CHAPTER

General Characteristics of Packaging Materials for Food System

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CHAPTER OUTLINE

Introduction

Within the packaging industry, which is the third largest industry in the world ($420 billion), food packaging is a major business sector and includes diverse elements of the packaging world (Datamonitor, 2010). Numerous new food products are launched in the market every year and face high levels of competition by fastidious consumers' choices. There is no doubt that the food product includes the food packaging system itself, which is becoming more influential in influencing a consumer's decisions to

Innovations in Food Packaging. DOI: http://dx.doi.org/10.1016/B978-0-12-394601-0.00002-3

purchase a particular product among the various brand names for the same type of food. Just as for food, food packaging should have high standards of quality and safety and should meet the requirements of governmental regulations and policies to be successful in the market.

The field of food packaging encompasses a variety of aspects, including the food itself; the selection, labeling, and design of packaging materials; and storage, transportation, and distribution. These elements are present during the entire food product lifecycle. An understanding of interactions among these elements is key to food packaging engineers delivering optimized packaging systems to both the manufacturer and customer in terms of cost, convenience, protection, marketing, and sales.

Food products have always been packaged in a wide range of materials—papers, earthenware, wood, vegetable fibers, plant leaves, glass, metals, plastics, and so forth. A combination of more than two packaging materials is sometimes necessary to provide the best packaging solution for certain food products. The selection of suitable packaging materials for existing or projected target foods is primarily determined by the properties and type of food being packaged (Siracusa, 2012). In addition, market image, costs, and environmental issues must also be considered. Therefore, it is very critical to understand not only the food itself but also the general characteristics of various packaging materials.

As people begin to recognize the potential threat to the environment and a healthy lifestyle posed by packaging materials and waste, new paradigms such as "Lifestyle of Health and Sustainability" are impacting the packaging industry and its future markets. The U.S. Environmental Protection Agency (USEPA, 2012) reported that the total amount of municipal solid waste (MSW) in 2010 was 250 million tons, and of that 85.1 million tons were recycled (representing about 34% of the MSW). Recycling rates of municipal solid waste have continuously grown since 1960; however, the recycling rate still needs to reach more than 50% to significantly reduce waste materials and save energy for production. If sustainability was a consideration for packaging companies in the past, today it has become an important concept among the packaging industry and community.

In this chapter, the general characteristics of major packaging materials for food products that food packaging engineers must consider are reviewed, and a brief discussion of the history of food packaging and requirements for packaging materials for a variety of food products is provided.

Types and properties of packaging materials for food systems

Paper and paperboard for food packaging

For a long time, paper and paperboard have been key materials for the entire packaging industry (Figure 2.1). They are categorized by the weight or thickness of the product, with paper being lighter than paperboard. Paper is used not only for general

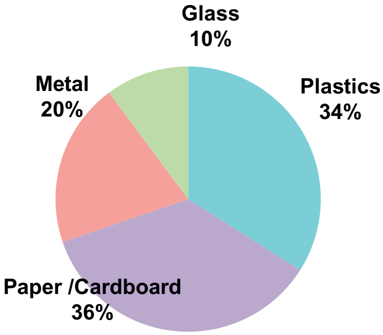


FIGURE 2.1

World packaging materials consumption.

(Source: World Packaging Organisation, www.worldpackaging.org.)

commodities such as writing and printing papers, tissues, and newsprint but also for packaging, such as wrapping paper, grocery bags, and shipping sacks. Paperboard falls into two major subcategories, folding carton and corrugated packaging, and has been used for packaging since 1831 when George Shyrock installed the first cylinder-type machine in a plant in Pennsylvania (Twede and Selke, 2005). Use of paper and paperboard is on the rise, despite the advent of the digital era, and is playing a significant role in modern society. Currently, the largest share of global packaging materials is comprised of paper and paperboard with a value of $370 billion and a volume of 390 million metric tons in 2011, equal to around 40% of the market. Paper and paperboard are major packaging materials for food products around the world.

Production of paper and paperboard begins with mainly wood pulp. The first pulp from wood was merely ground wood without chemicals until the first soda process was developed in 1852; since then, other chemical processes such as sulfite and sulfate pulping processes have become dominant and are used to produce kraft linerboard for corrugated board. The key objective of the pulping process is to extract cellulose fibers and remove other components such as hemicellulose and lignin as much as possible from the wood. Table 2.1 shows the composition of wood pulp. The fibers derived from wood create stronger webs compared to other plant fibers. Because of its low cost, paper has become a major packaging material for a diverse industry.

Major advantages of paper and paperboard packaging include not only low cost and machine processability during production but also easy collection, reuse, and recycling after use. It is lightweight and biodegradable and provides the rigidity or flexibility required for various types of commodities such as folding cartons, corrugated boxes, and bags. Due to its high printability, it is ideal for displaying product information and nutritional value for marketing purposes. To improve the gas or wet barrier properties and the strength of paper and paperboard, they can easily be combined with other materials such as oil, wax, polymers (plastics), and

Table 2.1 Composition of Wood Pulp

Material	Structure	Approximate wt%
Fibers		
Cellulose	Crystalline	45
Matrix		
Lignin	Amorphous	20
Hemicellulose	Semi-crystalline	20
Water	Dissolved in the matrix	10
Extractives	Dispersed in the matrix	5

Source: Gurav, et al., 2003.

metals through coating or lamination. Such multilayer packaging materials have been used in a variety of food products.

