CHAPTER 1

ANTIMICROBIAL PACKAGING POLYMERS. A GENERAL INTRODUCTION

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This chapter introduces in a general and brief fashion the subjects discussed across the book. Albeit the concepts can be generally considered, it has an application perspective that relates more intensely to the food area. This is because antimicrobials, thanks to the recent publication of the European Commission regulation on active and intelligent materials and articles intended to come into contact with food (EC 450/2009) as well as to the increasing number of submissions to the U.S. Food and Drug Administration (FDA), are attracting a lot of new academic and industrial interest for implementation into plastic packaging materials.

1.1 PATHOGENS IN FOOD: PUBLIC HEALTH IMPORTANCE

Without a doubt, the most relevant sectors regarding the seriousness of microbial contamination are hospitals and medical equipment and foods. Hence, antimicrobials have traditionally been of great relevance to these areas. Foods are perhaps attracting even greater general attention in particular nowadays because they constitute a permanent part of our daily life and are increasingly making use of plastic packaging for their presentation to the consumer. Infections and intoxications associated with consumption of foods are a growing concern worldwide. In this regard, the World Health Organization (WHO) and the European Food Safety Authority (EFSA) report annually on the main agents causing food-borne toxic infections. The results suggest that in recent years there has been a slight increase in food-borne diseases in many parts of the world and that the emergence of new or newly recognized food-borne problems have been identified and associated with consumption of foods. According to the WHO [1, 2], one of the main reasons for this increase is that the microbial population have adapted through natural selection leading to the development of antibiotic resistance, acquisition of new virulence factors, or changes in the ability to survive in adverse environmental conditions. In addition, the change of population dietary habits produced by the growing demand for prepared foods and minimally processed foods has contributed significantly in increasing the number of outbreaks of food-borne illnesses.

1.2 PRIMARY CONTAMINATION AND ITS CAUSES

Most pathogenic bacteria associated with food-borne diseases are zoonotic (animal origin), and their carriers are usually healthy animals from which are transmitted to a wide variety of foods such as *Salmonella* spp., *Escherichia coli*, or *Campylobacter jejuni*. Other pathogens such as *Listeria monocytogenes* are widely distributed in the environment or are part of the natural microbiota of humans as *Staphylococcus aureus*. In these two last cases, food contamination occurs during processing as a result of failures of hygienic practices in the food chain.

Farm animals usually acquire microbial hazards as a result of horizontal transmission from their environment. The principal sources are other infected animals, contaminated water, and wildlife such as birds or rodents. This horizontal transmission can be exacerbated by intensive husbandry, which promotes overcrowding and interferes with the maintenance of adequate hygiene to which animals are subjected in many farms [3, 4]. Finally, the products derived from these infected animals can reach the consumer at some point.

The rising incidence of microbial food-borne disease has focused attention on the sources of contamination. Because animal products have been directly responsible for more than the 50% of the total food-borne outbreaks in the 1990s, emphasis has been paid to these types of products such as meat, poultry, eggs, and milk [5]. Nevertheless, in recent years, the demand for fresh fruits and vegetables has increased in the industrial countries as a consequence of the awareness of the health benefits associated with eating fresh produce [6]. Nowadays, therefore, outbreaks of food-borne diseases have been increased probably because crops in the field can be contaminated with pathogens carried by farm animals and human beings. The main risk factors include proximity to irrigation wells and surface waterways exposed to feces from cattle and wildlife, exposure in fields to wild animals and their waste materials, and improperly composted animal manure used as fertilizer [7]. The public health implications are especially serious when the products affected are those usually consumed without cooking such as salad fruits and vegetables [8]. Although the frequency of food-borne outbreaks in gastrointestinal illness associated with fruit and vegetables seems to be low compared with products of animal origin, ready-to-eat fruit and vegetables requiring minimal or no further processing prior to consumption have been implicated as vehicles for transmission of infectious microorganisms. Even more, food-borne illnesses associated with fruit and vegetables seem to be increasing in many countries because of mainly the increase in global food distribution.

