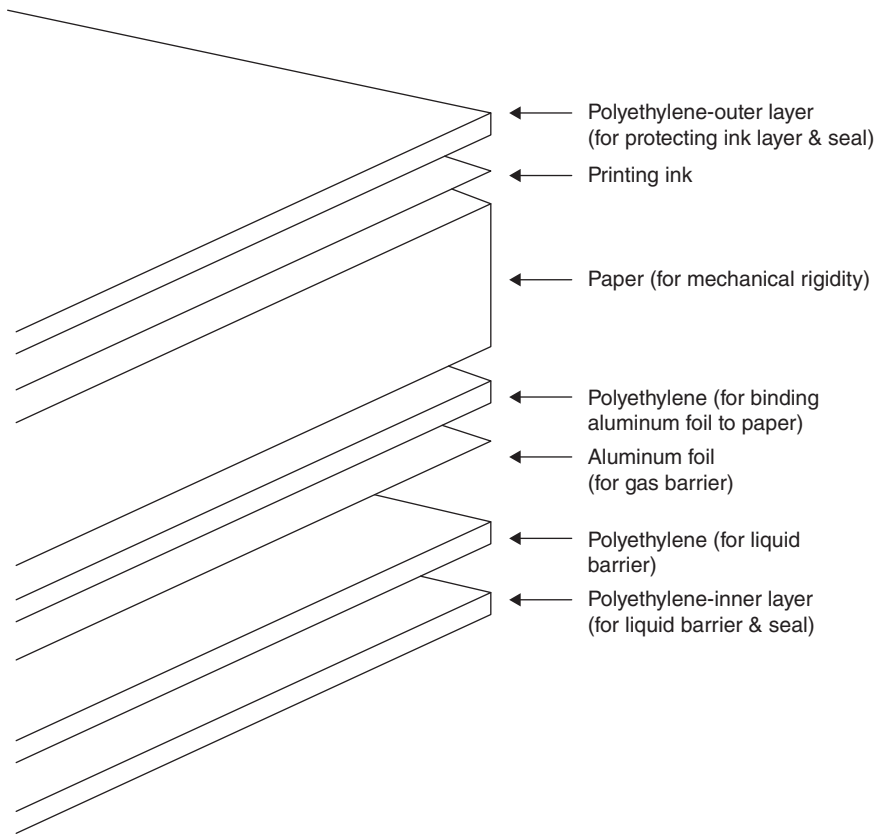


Figure 11.5 The structure of a typical laminated paperboard carton for aseptic packaging.

EVOH are used. Cup type aseptic packages are produced from HIPS, PP, or multilayer film. Multilayer films are the choice when high barrier properties are required. PVDC or EVOH is typically used as the barrier layer.

Maintaining the package integrity during distribution and handling is one of the most important issues in aseptic food packaging. Thus, various integrity tests are used commercially. Typically, electrolytic testing, dye penetration or vacuum leak tests are used for quality control during manufacturing. However, these traditional methods are destructive and therefore it is impossible to test and reject all faulty packages in the processing line. Thus, non-destructive test methods, such as gas leak detectors and ultrasound techniques, are gaining more attention from industry.

11.5.2 Modified atmosphere packaging

Modified atmosphere packaging (MAP) is based on modifying or altering the atmosphere inside the package to

prolong shelf life and maintain quality of products. The modification of the atmosphere can be achieved actively or passively. In active type MAP, the optimum gaseous environment is obtained by flushing a controlled mixture of gases in a package (“gas flush”). The passive type of MAP modifies the optimum gaseous environment in a package by a combination of the food’s respiration and the metabolism of microorganisms associated with the food and the permeability of the packaging. With the optimized gaseous atmosphere, degradation reactions in foods such as enzyme activity, oxidation, moisture loss, and postharvest metabolic activities as well as the growth of microorganisms are delayed. The three main gases used for MAP are nitrogen (N_2), carbon dioxide (CO_2), and oxygen (O_2). They are used either alone or, in most cases, in combination. Mixtures of carbon dioxide (CO) and argon (Ar) are also utilized commercially. Examples of gas mixtures that are used for fresh and processed foods are shown in Table 11.1.