General properties and testing methods of paper and paperboard

Properties of paper and paperboard are measured by weight, thickness, gloss, density, whiteness, brightness, tensile strength, tear resistance, stiffness, air resistance (porosity), and coefficient of friction. These properties primarily rely on the purity, type, and shape of raw materials such as fibers and pulps and secondarily on the moisture content and other chemical components of the paper and paperboard. To ensure accurate information regarding such properties, standard testing methods have been developed. The main sources of these methods are the Technical Association of the Pulp and Paper Industry (TAPPI; www.tappi.org) and the American Society for Testing and Materials (ASTM; www.astm.org). ASTM standards are generally more focused on the use of plastics, while TAPPI is focused on paper materials and products. The International Organization for Standardization (ISO; www.iso.org) was founded in 1946 and represents a harmonization of many countries' individual national standards. It is the world's largest developer of voluntary international standards. The Paperboard Packaging Council (www.ppcnet.org) represents paper and paperboard packaging manufacturers and equipment suppliers. Table 2.2 lists some of the standard tests for paper and paperboard.

Types of paper and paperboard

Many types of paper and paperboard are used for food packaging applications. Wax and kraft paper are often used for wrapping paper and as packaging materials such as grocery bags, multiwall sacks, or envelopes. These papers are generally characterized by their weight or thickness. Typically, paperboard is the most popular rigid material used for food packaging. It is mainly produced with virgin (primary) fiber and secondary fiber derived from old corrugated containers (OCCs) or old newspapers (ONPs); 100% virgin fiber can be used to produce kraft paperboard. Paperboard can be combined with other types of paperboard and

Table 2.2 Standard Testing Methods for General Properties of Paper and Paperboard

Property	Standard Method	
	TAPPI	ASTM
Air resistance (porosity)[a]	T460	D726
Basis weight	T410	D646
Bending stiffness	T489	—
Brightness	T452	—
Burst strength (Mullen)	T403, T807	—
Tear resistance (Elmendorf)	T414, T496	—
Coefficient of friction	T815, T816	D4521
Moisture content	T412	D644
Opacity	T425	—
Roughness (Sheffield)	T538	—
Tensile strength	T494, T404	D828
Thickness	T411	D645
Water vapor transmission	T464	E96

[a] *Does not apply for paperboard.*

materials; for example, coating or lamination with plastics produces multilayered food packaging.

Generally, the following paperboards are used in various food products:

- *White lined chip board (WLCB)* is a multilayered structure consisting of 60 to 100% recycled fiber. The top layer is produced with high-grade white preprinted waste paper or bleached chemical pulp for better appearance and printability. The middle layer and back layer are made out of waste paper. Direct food contact is not recommended due to the possibility of contamination from the paperboard.
- *Uncoated recycled board (URB)* may contain up to 20% virgin fibers and has no coating. It is often combined with other boards or paper and used for setup boxes and general packaging applications. Direct food contact is not recommended.
- *Solid bleached sulfate (SBS) board* is produced entirely of bleached chemical pulp resulting in premium grades for packaging and graphical purposes. It is often double coated and the back is either uncoated or lightly coated. Due to its high quality, it is often used for aroma- and flavor-sensitive products, including food.
- *Coated unbleached kraft (CUK) board* is made from unbleached higher strength sulfate pulp. The top layer under the coating may consist of bleached

chemical pulp. Also, some recycled fiber can be used to replace part of the unbleached sulfate pulp. It has been used for replacing SBS board for low-cost beverage carriers.

- *Folding box board (FBB)* is often multilayered; for example, it might have a bleached chemical top, mechanical pulp center, and bleached or semi-bleached chemical back. The top is coated with two layers of coating. It is a good substitute for SBS board in various applications including food, cosmetics, pharmaceuticals, and graphical products.

Plastics for food packaging

Since the first manmade plastic—Parkesine, a cellulose derivative created by Alexander Parkes—was publicly demonstrated at the 1862 Great International Exhibition in London, its many uses have been extensively developed and diversified. More than 100 million pounds of plastics, such as polyethylene, propylene, polystyrene, nylon, and polyvinyl chloride, were produced in 2011, according to the American Chemistry Council (ACC; www.americanchemistry.com). Plastics are recognized as "indirect food additives" by the U.S. Food and Drug Administration (FDA; www.fda.gov) and must meet the requirement listed in Title of 21 of the Code of Federal Regulations (CFR) for food packaging application. Typically, the field of packaging is a major consumer of plastics (Figure 2.2). Plastics are the second largest packaging material chosen by packaging engineers (Figure 2.1).

Plastics are categorized as thermosetting or thermoplastic, a special group of polymers with characteristics that differentiate them from fibers, rubbers, adhesives, and other polymeric materials. Plastics used for food packaging are considered either rigid plastic packaging or flexible plastic packaging. Rigid plastic packaging has a 20% bigger share of the market than flexible plastic packaging, according to research reported in 2008 by the World Packaging Organization (www.worldpackaging.org).

The most common polymers used in food packaging have performed well with regard to chemical and heat resistance; low, medium, and high gas permeability; water vapor transmission rate, abrasion resistance, thermal and mechanical behavior, and so on (Siracusa, 2012).