The last global report available from the European Union is from 2006. In this report, the number of food-borne outbreaks, causative agents, and number of affected people by these gastrointestinal illnesses were shown. For instance, in this year, 5,705 outbreaks involving a total of 53,568 people, resulting in 5,525 hospitalizations (10.3%) and 50 deaths (0.1%), were reported. Table 1.1 summarizes the number of reported food-borne outbreaks in the Europe Union (EU) in 2006. These results show that *Salmonella* was the food-borne pathogen most frequently recorded by the EU, although there has been a slight decline in recent years. *Campylobacter* infections are the second most common zoonotic agent, affecting 1,304 people (6.9%). *S. aureus* was the etiological agent of 4.1% of the outbreaks (236) and affected 2,057 people, causing two deaths. Verotoxic-producing *E. coli* was responsible for 0.8% of the outbreaks, and although it is one of the most harmful pathogens, it only caused one death. On average, *Listeria* was the most severe pathogen causing 9 outbreaks that affected 120 people, of which 74.2% (89) was hospitalized and 17 died. The most common food vehicle was eggs and egg products, which were responsible for 17.8% of

TABLE 1.1 Causative agents responsible for foodborne outbreaks, 2006 (all countries)

	Outbreaks				Human cases		
Causative agent	No.	% of total	General	Household	No.	No. admitted to hospital	No. of deaths
Salmonella	3,131	53.9	1,520	1,611	22,705	3,185	23
Unknown	952	16.4	610	342	9,437	947	2
Viruses	587	10.2	373	214	13,345	553	3
Campylobacter	400	6.9	116	284	1,304	65	0
Staphylococcus	236	4.1	157	79	2,057	277	2
Toxins	86	1.5	20	66	834	261	3
Clostridium	81	1.4	55	26	1,651	44	2
Bacillus	78	1.3	66	12	964	34	0
Histamine	71	1.2	62	9	370	41	0
Pathog. *E. coli*	48	0.8	25	23	750	103	1
Shigella	33	0.6	19	14	138	22	0
Yersinia	26	0.4	11	15	604	15	2
Giardia	18	0.3	13	5	44	—	0
Trichinella	18	0.3	5	13	202	113	0
Listeria	9	0.2	5	4	120	89	17
Other	9	0.2	5	4	31	2	0
Cryptosporidium	7	0.1	4	3	59	0	0
Brucella	6	0.1	3	3	43	3	0
Flavivirus	6	0.1	2	4	26	25	0
Klebsiella	3	0.1	2	1	109	1	0
Streptococcus	2	<0.1	2	0	236	—	—
EU Total	5,705	98.2	3,000	2,706	53,546	5,523	50
Total	5,807	100.0	3,075	2,732	55,029	5,780	55

Source: The EFSA Journal, 2007;130:252–352 [9].

these outbreaks, whereas unspecified meat was reported as the causative source in 10.3% of the outbreaks. Fish and fish products were the source of 4.6% and dairy products of 3.2% of the outbreaks [9].

Food-borne disease caused by microbiological hazards is a large and growing public health problem. Most countries with systems for reporting cases of food-borne diseases have documented significant increases over the past few decades in the incidence of diseases caused by microorganisms in foods, including *Salmonella* spp., *S. aureus*, *C. jejuni*, *L. monocytogenes*, or *E. coli* O157 among others.

1.2.1 *Salmonella* spp.

Salmonella spp. is a heterotrophic, mesophile, gram-negative bacteria that is worldwide one of the major infections transmitted via food ingestion, causing gastroenteritis, diarrhea, vomiting, abdominal cramping, enteric fever, septicemia, and in severe cases even death [10]. In August 2005, 2,138 cases of salmonella gastroenteritis were reported to the National Centre for Epidemiology (CNE) in Spain. The reported cases were epidemiologically and microbiologically linked to a single brand of precooked, vacuum-packed roast chicken that was commercially distributed throughout Spain. Although it did not report any human deaths, this produced a substantial economic loss to the producing company.

1.2.2 *L. monocytogenes*

Another more harmful microorganism is *L. monocytogenes*, a food-borne pathogen of particular concern in ready-to-eat (RTE) products because of its ability to survive and grow at refrigeration temperatures and of its capacity to tolerate high heat and high concentrations of salt [11]. Even after cleaning, a prevalence of *L. monocytogenes* of 10% was detected in surface samples of the investigated equipment of small Spanish processing plants of traditional fermented products [12]. *L. monocytogenes* causes food-borne listeriosis, a disease that occurs largely in pregnant woman and the elderly leading to illness, miscarriages, and death [13]. Recently, a *Listeria* outbreak linked to a meat product plant in Toronto has expanded to 26 cases, and 12 people have died, although it is not yet clear how many of the deaths were directly from the illness.