Table 11.1 Examples of optimum headspace gas mixtures (%) and storage temperature for fresh and processed food products

Product	Temperature (°C)	Oxygen (%)	Carbon dioxide (%)	Nitrogen (%)
Snack	23	0	20–30	70–80
Bread	23	0	60–70	30–40
Cake	23	0	60	40
Cheese (hard)	4	0	60	40
Cheese (soft)	4	0	30	70
Pasta	4	0	80	20
Pizza	5	0–10	40–60	40–60
White fish	0–2	30	40	30
Oily fish	0–2	0	60	40
Shrimp	0–2	30	40	30
Fresh red meat	0–2	40–80	20	0
Cooked/cured meat	1–3	0	30	70
Pork	0–2	40–80	20	0
Poultry	0–2	0	20–100	
Sausage	4	0	80	20
Apples	0–3	1–3	0–3	
Banana	12–15	2–5	2–5	
Broccoli	0–5	5–10	1–2	
Lettuce	0–5	2–3	5–6	
Tomato	7–12	4	4	

Adapted from: FDA (2001), Brody (2000), Parry (1993).

11.5.2.0.1 Nitrogen (N_2)

Nitrogen is the most commonly used gas in MAP. It is an inert gas with no odor or taste. Nitrogen also has low solubility in water (0.009 g/kg at 20 °C). Nitrogen does not directly provide any microbial retardation but it delays aerobic microbial growth and oxidation by replacing oxygen.

11.5.2.0.2 Carbon dioxide (CO_2)

Carbon dioxide is colorless with a slightly pungent odor. The most important function of this gas is related to its bacteriostatic and fungistatic properties. Usually, a higher concentration is more effective against microorganisms. However, color changes and acid tastes have been reported by several researchers due to exposure to high CO_2 . Carbon dioxide has high solubility in water (1.69 g/kg at 20 °C). Thus, packages containing moist foods with CO_2 in their headspace may collapse.

11.5.2.0.3 Oxygen (O_2)

Oxygen is a colorless, odorless, and highly reactive gas. It promotes food deteriorative reactions such as fat

oxidation, browning reactions, and aerobic microbial growth. For this reason, the desired oxygen content in the headspace of most foods is often extremely low. However, oxygen is still needed for the retention of color in red meat and for fruit/vegetable respiration.

11.5.2.0.4 Carbon monoxide (CO)

Carbon monoxide is a colorless, tasteless, and odorless gas. When carbon monoxide combines with myoglobin, a bright red pigment (carboxymyoglobin) is formed, which is more stable than normal red meat pigment (oxymyoglobin). The use of carbon monoxide is not for quality issues but for its visual effect. Since carbon monoxide is a toxic and highly flammable gas, its commercial use is limited. In the US, carbon monoxide is currently used for red meat but the level of its use is limited to 0.4% (FDA, 2005a).

11.5.2.0.5 Argon (Ar)

Argon is a chemically inert, colorless, tasteless, and odorless gas which is denser and heavier than air. Compared to nitrogen, argon is a more effective gas for use in flushing

out air. However, due to the high cost of argon, nitrogen is mostly used for flushing.

11.5.2.1 Modified atmosphere packaging for meat

For red meat, oxygen is necessary to maintain the red color of oxymyoglobin in unprocessed meats. On the other hand, a low oxygen level is desired to prevent the growth of microorganisms and oxidative rancidity of fat. Typically, the shelf life of fresh red meat is extended by packaging it in an atmosphere of 20% CO₂, 60–80% O₂, and up to 20% N₂. However, off-odors and rancidity have been reported in meats stored at high O₂ concentrations (Taylor, 1985). Thus, maintaining a low temperature (0–2 °C) is desired when high-O₂ MAP is used.

Poultry has low myoglobin content so it does not need oxygen to maintain its color. A higher CO₂ concentration (20–100%) is possible to extend the shelf life. However, a few studies report color change with high CO₂ concentration in poultry products (Dawson, 2004).