General properties and structures

The properties of plastics are mainly affected both by the chemical composition of the raw materials and by their environmental and physical states. Because plastics are made out of monomers that contain various types of atoms, the arrangement, configuration, conformation, and number of molecules and atoms are key factors for the characteristics of individual plastics. Plastic polymers are often defined by their linearity: linear polymer, branched polymer, cross-linked polymer, or network polymer. Due to the numerous properties based on environmental and physical states, such as linearity, molecular weight and its distribution, degree of density,

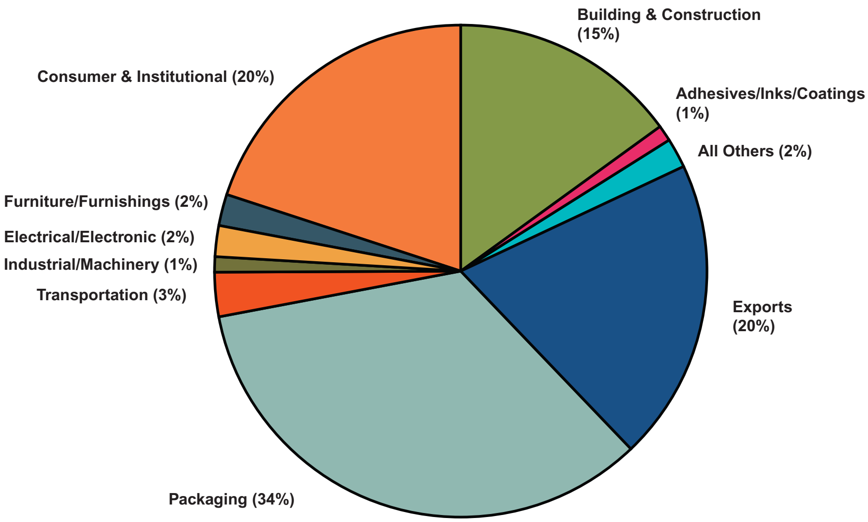


FIGURE 2.2

Percentage distribution of thermoplastic resins according to sales and captive use by major market.

(Source: American Chemistry Council, http://www.americanchemistry.com.)

crystallinity, humidity, and varying temperatures, plastics provide a very usable and multi-versatile functionality for food packaging systems. For example, as molecular weight increases, various properties of polyethylene such as tensile strength, impact strength, clarity, and ultimate elongation also increase. As density increases, these properties, except for tensile strength, decrease. As the morphological properties of a plastic packaging polymer such as crystallinity change, other properties are substantially affected, as shown in Table 2.3.

The following properties are considered when designing plastic packaging systems:

- Density
- Degree of polymerization
- Thermal properties, such as glass transition temperature, melting temperature, crystallization temperature, enthalpy, heat expansion, and heat deformation temperature (HDT)
- Chemical resistance
- Permeability (solubility and diffusivity)
- Physical properties, such as coefficient of friction, tensile strength, elongation, viscosity, elasticity, plasticity, modulus
- Morphological properties.

Table 2.3 Property Changes Occurring When Crystallinity of Plastic Packaging Polymer Increases

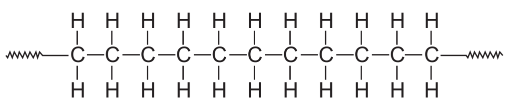
	Value	
Property	**Increased**	**Decreased**
Physical property	Density	Permeability
	Opacity	Clarity
Thermal property	Heat sealing temp.	Heat sealing range
Mechanical property	Compression strength	Tear resistance
	Tensile strength	Impact strength
		Toughness
		Ductility
		Ultimate elongation

In general, plastics provide the following advantages when used in food packaging:

- Very light weight and low cost with significant strength compared to other packaging materials
- Good oil and chemical resistance
- Excellent gas and water vapor barrier properties
- Sealing property
- Thermally stable and electrical insulation properties
- High processability (thermoforming, injection, and extrusion)
- Easily enhanced by the addition of other components such as colorants, fillers, and active agents
- Easily combined with other packaging materials
- Easily reused and recycled in terms of sustainability.

Type of plastics and applications

Polyethylene (PE)



Polyethylene (PE) is a member of the polyolefin family, which also includes polypropylene and encompasses various types of plastics based on the linearity of molecules, density, polymerization process, and type of substitution (Table 2.4). This category includes plastics commonly used for food packaging, such as low-density polyethylene (LDPE; 0.910 to 0.940 g/cm^3), high-density polyethylene

Table 2.4 General Properties of Plastic Polymer Used for Food Packaging Systems

Plastic	Thermal Properties				Strength		Density (g/cm^3)
	T_m[a] (°C)	T_g[b] (°C)	HDT[c] (°C)	CTE[d] (ppm/°C)	Tensile (K psi)	Compressive (K psi)	
LDPE	98–115	−25	40–44	100–220	1.2–4.6	—	0.910–0.940
LLDPE	122–124	—	—	—	1.9–4.0	—	0.916–0.940
HDPE	130	—	79	59	3.2	2.7	0.940–0.970
PMMA	—	85	79	50	7.0	10.5	1.17
PP	168–175	−20	107–121	81–100	4.5–6.0	5.5–8.0	0.89–0.92
PS	—	74–105	68–96	50–83	5.2–7.5	12.0–13.0	1.04–1.05
PVC	—	75–105	57–82	50–100	5.9–7.5	8.0–13.0	1.3–1.58
PVDC	172	−15	54–66	190	3.5–5.0	2.0–2.7	1.65–1.72
Polyamide	—	310–365	277–360	45–56	10.5–17.1	30.0–40.0	1.36–1.43
PET	245	73	21	65	7.0	11.0	1.29