1.2.3 *S. aureus*

S. aureus is a gram-positive bacterium able to produce sufficient enterotoxins to cause illness from an inoculum size of ca. 10^5 CFU/mL. Although death from staphylococcal food poisoning is rare (0.03% of cases), it presents several symptoms such as vomiting, diarrhea, or abdominal cramping. A wide range of foods is involved as sources of staphylococci food poisoning in restaurants where meals are previously prepared in a central chicken and subsequently transported. As *S. aureus* lives in the nasal membranes, skin, gastrointestinal tract, and so on, carriers or infected food handles may easily transmit these organisms to food. If food is contaminated and temperature abused before cooking, heating will destroy the bacteria, but heat-stable enterotoxin may remain and cause illness. A recent study conducted on determination of histamine in swordfish filets implicated in an incident of food-borne poisoning that caused illness in 43 victims in December 2004 in central Taiwan revealed that *S. aureus* seemed to be the histamine former strain [14].

1.2.4 *C. jejuni*

Campylobacter infection is estimated to be the leading cause of bacterial food-borne illness in the industrial countries, and food-borne transmission accounts for approximately 80% of all infections [15]. More than 90% of all human *Campylobacter* infections are caused by *C. jejuni* and *C. coli*. Natural reservoirs are wild birds, and chickens become colonized shortly after birth and are the most important source for human infection. *C. jejuni* is a gram-negative microaerophile, and its optimal grown conditions are a neutral pH and 41°C to 42°C of temperature. It has been frequently isolated from the gastrointestinal tract of wild birds, humans, and other mammals [16]. Human infections are normally attributed to consumption of contaminated uncooked poultry and cross-contamination from this source as well as to contact with cattle including consumption of beef and milk. Symptoms and signs usually include fever, abdominal cramping, and diarrhea as a mild illness but occasionally severe, leading to meningitis, pneumonia, miscarriage, and Guillain–Barré syndrome [17]. Deaths attributable to *C. jejuni* infection have been reported but rarely occur [18].

1.2.5 *E. coli* O157:H7

E. coli infection is transmitted to humans mainly through consumption of contaminated foods such as raw or undercooked meat and milk. Fecal contamination of water and other foods, as well as cross-contamination during handling, are also important causes of infection. The main symptoms that occur after infection are abdominal pain and diarrhea that may progress to bloody diarrhea. Recovery is usually carried out in 10 days, but when it affects the elderly or children, it can lead to hemolytic uremic syndrome characterized by acute renal failure and hemolytic anemia [19]. Most confirmed human *E. coli* O157:H7 outbreaks have been associated with the consumption of undercooked ground beef and, less frequently, unpasteurized milk. *E. coli* O157:H7 is in a close relation to modern approaches to food preservation such as minimally processed foods. Although the incidence of outbreaks produced by this organism is low, in recent years, it has been slightly increased. The latest data available from the EFSA provided by the EU countries for 2006 collected a total of 4,916 cases of toxic infections associated with *E. coli* O157:H7, of which 13 occurred in Spain. An important virulence factor of this microorganism is its acid resistance.

The bacteria possess at least three acid-resistance systems that account for their well-known ability to tolerate acid environments [20]. Some studies have revealed that *E. coli* O157:H7 isolates are resistant to antibiotics [21].

1.3 PREVENTION AND CONTROL

Hazards can be introduced at any point from farm to table. To control food-borne diseases, careful attention has to be paid in the following major factor groups: inappropriate temperature, use of inadequate raw materials, environmental factors, and inadequate handling [1]. Even though heating of foods kills potentially hazardous pathogens, and refrigeration prevents their multiplication, an inappropriate use of temperature such as inadequate refrigeration and inadequate cooking could be resulting in human outbreaks. Use of microbiological contaminated raw materials or contained contaminated ingredients was reported in 20% of the outbreaks in Europe in the 1990s. Inadequate handling such as cross-contamination, inadequate processing, insufficient hygiene, and reusing leftovers are also high-risk factors resulting in food-borne diseases. Among environmental factors, contamination by personnel was the most frequently reported contributing factor, followed by contaminated equipment and use of inadequate rooms.