11.5.2.2 Modified atmosphere packaging for seafood

Seafood such as fish and shellfish is highly perishable owing to its high water activity (a_w), pH, and the presence of autolytic enzymes, which cause rapid development of undesirable odors. A low oxygen atmosphere can delay the occurrence of undesirable odor and growth of aerobic microorganisms. For example, packaging tilapia fillets in 75% CO₂:25% N₂ extended their shelf life up to 80 days at 4 °C (Sivertsvik et al., 2002). However, fresh fish may be contaminated with the anaerobic *C. botulinum* either as a result of being present in the microbiota of the fish ecosystem or due to postcatch contamination during processing. A low oxygen atmosphere poses a potential threat for a packaged fish to become toxic prior to spoilage. To assure the safety of MAP fish products, the product must be maintained at or below 3 °C at all times. Since chilled storage control is a critical factor to determine the shelf life, some companies use time temperature indicators (TTI) to monitor for temperature abuse.

11.5.2.3 Modified atmosphere packaging for fresh fruits and vegetables

Fresh fruits and vegetables keep consuming O₂ and emitting CO₂ even after harvest. The purpose of MAP for fresh fruits and vegetables is to minimize the respiration and senescence without causing suffocation and damage

to metabolic activity that rapidly reduces their shelf life. However, a low oxygen and high CO₂ atmosphere that develops inside the package due to respiration of the product may result in the accumulation of ethanol and acetaldehyde, and fermentation could start. Thus, the package material needs to be somewhat permeable to oxygen and CO₂ to allow the transfer of the gases from outside and inside. The change in gas composition during storage depends on the permeability of the container to water vapor and gas, storage temperature, and the mass of the food.

11.5.3 Active packaging in food processing

Active packaging is an important and rapidly growing area. There are several different definitions that can be found in the literature for active packaging. This type of packaging usually involves an interaction between the packaging components and the food product beyond the inert passive barrier function of the packaging material (Labuza & Breene, 1989; Soroka, 2008b). The major active packaging technologies include oxygen scavengers, moisture absorbers, antimicrobial agent releasers, ethylene scavengers, flavor/odor absorbers, and temperature control packaging. In order to apply this technology, the major deteriorative factor(s) for food products should be understood. For example, the shelf life of a packaged food is affected by numerous factors such as acidity (pH), water activity (a_w), respiration rate, oxidation, microbial spoilage, temperature, etc. By carefully considering all of these factors, active packaging can be developed and applied to maintain the quality of the product and/or to extend its shelf life. Active agents are contained in sachets or incorporated directly into packaging containers.

11.5.3.1 Oxygen scavengers

Oxygen scavengers are the most commercially applied technology in the active packaging market. By scavenging oxygen molecules in the package headspace, oxidative damage to food components such as oil, flavors, vitamins, color, etc. can be prevented. In addition, reduced O₂ concentration in the package retards the growth of aerobic bacteria and mold.

The basic principle of oxygen scavenging is related to oxidation of the scavenging agents (either metallic or non-metallic based materials) to consume oxygen. The most common O₂ scavengers used in the food industry are sachets with iron powder, which are highly permeable to oxygen. By using iron powder, the O₂ concentration in

the headspace can be reduced to less than 0.01% while vacuum or gas flushing typically achieves 0.3–3.0% residual O₂ levels (Robertson, 2007). The metal-based oxygen scavengers normally cannot pass the metal detectors on the packaging lines and cannot provide transparent packages if they are directly incorporated into packages. Non-metallic O₂ scavengers, such as ascorbic acid or glucose oxidase, can be used as an alternative choice. However, the use of non-metallic O₂ scavengers is not widespread.

O₂ scavengers can be incorporated into plastic film/sheet when there are market concerns about accidental consumption of sachets or when an O₂ scavenger needs to be used for liquid foods. In this case, the O₂ scavenger-impregnated layer is typically sandwiched between film layers. The outside layer provides high oxygen protection and the inner layer prevents direct contact between the scavenger-containing matrix layer and the food.