[a] *Melting temperature.*
[b] *Glass transition temperature.*
[c] *Heat deformation temperature under a 66-psi load.*
[d] *Coefficient of linear thermal expansion.*

(HDPE; 0.940 to 0.970 g/cm^3), and linear low-density polyethylene (LLDPE; 0.916 to 0.940 g/cm^3). Typically, these PEs offer not only good processability (e.g., can be converted into bags, films, bottles) but also an excellent water vapor barrier property which is required for many water-sensitive food products such as dried and liquid food products. However, this type of plastic is not appropriate for oxidation-sensitive food products due to its low oxygen barrier properties (Alter, 1962). Table 2.5 lists the general gas and water vapor permeabilities of plastic packaging polymers.

As shown in Equation 2.1, the properties of polyethylene can be significantly affected by various conditions and factors, such as density, crystallinity, presence of free volume, polarity, humidity, and temperature:

$$\text{Permeability } (P) = \text{Permeation rate (transmission rate)} \times \text{Film thickness} \quad (2.1)$$

Table 2.5 Gas Permeability and Water Vapor Transmission Rates of Common Plastics for Food Packaging

	Gas Permeability at 23°C (nmol/m•s•GPa)[a]			
Polymer	**O_2**	**N_2**	**CO_2**	**WVTR[b] (nmol/m•s/day)[c]**
High-barrier vinylidene chloride copolymers	0.04–0.03	0.01–0.1	0.1–0.5	0.02–0.1
Nitrile barrier resin	1.6	—	6	1.0–1.2
Nylon-6,6; nylon-6	2–5	—	3–9	1.5–5.5
Polypropylene	300	60	1200	0.06–0.2
Poly(ethylene terephthalate (PET)	10–18	2–4	30–50	0.4–0.7
Rigid poly(vinyl chloride)	10–40	—	40–100	0.2–1.3
High-density polyethylene	300	—	1200	0.1
Low-density polyethylene	500–700	200–400	2000–4000	0.2–0.4
Polystyrene	600–800	40–50	2000–3000	0.5–3.0
Ethylene vinyl alcohol				
32 mol% ethylene				
0% rh	0.02	0.002	0.09	0.9[d]
100% rh	2.3	—	—	—
44 mol% ethylene				
0% rh	0.18	0.015	0.8	0.3[d]
100% rh	1.3	—	—	—

[a]*To convert nmol/(m•s•GPa) to cc•mL/(100 in.^{2}•d•atm), divide by 2.*
[b]*WVTR = water vapor transmission rate at 90% rh and 38°C.*
[c]*To convert nmol/(m•s) to g•mL/(100 in.^{2}•d), multiply by 4.*
[d]*40°C.*
Source: *Brown 1992, Koros 1990.*

For example, the permeation *versus* density relationship for PE polymers has been intensively investigated and can be modeled as shown in Equation 2.2:

$$P = K(1 - \text{density})^n \tag{2.2}$$

where K and n are constants. Values for n of 2.160, 2.181, and 2.057 for nitrogen, oxygen, and carbon dioxide, respectively, have been reported. The water vapor transmission rate of PE films decreases as the density increases, as shown in Table 2.6.

Low-density polyethylene is more suitable than high-density polyethylene for flexible films because it is soft, flexible, and stretchable. Total film and sheet applications of LDPE in the worldwide market accounted for 67% of total LDPE use in 2011. The majority of these applications made use of film rather than sheets. LDPE film was used for such foods as bakery, frozen, fresh produce, meat and poultry, and confectionery products.

Linear low-density polyethylene is produced as either a homopolymer or copolymer having comonomer alkenes such as butane, hexane, and octane. The amount of comonomer ranges from 1 to 10% on a molar basis. This plastic provides improved properties (e.g., mechanical) compared to LDPE at the same density. It delivers clarity, good heat sealing, strength, and toughness and is often used for stretch/cling film, grocery sacks, and heavy-duty shipping sacks.

Different from the LDPE, high-density polyethylene is a translucent polymerized film that has higher crystallinity and provides a good barrier against gas and water. The mass density of HDPE ranges between 0.93 and 0.97 g/cm^3. HDPE offers high stiffness and hardness.

Table 2.6 Effect of Density on the Permeability of Oxygen and Water in Polyethylene

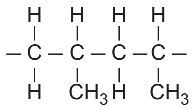
Density of PE (g/m^3)	WVTR[a] (g•μm/m^2•day)	Oxygen Permeability (cm^3•μm/m^2•day•atm)
0.910	0.866	275
0.915	0.779	256
0.920	0.685	225
0.925	0.579	201
0.930	0.465	165
0.935	0.366	137
0.940	0.276	104
0.945	0.244	91.3
0.950	0.208	76.4
0.955	0.185	70.1
0.960	0.145	61.0

[a]*WVTR = water vapor transmission rate at 90% rh and 38°C.*
Source: *Hernández, et al., 2000, p. 102.*