Therefore, preventing and controlling food-borne infections requires constant efforts along the entire chain of production [22]. The above detailed epidemiologic investigations of how contamination occurs in outbreaks settings can identify such points of contamination and, thus, can target the development of improved control strategies. In this sense, an extensive list of options is available for improving the prevention and control of food-borne diseases. Among them the most relevant was the implementation of the Hazard Analysis Critical Control Point (HACCP) process. All of these programs require the food industries to identify points in food production where the contamination may occur and target resources toward processes that may reduce or eliminate food-borne hazards [23]. To provide a basis for educating food handlers and consumers is also crucial.

New prevention technologies will be critical to food safety in the future. To ensure the food safety and to extend the shelf life of food products, processing, such as freezing, drying, pasteurization, or sterilization, is often necessary [24]. The growing demand for slightly processed products with the same guarantees of innocuousness than those treated by traditional methods of preservation has urged researchers to focus most of their efforts on studying new ways of ensuring the food safety and extending the shelf life of food products [25]. Nowadays, diverse methods such as mild heating, irradiation, high pressure, and modified atmosphere or antimicrobial packaging are applied, often combined, for food preservation. The use of mild treatments combined with refrigeration has led to a continuous increase in the incidence of emergent pathogens [26].

One way to prevent the growth of pathogens in food is to use antimicrobial agents [27]. Prudent use of antimicrobials may prolong their effectiveness by preventing serious public health problems such as the antibiotic acquired and cross-resistances in some pathogenic bacterial strains [28].

1.4 ANTIMICROBIAL AGENTS FOR FOOD PRESERVATION

Antimicrobial agents are playing a great role in effective control of food-borne pathogens, food manufacturers, and others within the food industry [29]. Food antimicrobials are compounds employed to control microbial contamination by reducing the growth rate and maximum growth population, extending the lag phase, or inactivating microorganisms in the food, while maintaining sensorial and nutritional quality and freshness. Traditionally, the main use of food antimicrobials has been to extend shelf life and preserve the quality by inactivation of spoilage microorganisms [30]. And only a few antimicrobials have been used exclusively to control the growth of specific food-borne pathogens [31]. The most relevant cases are nitrates to inhibit the growth of *Clostridium botulinum* in cured meats, nisin and lysozyme to inactivate *C. botulinum* in pasteurized processed cheese, and lactate and diacetate against *L. monocytogenes* among others [32]. Nowadays, however, antimicrobials have been used increasingly to inhibit the outgrowth of pathogens in foods because the increase in consumer demand for minimally processed foods is causing the appearance of food-borne pathogen outbreaks. As many antimicrobial agents are bacteriostatic or fungistatic, they are often applied in combination with other food preservation procedures in order to prolong the shelf life of the food products. The combination of several microbial controls is sometimes called "hurdle technology" [33].

An antimicrobial agent is a chemical or biological agent that either destroys or inhibits the growth of pathogenic and spoilage microorganisms. Antimicrobials can be classified as traditional or naturally occurring [34, 35].

These chemicals may include synthetic compounds, which are added intentionally to the foods or natural occurring, biologically derived substances, the so-called naturally occurring antimicrobials [36]. Examples of synthetic additives include chemical antimicrobials such as formic and propionic acid [37].

Natural antimicrobials may exhibit antimicrobial activity as additives in foods [38] and include those that are present or derived from plant or animal tissues and those produced by microorganisms.

Different chemicals such as propionates, sorbates, and benzoates have been successfully used as reliable antimicrobial substances to control several microbial hazards. However, increasing concern of the suspected carcinogenic nature of synthetic additives, such as butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) [39], has resulted in a consumer increase in avoiding foods prepared with preservatives of chemical origin [40]. Legislation has

TABLE 1.2 Relevant antimicrobial systems: Chemical synthetic *versus* naturally occurring compounds

Chemically synthetic antimicrobials	Naturally occurring antimicrobials
• Organic and inorganic acids	• Lactoferrin
• Thiosulphinates	• Enzymes
• Antibiotics	• Bacteriocins
• Fungicides	• Plant essential oils
• Metal salts	• Spice essential oils
• Isothiocyanates	• Chitosan
• Chelating agents	• Porphyrins
	• Metals

restricted the use and permitted levels of some currently accepted preservatives in different foods. This has created problems for the industry because the susceptibility of some microorganisms to most currently used preservatives is diminishing [41]. Although the use of chemical preservatives is still essential in food processing, the replacement of chemicals by more natural alternatives is appropriate when the chemicals are no longer acceptable.