11.5.3.2 Moisture absorbers

Moisture in packages is a major cause of food deterioration such as microbial growth-related spoilage and product softening. Moisture-absorbing sachets are used in food packaging for humidity control. Several desiccants such as silica gel, calcium oxide, and activated clays and minerals are typically contained in sachets. Drip-absorbent pads and sheets are also used to absorb liquid in high a_w foods such as meats, fish, poultry, fruits, and vegetables. A superabsorbent polymer is sandwiched by a microporous non-woven plastic film such as polyethylene or polypropylene. Polyacrylate salts, carboxymethyl cellulose (CMC), and starch co-polymers are typically used as the absorbent polymer.

11.5.3.3 Antimicrobial agent releasers

Typically, surface contamination during food handling and transportation is one of the most common sources of food-borne illness, and lower amounts of antimicrobial agents are required to control the surface microbial contamination/growth if they are incorporated into or onto packaging material rather than directly added into the food itself. There are two mechanisms for antimicrobial action: one is controlling microbial growth by slow and controlled release (or migration) of the antimicrobial agents over the product shelf life. The other type is controlling microbial growth by contact without release of the antimicrobial agents, which are immobilized on the surface of the package. Despite the large number of experimental studies on antimicrobial packaging, the

technology has not been widely used in food markets yet, because of cost or regulatory constraints. An example of a commercial application of an antimicrobial packaging is silver ion-based film. This film is an effective antimicrobial agent with very low human toxicity and it has been used in food containers. Other examples of antimicrobials used (or studied) include nisin, pediocin, organic acids, grapefruit seed extract, cinnamon, and horseradish (Han, 2003).

11.5.3.4 Ethylene scavengers

Ethylene works as a plant growth regulator which accelerates the respiration rate and senescence of fruits and vegetables. Removing ethylene from the environment can extend the shelf life of horticultural products. One of the most common ethylene scavengers is made from potassium permanganate (KMnO₄) immobilized on an inert mineral substrate such as alumina or silica gel. Activated carbon-based scavengers with various metal catalysts are also used as effective ethylene scavengers. In recent years, packaging films and bags have been commercialized based on the reputed ability of certain finely dispersed minerals to absorb ethylene (such as clays, zeolites, coral, ceramics, etc.) (Rooney, 2005).

11.5.3.5 Flavor and odor absorbers

Undesirable flavor scalping by the packaging material can result in the loss of desirable food flavors, while foods can pick up undesirable odors or flavors from the package or the surrounding environment. For example, fruit juices in PET bottles or water in HDPE bottles can absorb unwanted odors that result from aldehydes such as hexanal and heptanal originating in oxidation of the plastics. Another example is that an unpleasant “confinement odor” can accumulate inside PE bags in a distribution center. One type of flavor/odor-absorbing technology is based on a molecular sieve with pore sizes of approximately 5 nm. Cyclodextrin is a common example of an odor absorber. Wood (2011) reported that cyclodextrin, grafted to a PE layer, was applied to military ration pouches to absorb accumulated odor from food decomposition. Synthetic aluminosilicate zeolite, which has a highly porous structure, has been incorporated in packaging materials, especially papers, to absorb odorous gases such as aldehyde (Day, 2003).

On the other hand, absorbers can also be used in a flavor/aroma-releasing system. Aroma compounds can be released inside the package to enhance the flavor/aroma

of the product or outside the package to attract consumers to the products on a retail store shelf (Lagaron & Lopez-Rubio, 2009).

11.5.3.6 Temperature-controlled packages

Temperature-controlled active packages generally include self-heating and self-cooling systems. The fundamental concepts for self-heating are not new. An exothermic chemical reaction between CaO (quicklime) and a water-based solution generates heat. The challenging part of this system is optimizing the reaction and the thermal design of the container to provide an efficient, safe, and cost-effective package. Self-heating packages are commercially available for coffee, tea, and ready-to-eat meals. Self-cooling cans use endothermic chemical reactions; the latent heat of evaporating water is often used to produce the cooling effect. One example is dissolution of ammonium nitrate and chloride in water to cool the product (Day, 2008).