Ethylene copolymers such as ethylene vinyl acetate (EVA), ethylene acrylic acid (EAA), and ethylene methacrylic acid (EMAA, an ionomer) are produced by copolymerization with ethylene and other monomers. They basically fall under the heading of branched PE. Due to the increased irregularity and polarity in structure induced by substitution groups, crystallinity and intermolecular forces are significantly affected, resulting in improved flexibility, toughness, hot tack and adhesion, heat-sealing strength, and gas barrier properties. These polymers are very often used for such food products as meats, cheeses, and snack foods, as well as medical products. In general, the amount of comonomer is limited by 20 to 25% due to the safety issues for food products. Ionomers (e.g., Surlyn® produced by DuPont) have relatively higher processing temperatures (175 to 290°C) due to their ionic cross-linked bonds. Ionomers offer excellent elongation viscosity and pinhole resistance. When combined with other food packaging materials such as polyvinyliene dichloride (PVDC), HDPE, or foil layer, ionomers provide excellent barrier properties.

Newer linear polyethylene polymers, *metallocene polymers*, emerged in the 1990s. They are produced by specific polymerization processes by using either a single catalyst composed of positively charged metal ions and negatively charged organocyclic ring anions or a combination of catalysts (Young and Lovell, 2011). This technology has introduced significant new ways to modulate the properties of linear polyethylenes and other polyolefins such as degree of polymerization, linearity, and configuration. It also allows the use of various strengths, flexibility, and crystallinity.

Polypropylene (PP)

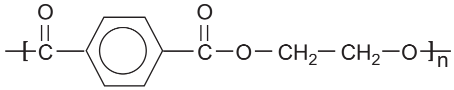


Polypropylene is generally available as both a PP homopolymer and a PP random copolymer for use as a food packaging material. In general, it is characterized by low density, relatively low transition temperature (T_g) and a medium level of melting temperature (T_m), and good oil and chemical resistance, as shown earlier in Table 2.4. Due to its superior properties such as excellent low-temperature impact strength, high heat deflection temperature (HDT), and suitable flexibility and rigidity, this polymer is often used for a variety of food products ranging from cold-chain food products to heat-treated food products, including microwaveable products available in either flexible or rigid plastic packaging. Due to its poor oxygen barrier properties, polypropylene is very often combined with high-oxygen-barrier layers such as Saran™, ethylene vinyl alcohol (EVOH), nylon, or foil for oxygen-sensitive food products such as apple products, ready-to-eat meat products, soup, baby food, ketchup, and cooked rice in both flexible and rigid plastic packaging.

Polyester

Polyester packaging plastics are very often used for rigid plastic packaging. Polyester offers reasonably good gas and water vapor barrier properties and proper stiffness and strengths for solid container systems. Its general structural formula is

$$\mathrm{HO-(CO-R-CO-OR'-O)}_n\mathrm{H}$$

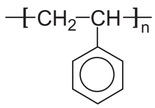


A variety of plastic polymers fall into this group, such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and other copolyesters such as glycol-modified PET (PETG). These are often mixed together to deliver specific properties or to reduce costs. Like other polymers, the barrier properties of polyester can be improved by coating it with copolymers such as LDPE or polyvinylidene chloride (PVDC).

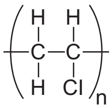
Polyethylene terephthalate is a major packaging material for bottled products and offers numerous advantages in that it is highly transparent, light in weight, unbreakable, convenient, cost effective, resealable, and recyclable. PET bottles are gradually taking the place of metal cans and glass bottles (Kodama et al., 2006). Carbonated soft drinks, tea, water, soy sauce, and edible oils are primarily packed in PET bottles. In general, PET is made out of *para*-xylene and ethylene. The *para*-xylene is converted into either dimethyl terephthalate or terephthalic acid, and the ethylene into ethylene glycol. These monomers are polymerized into PET and give off water or methanol as byproducts. Depending on the degree of crystallinity, which is controlled during the manufacturing process, PET is categorized as amorphous (APET) or crystallized (CPET). CPET is well suited for ready meals, which can be taken directly from the freezer to either a conventional oven or a microwave oven due to the product's high HDT property. Most CPET packaging products have a top layer of APET, which gives CPET excellent sealing properties and a superb glossy finish. Major applications are in ready meals, frozen foods, bakery products, and home-bake products.

Substituted olefins

The diversity of olefins was easily developed through substitution processes using vinyl structure monomers such as propylene, vinyl chloride, vinylidene chloride, vinyl alcohol, acrylonitrile, vinyl acetate, and styrene. Polystyrene (PS) is atatic, resulting in an amorphous polymer. It is a very stiff, brittle, and hard material (T_g, 74–105°C). It is one of the most versatile plastic resins for food systems. The amorphous grade, crystal PS, is used to make bottles for pills, tablets, and capsules. High-impact PS (HIPS) is commonly used as thermoformed containers for dairy food products. PS foam has good shock-absorbing and heat insulation characteristics. Applications in food packaging includes egg cartons and meat trays. Varieties of styrene-based copolymers have also been developed to exhibit special combinations of properties.