Although the use of chemical preservatives is still essential in food processing, the replacement of chemicals by more natural alternatives is appropriate when the chemicals are no longer acceptable or questioned because of toxicological side effects. Natural alternatives are therefore needed to achieve a sufficiently long shelf life of foods and a high degree of safety with respect to food-borne pathogenic microorganisms [40]. Attention is therefore shifting toward the use of natural preservatives [42]. However, it is evident that these natural alternatives are not always as effective as the traditionally used synthetic chemicals. The major antimicrobial compounds included in plastics are shown in Table 1.2.

1.5 METHODS TO DETERMINE THE ANTIMICROBIAL ACTIVITY

There have been nearly as many methods used for determining antimicrobial efficacy as there are compounds [43]. This makes it difficult to compare results from different laboratories and even more complex to determine the potential success of an antimicrobial in food because of methods that are inappropriate or lack significance [44]. Despite the large number of methods available, the agar diffusion method has almost certainly been the most widely used method for determining the antimicrobial activity or for screening antimicrobial substances [44, 45] and has often been referred to as the disk assay [43]. Figure 1.1 shows the major methods used to evaluate the efficacy of food antimicrobial agents.

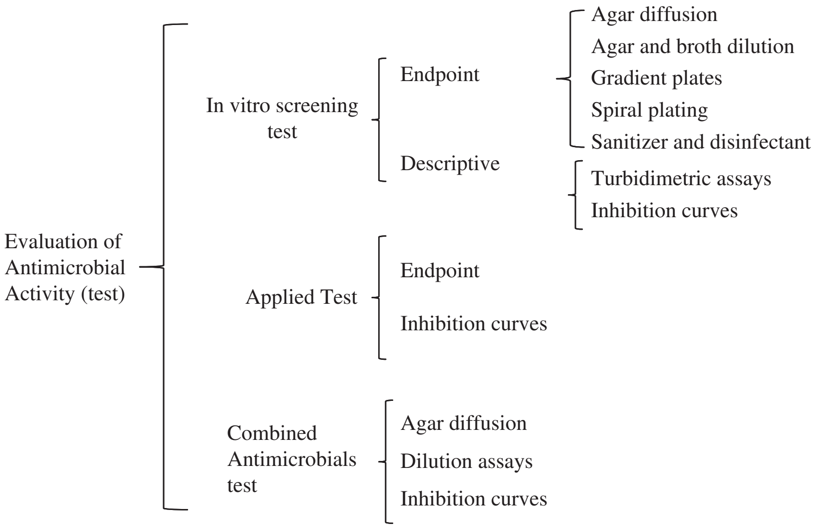

FIGURE 1.1 Methods of evaluation of antimicrobial activities.
Source: Davidson and Parish (1989) and López-Malo et al. (2000a)

1.6 PLASTICS AND BIOPLASTICS IN PACKAGING

Plastics are a family of materials whose use has been increased in many applications since the late 1930s. The most rapidly adopting area of application for plastics has been packaging. To the extent that nowadays, plastic packaging is the largest application for plastics (ca. 37% in Europe), and within the packaging niche, food packaging amounts to the largest plastics demanding application. Plastics bring in enormous advantages, such as thermoweldability, flexibility in thermal and mechanical properties, lightness, integrated projects (integrating forming, filling, and sealing), and low price [46–48]. Nevertheless, plastics also have some limitations when compared with more traditional materials like metals, alloys, or ceramics. One of the most relevant characteristics of plastics, often regarded as a disadvantage, is their permeability to the transport of low-molecular-weight components in the form of permeability, migration (of polymer residues and/or additives), or scalping (sorption of aroma compounds). Transport or barrier properties are determined by permeability ($P = S \times D$), diffusion (D), solubility (S), and partition (P) coefficients. Other limitations of plastics are a comparatively low thermal resistance and a strong interdependence between thermal and mechanical properties and barrier properties. Despite that plastic materials continue to expand and replace the conventional use of paperboard, tinplate cans, and glass, because of the above-mentioned positive characteristics and the development of multilayer systems, which can include metalized layers for the higher barrier and ultraviolet (UV) protection demanding applications.