11.6 Sustainable food packaging

11.6.1 Recycling of food packaging

Food packaging has the largest demand for packaging industries, whether it is paper, plastics, glass, or metal. Finding or improving ways to reduce landfilled waste is important to meet current demands for environmentally friendly packaging (Arvanitoyannis & Kasaverti, 2008). Recycling can be defined as diverting materials from the solid waste stream for use as raw materials in the manufacture of new products. The overall recycling rate of packaging material in the US is 40%, and is far behind the rate in Europe, which is about 59% (Fischer & Davisen, 2010).

11.6.1.1 Recycling of paper and paperboard

Packaging materials are the largest sector in which recycled paper is used in the US, as shown in Figure 11.6. The recycling rate for paper and paperboard has been increasing during the last decade. In 2010, 37.7 million tonnes of paper and paperboard packaging waste were generated and 71.3% of the used material was recycled (EPA, 2010). Even if most types of paper are recyclable, recycled paper is not suitable for most food contact packaging applications because the recycling processes may allow contaminants to be present in the recycled paper products. In many applications, recycled

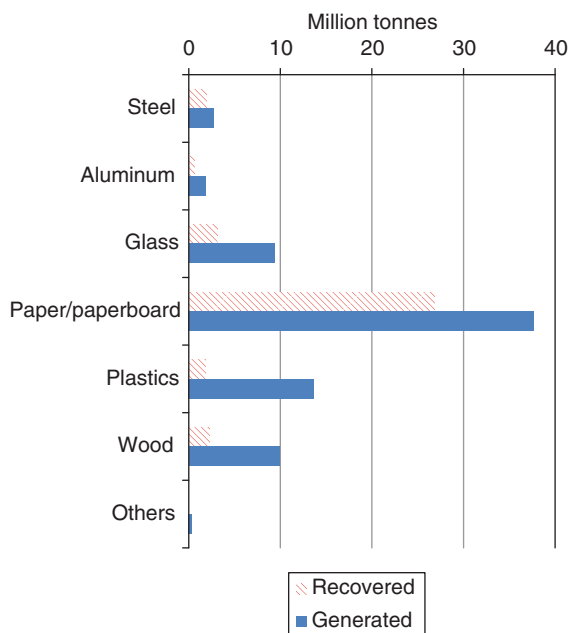


Figure 11.6 Generation and recovery of packaging materials in the United States (EPA 2010).

paper is not used in direct contact with food, so migration is of little or no concern. Another issue is related to paper properties: recycled paper normally has a damaged and weak fiber structure. In order to obtain suitable physical and mechanical characteristics, mixing virgin and recovered fibers in different proportions is often required.

11.6.1.2 Recycling of glass

Glass is the next most recycled packaging material, in terms of weight recovered; 9.36 million tonnes of glass packaging waste were generated in the US in 2010, and 33.4% of the used material was recycled (EPA, 2010). Unlike paper-based material, the properties of glass are not affected by recycling. Cullet can be reprocessed into glass containers with physical properties identical to the original material. Glass recycling also reduces energy consumption: addition of 10% cullet reduces energy consumption by 2.5% (Dainelli, 2008). One of the major problems for food packaging applications originating from recycling is the presence of contaminants. Contaminants such as metals, papers, plastics, organic substances, ceramics, and heat-resistant glass (such as borosilicates), if not removed, can cause problems in making new food

containers. Combination with colored glass is another problem, especially in the manufacture of colorless glass. This can result in off-color containers that are not acceptable for demanding applications such as food packaging. Mixed color cullet may be used for alternative applications such as abrasive paper, water filtration media, construction materials, and so on. Efficiently removing or sorting these contaminants or colored cullet requires a high level of investment. In addition, cullet is heavy and therefore expensive to ship. Collection within an acceptable transport distance is a critical point in glass recycling.

11.6.1.3 Recycling of aluminum

Aluminum is a metal largely used for industrial and consumer goods applications; 1.9 million tonnes of total aluminum packaging waste were generated in the US in 2010, and 35.8% of the used material was recycled (EPA, 2010). Like glass, recycled aluminum does not lose its physical properties and is safe for food packaging. Using recycled aluminum can save 75–90% of energy compared with its production from natural sources (Dainelli, 2008). Collection of aluminum for recycling is through a combination of deposit, curbside, and drop-off programs. During the recycling process, aluminum is easily separated from other metals. Since it is lighter and not magnetic, iron or other ferrous metals can be separated using a magnetic separator or flotation. Internal coatings, printed ink, and any other organic contaminants are destroyed during the recycling process.