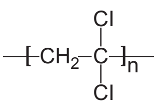


Polyvinyl chloride (PVC) properties are predominantly affected by the amount and type of ingredients used, such as plasticizers. PVCs are often classified according to the plasticizer used. Unplasticized PVC has high strength, rigidity, and hardness, while plasticized PVC is known for low impact strength at low temperatures. The melting temperatures of plasticized PVC and unplasticized PVC are 170 to 200°C and 180 to 210°C, respectively. PVC is generally known as "vinyl" in the market. PVC is used for the rigid plastic packaging of milk, dairy products, edible oils, and liquor. Flexible PVC film is used as wrapping materials for food products, particularly fresh red meat. The oxygen permeability of PVC film with a liquid plasticizer is well suited to maintaining the necessary oxygen requirements of red meat, preserving its red color and the appearance of freshness. Almost all poultry producers in the United States use PVC stretch films for chilled, tray-packed poultry parts.



Barrier properties of plastic polymers

Polyvinylidene chloride (PVDC), a substituted olefin polymer, is produced by copolymerizing vinylidene chloride with other comonomers. It was first produced by Ralph Wiley, a Dow Chemical lab worker at DuPont in 1933. Its most valued performance property is its low permeability to a wide range of gases, flavors, and vapors for a variety of commodities (Kirk-Othmer, 1997).



It is capable of extending the shelf life of food because of its effective oxygen and water vapor barrier, which makes it ideal for use in food packaging and

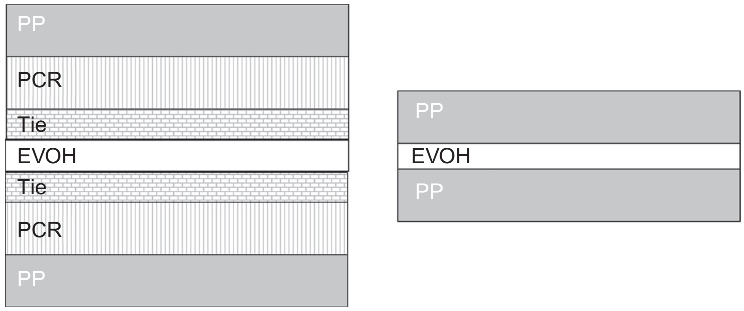
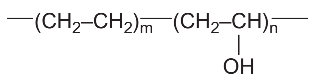


FIGURE 2.3

General multilayer structures using ethylene vinyl alcohol (EVOH) for food packaging applications.

consumer wraps that require excellent resistance to aggressive environments. Saran resins for food contact can be extruded, coextruded, or coated to meet specific packaging needs. About 85% of PVDC is used as a thin layer for multilayered structures comprised of cellophane, paper, or plastic packaging to improve barrier performance. Monolayer use is commonly found in household wrap. It is very often compared to ethylene vinyl alcohol copolymer (EVOH), which is a barrier resin often used in multilayered food packages and blow-molded rigid containers (see Figure 2.3). The majority of EVOH is primarily produced by two Japanese companies, Kuraray and Nippon Synthetic Chemical Industry Company.



It is well known that EVOH offers great processability and provides effective barrier properties against oxygen, odors, and gases. Because it is very sensitive to wet conditions, it is always used in multilayered structure systems. Its applications depend on the processing methods used and the type of food product. Processed meats and cheese products are packaged with the structure of PET/EVOH/EVA. Red meat products are packaged with LLDPE/EVOH/LLDPE through the blown coextrusion process. The structures of the majority of thermoforming food packaging products are shown in Figure 2.4.

Multilayered structures include about 3 to 8% EVOH, depending on machine processability and the individual food products. Post-consumer resin (PCR) may also include some pre-consumer resin, such as scrap materials collected during the thermoforming process. Therefore, the miscibility among individual layers is very important to the manufacturer in terms of recyclability and compatibility. Products that include such thermoforming products are commonly hazy or less

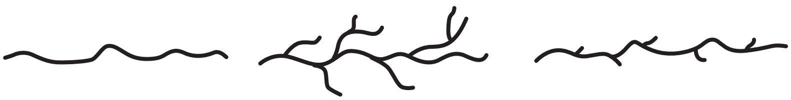


FIGURE 2.4

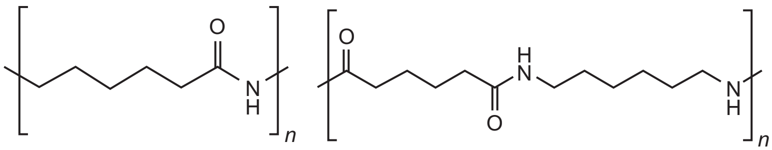
Structural views of polyethylene (PE): (A) high-density polyethylene (HDPE; linear PE), (B) low-density polyethylene (LDP; branched PE), and (C) linear low-density polyethylene (LLDPE; slightly branched PE).

transparent. Yogurt, applesauce, ready-meal food, and cooked rice are packaged using these structures.

Plastic beer bottles and ketchup bottles are made by a coextrusion process using a basic structure of PET/EVOH/PET (Bucklow and Butler, 2000).

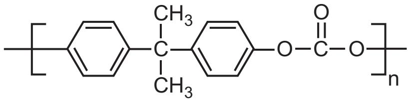
Other plastic polymers

Polyamides (nylons) are made from either the condensation of diamines and dibasic acids or the condensation of amino acids containing both amine and acid functional groups in single molecules. Major polyamides for packaging materials are polyamide 6 and polyamide 66. Both polymers are semicrystalline and known for hardness. Polyamide 6 is also known for stiffness. Polyamide 66 is known for other properties such as abrasion resistance and high heat deflection temperature. Polymer 66 is tougher than polyamide 6. The melting temperatures of polyamide 6 and polyamide 66 during the molding injection process are 230 to 280°C and 260 to 320°C, respectively (Osswald and Hernández-Ortiz, 2006). Polyamides have good puncture resistance, impact strength, and temperature resistance, as well as acceptable gas barrier properties. The properties of polyamides are due to the intermolecular forces and hydrogen bond induced by amide linkage. For food packaging systems, polyamides are often used in a multilayered structures to provide both strength and toughness. Polyolefins are coextruded with nylons to provide heat sealability and a moisture barrier, as well as to reduce costs.