More recently there has been a current trend to substitute petroleum-based materials by renewable biobased-derived plastics, which will reduce the oil dependence, facilitate the afterlife of the packaging by for instance composting, and reduce the carbon footprint of the food packaging industry. Regarding biodegradable (renewable and nonrenewable) materials, three families are usually considered: polymers directly extracted from biomass such as the polysaccharides chitosan, starch, and cellulose and proteins such as gluten and zein. A second family makes use of oil-based monomers or of biomass-derived monomers but uses classic chemical synthetic routes to obtain the final biodegradable polymer; this is the case of, for instance, polycaprolactones (PCLs), polyvinyl-alcohols (PVOHs), and copolymers (EVOHs) and for the case of sustainable monomers of polylactic acid (PLA) [46–48]. The third family makes use of polymers produced by natural or genetically modified microorganisms such as polyhydroxyalcanoates (PHAs) and polypeptides [49]. The latter materials can be engineered to exert antimicrobial performance.

The bioplastics more commercially viable at the moment are some biodegradable polyesters, which can be processed by conventional processing equipment and are being used in several monolayers and multilayer applications already, particularly in the food packaging and biomedical field. The most widely researched thermoplastic sustainable biopolymers for monolayer packaging applications are starch, PHA, and PLA. From these, starch and PLA biopolymers are without a doubt the most interesting families of biodegradable materials because they have become commercially available (by, for instance, companies such as Novamont and Natureworks, respectively), are produced on a large industrial scale, and present an interesting balance of properties. Of particular interest in food packaging is the case of PLA because of its excellent transparency and relatively good water resistance. Nevertheless, these materials suffer from shortages such as barrier and thermal properties when compared with, for instance, PET, and therefore, it is of great industrial interest to enhance the barrier properties of these materials while maintaining its inherently good properties such as transparency and biodegradability [50–56].

Despite this, other materials also are extracted from biomass resources such as proteins (e.g., zein), polysaccharides (e.g., chitosan), and lipids (e.g., waxes) with excellent potential as carriers of antimicrobial systems. The main drawbacks of these families of materials is their inherently high rigidity, difficult processability using conventional processing equipment, and for the cases of proteins and polysaccharides, the very strong water sensitivity originating from their hydrophobic character, which leads to a strong plasticization of many properties including the excellent oxygen barrier as relative humidity and water sorption increase in the material. The low water resistance of proteins and polysaccharides strongly handicap to some extent its use. Nevertheless, chitosan and zein biopolymers exhibit two very interesting characteristics, one is that the chitosan displays antimicrobial properties [57, 58] and the other is that zein shows an unusually high water resistance compared with other similar biomaterials [59]. Furthermore, the zein in a resin form can also be heat processed.

In general, polymers and particular biomass-derived polymers, because of their intrinsic mass transport properties discussed above, constitute ideal carriers for antimicrobials because of the advantage of being tuneable in terms of control release and the possibility of combining several polymers through blending or multilayer extrusion, to tailor the performance.

Traditional plastic use in, for instance, packaging has been defined as a passive barrier to delay the adverse effect of the environment over the contained product. Nevertheless, the current tendencies include the development of plastic technologies that interact with the environment and with the product, playing an active role in its preservation. Moreover, plastics, when applied to, for instance, food packaging, can also be designed to impact the safety of the consumer by integration of functional active ingredients in the packaging structure. These new food packaging systems have been developed as a response to trends in consumer preferences toward mildly preserved, fresh, tasty, healthy, and convenient food products with prolonged shelf life and can be used to compensate for shortages in the packaging design. In addition, changes in retail practices, such as globalization of markets resulting in longer distribution distances, present major challenges to the packaging industry that finally act as driving forces for the development of new and improved packaging concepts that extend shelf life while maintaining the safety, quality, and health aspects of the packaged foods.

The use of new active packaging strategies compatible with minimal processing technologies has attracted much attention from the food industry because it could have a significant impact on shelf life extension without compromising the food safety. Antimicrobial packaging has been identified as one of the most promising forms of active food packaging technologies. Therefore, research into this area has been increased significantly during the past 10 years. Basically, antimicrobial compounds can be incorporated into or coated onto plastic packaging to control microbial contamination by reducing the growth rate and maximum growth population, extending the lag-phase, or inactivating microorganisms present on the food surface through contact [60].