11.6.1.4 Recycling of plastics

Plastics are recycled the least of the major packaging materials in the US; 13.68 million tonnes of plastic packaging waste was generated in the US in 2010, and 13.5% of the used material was recycled (EPA, 2010). During recycling, plastics can undergo several types of reactions such as chain scission, cross-linking, oxidation, and hydrolysis. Thus, the overall physical performance of the recycled plastics may decrease significantly. In addition, all recycled plastics cannot be mixed together due to their chemical incompatibility. In most applications, achieving good performance properties requires separation of the recycled plastics by resin type. Therefore, recycling of plastic packaging wastes is more difficult and costly than that of some other packaging materials. Energy recovery, such as incineration, may be the preferred option for multilayer plastics which cannot be separated by type, while cleaning and reprocessing into pellets for use in new

plastic products is often the best choice for homogeneous plastics. Another option in some cases is depolymerization to monomers, purification, and repolymerization.

Since the potential migration of contaminants to food or other products is often a concern, most recycled plastics are used for non-food applications, including packaging containers, film and sheet, and also non-packaging applications such as fiber and carpet. In order to obtain food contact-grade plastic, the recycled plastics need to be processed and used in a way that effectively removes the potential for such contamination.

One option, as mentioned above, is chemical recycling, in which after depolymerization, the monomers are purified and repolymerized. Polymers produced in this way are identical to those produced from ordinary raw materials. Chemical recycling can be used for PET and PA, but is often not economical.

Another option for recycled plastic in food packaging is using it as a component in a multilayer structure. The recycled plastic is sandwiched inside, and a “barrier” layer of virgin plastic separates the recycled plastic from the product.

Another widely used option for PET is intensive cleaning to remove most potential contaminants. A number of companies have received “non-objection” letters from the US FDA for plastics recycling processes that have been demonstrated to remove potential contaminants from recycled PET streams to a degree that makes them acceptable for food contact (FDA, 2008). One example is the Superclean process, which consists of a series of processes that can remove the volatile contaminants as well as increase the viscosity of the recycled PET so that it is suitable for injection blow molding (Franz & Welle, 2002).

Most “non-objection” letters for recycled plastics have been issued for PET recycling processes. HDPE is both more susceptible to sorption of contaminants and more difficult to clean. While there have been a few processes approved for use of recycled HDPE in food packaging, there is little commercial use. On the other hand, recycled PET is used to a considerable extent in food packaging applications.

11.6.2 Biodegradable and compostable food packaging

Due to growing concerns about waste disposal problems and the environmental effects of petroleum-based plastics, natural biopolymers derived from renewable sources that are biodegradable appear to be a good alternative to conventional plastics. In addition, in recent times, oil

prices have increased markedly. These facts have caused increased interest in non-petroleum based biodegradable polymers. The biodegradation takes place through the action of enzymes and/or biochemical deterioration associated with living organisms, and the biodegradability depends not on the raw material sources to produce the polymer but rather on the chemical structure of the polymer and the environmental conditions because chemical structure, such as the chemical linkage, pending groups, etc., is related to susceptibility to degradation, and environmental condition is related to living organisms' activities.

The common challenges in using biodegradable packaging materials are ensuring durability to maintain their mechanical and/or barrier properties during the product's shelf life, and then, ideally, the ability to biodegrade quickly on disposal. Ideally, the materials need to function in a similar way to conventional packaging in filling and sealing equipment with equivalent costs. Biobased biodegradable polymers can be classified into three main

categories according to their origin and method of production (van Tuil et al., 2000).

- Polymers directly extracted/removed from biomaterials (for example, starch, cellulose, casein, etc.).
- Polymers produced by classic chemical synthesis from monomers produced from biomaterials (for example, polylactide polymerized from lactic acid monomers).
- Polymers produced directly by microorganisms (for example, polyhydroxyalkanoates).

A schematic presentation of these three categories is given in Figure 11.7.