Nylon 6 Nylon 6,6

Polycarbonate (PC) is an amorphous polymer known for its stiffness, toughness, hardness, optical properties, and high surface gloss. The melting temperature range is between 280 and 320°C. Its mechanical properties can be improved by reinforcement with glass fiber. Despite its great potential for food packaging, the use of polycarbonate is limited due to health and safety concerns regarding bisphenol-A, which is a major monomer for PC.



In the early 20th century, cellophane film was first introduced in Europe and then later in the United States in 1924 (Sacharow and Griffin, 1980). Cellophane is a lightweight and clear packaging film. Due to a lack of strength, cellophane film can be coated with nitrocellulose or polyvinylidene chloride to improve its heat sealing and barrier properties (Jenkins and Harrington, 1991).

Plastic polymers derived from bio-based materials

A major trend in the packaging industry is seeking out new technologies capable of replacing less-sustainable life cycles of products. Currently, the most practical way is to reduce, reuse, and recycle (3Rs). Bioplastics that act like plastic polymers include both biodegradable polymers and bio-based plastics. Unfortunately, their use is limited due to their production costs, functionality, and compatibility with other polymers in current recycling streams (Roberts et al., 2011). Most commercialized bioplastics for food packaging fall into the following categories:

- *Compostable*—Polylactic acid (e.g., Ingeo™, http://www.natureworksllc.com); used for snack bags, yogurt containers, nutraceutical product containers, and disposable cups, plates, and trays
- *Biodegradable*—Polyhydroxy alkanoate (PHA); used for disposable cups, plates, and trays
- *Bio-based plastics*—Bio-polyethylene and bio-polyethylene terephthalate; used for drink and beverage containers
- *Other bio-based copolyesters*—(e.g., Ecozen®, http://www.skecozen.com); used for sports water bottles, 5-gallon water bottles, and food storage containers
- *Bio-monomers*—Bio-succinic acid, bio-lactic acid, butadienol (Evans, 2011).

Standard biopolymers such as starch, gelatin, and gums are also used as food packaging materials (e.g., coating layers, capsules, edible films), but these biopolymers are not plastic, and it is not feasible to produce biopolymers using the existing machinery in plastic packaging plants. Generally, biopolymeric materials provide high oxygen and flavor barrier properties but lower water barrier properties, mostly depending on moisture content and the amount of plasticizers (Kim et al., 2007a). They have been used successfully in the areas

Table 2.7 Resin Identification Codes

	SPI Resin Identification Code						
	1	2	3	4	5	6	7
Type of plastic resin content	PET	HDPE	Vinyl	LDPE	PP	PS	Other[a]

[a]*All other plastics, including bioplastics, polycarbonate, and mixed plastics.*
Source: *www.epa.gov*.

of food coatings (Ramos et al., 2012), plant-based capsules, and rigid and flexible food packaging. Biopolymers directly improve the shelf life and quality of agricultural products and food systems.

Plastic identification code

Plastic resin labels are codes, or numbers, that indicate the specific type of plastic used to manufacture a product (Table 2.7). The coding system for plastics was first introduced by the Society of the Plastics Industry in 1988. Most food packaging products made out of plastics are labeled with this coding system. Due to its similarity to the recycle symbol, it is often misleading to both the consumer and manufacturer.

Glass for food packaging

The first use of glass as a packaging material occurred in approximately 3000 BC (Robertson, 2006). Glassware produced by the blowing technique and transparent glassware were developed after the production of opaque glass bowls and cups using the sand-molding technique around 1000 BC. Until the early 20th century, glass was expensive due to the lack of a mass production technique. In 1904, however, Michael J. Owens was granted a patent for a fully automated glass-shaping machine for producing glass bottles. As a food packaging material, glass has both disadvantages and advantages. It is prone to breakage upon physical impact and high pressure, for example, but it has good barrier properties against gases and chemicals and is suitable for heat processing at higher temperatures. Also, glass can be durable and provides insulation to keep foods fresh during storage. The majority of glass used for food and beverage containers can be easily reused and recycled. According to the USEPA (2012), 11.5 million tons of glass were generated in 2010, about 27% of which was recovered for recycling. Making new glass from recycled glass is typically less expensive than using raw materials. See Table 2.8.

Table 2.8 Composition of Glass

Oxides	Weight (%)	Raw materials
SiO_2	73.0	Sand
Al_2O_3	1.7	Sand, feldspar
Na_2O	13.1	Soda ash, sodium sulfate
K_2O	1.2	Sand
CaO	11.0	Limestone
Fe_2O_3	0.04	Sand

Source: *Yamato, 1990.*

Metals for food packaging

Metal can provide good protection against physical damage or impact during transportation, distribution, handling, and storage of food products. It also can provide a good barrier against water, oxygen, and gases because of its impermeability. On the other hand, metal is not suitable for modified atmosphere packaging (Oraikul and Stiles, 1991). Tinplate is a typical packaging material used in metal packaging containers. Peter Durland developed a canning process using tin cans in 1810 that preserves liquid foods and extends their shelf life. Aluminum is an abundant metallic material in the earth that was isolated in 1825 by Danish chemist Hans Christian Oersted after numerous trials. At about the same time, the use of cryolite to dissolve alumina powder was developed independently by the American Charles Martin Hall and the Frenchman Paul Héroult. This is the method used for commercial processes.

Selection of packaging materials for food systems

The selection of packaging materials depends on the characteristics of the food to be packaged. Packaging engineers need to predict any interactions that might occur between a packaging material and the food it contains because diffusion or migration of undesirable packaging components might occur. Moreover, the selection should take into consideration system-based packaging, from primary to tertiary packaging elements, to prevent undesirable issues arising throughout the product's life cycle. Another important factor in the selection of packaging materials is whether the packaging complies with government regulations and policies. Various federal or governmental agencies (e.g., FDA, USDA, USEPA, OSHA) monitor and inspect materials with a focus on health and safety aspects (Hirsch, 1991). Also, good manufacturing practices (GMPs) should be observed during processing.

Food contact substances (FCS) are regulated by the U.S. Food and Drug Administration (FDA), and two major factors regarding the intended use of FCS should be considered in advance: (1) the maximum temperature to which the materials will be exposed, and (2) the types of food that will be contacted (e.g., aqueous, acidic, fatty, alcoholic). As listed in 21 CFR, following are the regulated categories of FCS:

- Condition of Use A—high temperature heat-sterilized (e.g., over 212°F)
- Condition of Use B—boiling water sterilized
- Condition of Use C—hot filled or pasteurized above 150°F
- Condition of Use D—hot filled or pasteurized below 150°F
- Condition of Use E—room temperature filled and stored (no thermal treatment in the container)
- Condition of Use F—refrigerated storage (no thermal treatment in the container)
- Condition of Use G—frozen storage (no thermal treatment in the container)
- Condition of Use H—frozen or refrigerated storage (ready-prepared foods intended to be reheated in container at time of use).

In general, most food packaging manufactures are more interested in Condition of Use B when they introduce new materials to their food packaging systems. New packaging materials must be approved by the FDA through a Food Contact Notification (FCN) to ensure the safe use of substances. Moreover, the selection of packaging materials also depends on the following future trends:

- *Health and safety assurance packaging*—Green and healthy products are a new trend driving food products in current and future markets. As organic and natural products increase in food markets, antimicrobial or antioxidant activity-enhancing packaging to provide better health and safety assurance packaging will need to be developed.
- *Sustainable packaging*—Consumers' are shifting toward the use of more sustainable systems and materials (e.g., less energy consumption; reducing effects on the environment; greater use of recyclable, renewable, or biodegradable packaging materials) to reduce their "carbon footprint" (Kourtisimanis et al., 2012). Pouch packaging, for example, requires less energy to produce compared to the traditional canning process. Eco-Fresh pouch packaging uses about 45% less energy than the energy used to process cans (Lamontagne, 2012). Biodegradable yogurt packaging is growing in popularity; in Europe, DANONE replaced their polystyrene yogurt cups with polylactic acid (PLA) cups capable of being composted. The company claims that it has improved the product's packaging carbon footprint by 25% and uses 43% less fossil resources.
- *Nano-based packaging*—Since nano carbon was introduced in the 20th century, nano-scale materials have found many applications, including packaging materials. The extremely small size of nano-scale materials

gives them novel properties which provide an excellent barrier for undesirable substances in the packaging systems. Nano composites applied on commercial films could improve barrier properties against oxygen, water vapor, and flavors (Lamontagne, 2012), although there is some concern about their safety.

- *User-friendly designable packaging*—Packaging has traditionally been designed to maintain or extend the shelf life of food products, thus addressing the quality and safety of the food rather than appealing to consumers through its design. Advances will be driven by rising demand for convenience-oriented and other further processed food items (Palevsky, 2012) available in user-friendly packages. Practicality will be important. Examples include smaller size packaging, reclosable/resealable packaging, and microwavable packaging that is more convenient and saves time for customers.
- *Moving forward to smart packaging*—Smart packaging is the result of combining multiple or integrated systems with aspects of mechanics, chemistry, electricity, and electronics (Mahalik and Nambiar, 2010). Such systems interact with the product or the headspace between the package and food to obtain a desired outcome, such as increased shelf life or enhanced safety or sensory properties (Kim et al., 2007b). For example, multilayer PET bottles, due to a coextrusion process, often contain active agents such as oxygen-scavenging materials inside polymer layers to react with the gas before it reaches to oxygen-sensitive food products. These active barrier bottles are generally of a three-layer composition, with the outer PET layers surrounding a functional barrier layer. Radiofrequency identification (RFID) or information technology (IT) may be included in a package to significantly improve the traceability of products and communication with the consumer (Brody, 2012). Biosensor indicators can detect deterioration from microbial contamination, gas composition, or the occurrence of oxidation, thus allowing monitoring the safety and quality of food products very efficiently for longer periods of time (Kerry et al., 2006). Thanks to such new technology, consumers could obtain useful information simply by scanning a label with their smart phone, reader, or scanner when selecting food products.

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