11.6.2.1 Biodegradable polymers from agricultural crops

Polymers produced from starch are examples for this class. Starch is a widely available, environmentally friendly material with low cost. Corn is currently the most commonly used source of starch for bioplastics. However, potato, wheat, rice, barley, and oats can also be used as

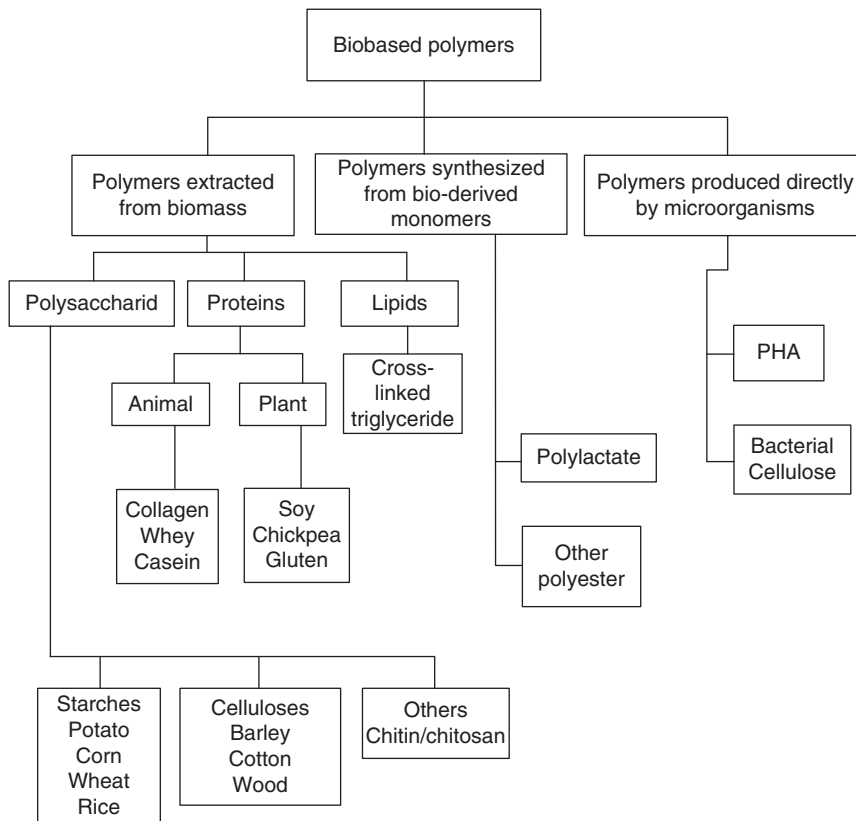


Figure 11.7 Biobased polymers for food packaging (from van Tuil et al., 2000).

starch sources (Liu, 2006). Without modification, starch films are hydrophilic and have relatively poor mechanical strength. They cannot be used for packaging applications. The brittleness of starch-based bioplastics can be decreased by using biodegradable plasticizers, including glycerol and other low molecular weight polyhydroxy compounds, polyethers, etc. (van Tuil et al., 2000).

Cellulose is the most widespread polysaccharide resource produced by plants. Cellulose is composed of glucose monomers that form a linear polymer with very long macromolecular chains. Cellulose is highly crystalline, brittle, infusible, and insoluble in all organic solvents (Chandra et al., 2007). These properties make cellulose impossible to process without modification. Cellophane films are produced by chemical modification of cellulose to render it soluble, and then regeneration of the cellulose after it is formed into film.

Another common practice is to use cellulose derivatives (cellulosic plastics) to improve the properties. The derivatives, such as ethers, esters and acetals, are produced by the reaction of one or more hydroxyl groups in the repeating unit, and can impart good film-forming properties. Cellulosic plastics are used for wrapping films, and for injection molded or blow molded containers. Tenite® (Eastman, USA), Bioceta® (Mazzucchelli, Italy), Fasal® (IFA, Austria), and Natureflex® (UCB, Germany) are trade names of some cellulose-based polymers.

11.6.2.2 Biodegradable polymers synthesized from bio-derived monomers

Poly(lactic acid) (PLA) is a biodegradable, thermoplastic polyester that is derived from lactic acid. Lactic acid can be produced economically by microbial fermentation of glucose obtained from biomaterials such as corn or wheat starch, lactose in whey, or sucrose. PLA is now produced on a comparatively large scale. PLA is usually obtained from ring-opening condensation of lactide, which is a lactic acid dimer. Two forms of the monomeric acid (D- or L-lactic acid) exist. The properties of PLAs can be varied by adjusting the relative amounts of the two lactic acid isomers (D- or L-) in the polymer. For example, 100% L-lactic acid or 100% D-lactic acid forms highly crystalline PLA whereas amorphous PLA is obtained from DL-co-polymers across a wide composition range. The L-isomer is predominant in most PLA resins as most lactic acid obtained from biological sources is the L form; 90%L/10%D PLA is a common formulation. The formation is able to crystallize but melts more easily than 100%L and is suitable for production of packaging films.

Different companies have commercialized PLA with various ratios of D/L lactide, with trade names including Natureworks®, Galacid®, Heplon®, etc.

Poly(lactic acid)s generally have reasonable moisture and oxygen barrier properties and are suitable for various plastic package forming processes such as blown and cast film, injection molding, and vacuum forming. PLA is currently utilized in wraps for bakery and confectionery products, paperboard coatings for cartons, disposable foodservice tableware items, containers for fresh produce, and water bottles. The rate of degradation of PLA depends on the degree of crystallinity. Increasing the amount of D-isomer in predominantly L-PLA tends to suppress crystallinity and therefore increase the rate of biodegradation. There has been some research on enhancing the biodegradability of PLA by grafting with chitosan (Luckachan & Pillai, 2006).

11.6.2.3 Biodegradable polymers produced directly by microorganisms

Poly(β -hydroxyalcanoate)s (PHAs) are natural polyesters which are produced by bacteria from sugars or lipids. They are actually “grown” inside the cellular structure and then harvested. The use of PHAs is currently limited due to their high production costs. The performance properties are similar to conventional plastics, but the polymers are completely biodegradable. Thus, PHAs have potential as biodegradable alternative materials for conventional bulk commodity plastics (Foster et al., 2001). One of the family of PHAs, polyhydroxybutyrate (PHB), is the most commonly produced and researched bioplastic. PHB has high thermal resistance and water barrier properties. However, a narrow processability window and low impact resistance have hampered widespread use of PHB for packaging application. Blends of PHB with other polymers may improve its properties. For example, poly(ethylene oxide), poly(vinyl butyral), poly(vinyl acetate), poly(vinylphenol), cellulose acetate butyrate, chitin, and chitosan have been studied as blend materials with PHB. Another common method to improve the processability of PHB is to induce the microorganisms to form a co-polymer rather than the homopolymer. Polyhydroxybutyrate-valerate, PHBV, is the most common of these.

11.6.2.4 Synthetic biodegradable polymers

In addition to the biodegradable plastics based on natural substrates, there are synthetic biodegradable plastics produced from petrochemical feedstocks that have groups

which are susceptible to hydrolytic microbial attack. Polycaprolactone (PCL) is a semi-crystalline aliphatic polyester which has a relatively low melting point (60 °C). It is completely biodegradable in marine, sewage, sludge, soil, and compost ecosystems (Khatiwala et al. 2008).

Polyvinyl alcohol (PVOH) is another synthetic biodegradable polymer which is completely soluble in water. The combination of starch and PVOH as a biodegradable packaging material has been studied since 1970. Currently, it is used to produce starch-based loose fillers as a substitute for expanded PS. Other types of synthetic biodegradable polymers include polyesters, polyamides, polyurethanes and polyureas, poly(amide-enamine)s, polyanhydrides (Chandra et al., 1998; Nair & Laurencin, 2007).

Synthetic polymers can be manipulated for a wide range of properties to obtain required mechanical properties (flexibility, toughness, etc.) as well as the degree of degradation. Rather than food packaging, the application of synthetic biodegradable polymers has been gaining more attention in the biomedical area such as tissue engineering scaffolds, orthopedic fixation devices, etc. (Gunatillake et al., 2006).

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