1.7 ANTIMICROBIALS IN POLYMERS

The demand for antimicrobial packaging is forecast to expand rapidly from a very low base over the next decade. The main objective of antimicrobial plastics is to control undesirable microorganisms by means of the incorporation of antimicrobial substances into or coated onto the packaging materials [61, 62]. Additionally, biocides are included into plastics to stabilize or fixate them, to promote antistaining and self-cleaning performance, and for the control release of these. The principles of action of antimicrobial packaging technologies are based on (1) intended migration (control release, see Figure 1.2) of biocide species either to the liquid phase and/or to the head space, (2) absorption of essential components for microbial growth, and (3) by direct contact

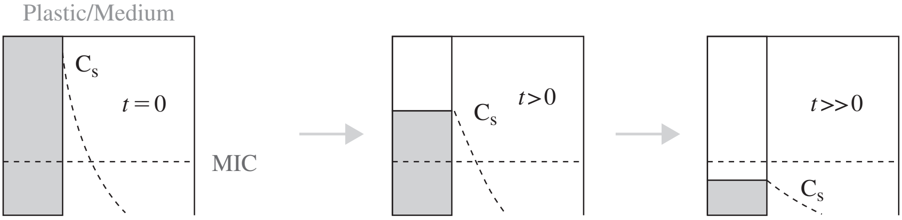

FIGURE 1.2 Schematics showing a control release process from an antimicrobial plastic. Sufficient uptake above the minimum inhibitory (MIC) concentration is essential in antimicrobial plastic packaging.

(nonintended migration). The basic requirements for the selection of biocides to constitute antimicrobial plastics are product stability during shelf life and with the polymer matrix, sufficient solubility in the polymer to avoid biocide concentration depletion below the minimum inhibitory concentration during service (see Figure 1.2), efficacy at low concentrations, biocidal against a broad spectrum of pathogenic microorganisms, thermally stable during polymer processing, does not alter the quality of the product by providing odor or taste, and cost effective.

Different chemicals such as organic and inorganic acids, chlorine dioxide, silver ions and nanoparticles, zinc oxide, magnesium oxide, chitosan, alcohols, ammonium compounds, or amines have been successfully incorporated as antimicrobial substances into plastic materials. However, the current trend nowadays is the preference for natural over synthetic chemistries; therefore, much attention is being paid to the use of bacterial starter cultures, biopreservatives, and plant extracts as antimicrobial hurdles as they present a perceived lower risk to the consumers. Thus, these natural antimicrobial additives are expected to be of increased interest because degradation into harmful products or by-products is thought to be lower than for synthetic chemicals. The biopreservatives suggested as antimicrobials include bacteriocins such as nisin and pediocin and antimicrobial enzymes such as lysozyme, lactoperoxidase, chitinase, and glucose oxidase.

Different systems have been developed that have been widely reported in the previous literature. Ag-substituted zeolite is commercialized in Japan and other countries and exhibits strong and broad antimicrobial attributes [63]. Nevertheless, the real effectivity of this system is not well understood, the requisite migration from polymers is minimal, and the silver ions antimicrobial effects are weakened by sulfur-containing amino acids in many food products [64].

Commercial examples of Ag-based zeolites are Zeomic (Shinanen New Ceramics Co. Ltd., Tokyo, Japan), AgIon (AgIon Technologies Inc., Wakefield, MA), and Apacider (Sangi Group America, Los Angeles, CA). EU and FDA food-contact–approved nanotechnology systems based on biocide metals, natural extracts, and other principles and to be used within plastics and ceramic substrates are also commercially available by a nanotech company under the general trade name of Bactiblock (NanoBioMatters S.L., Valencia, Spain) [65–67]. Nanodispersion of these systems in plastics and bioplastics leads to synergies in other properties (enhanced barrier, etc.) while retaining transparency and other good properties of the polymeric matrix.

Volatile substances, like SO_2, chlorine dioxide, or allyl isothiocyanate, have also been studied to be incorporated into plastics [68]. Chlorine dioxide received FDA acceptance as a packaging material antimicrobial agent. It is an antimicrobial gas released from a basic chlorine containing chemical upon exposure to moisture. Its main advantage is that it functions away from the plastic, and thus, it is one of the few packaging antimicrobials that do not require direct contact with the food. The antimicrobial properties of dermaseptin S4 derivative [69] have also been discussed in plastic packaging.

Other possible antimicrobial substances are food preservatives such as sorbates, benzoates, propionates, and parabens, all of them covered by FDA regulations [70]. Sorbate-releasing plastic films are a good example of successful research and development of antimicrobial packaging. The plastic resin and the antimicrobial agents were mixed, extruded, and pelletized to produce masterbatch resins. Films containing sodium propionate have also been proved to be useful in prolonging the shelf life of bread by retarding microbial growth [71].

An interesting commercial development is the marketing of food-contact–approved kitchen products such as chopping boards, tabletops, dish cloths, and so on, which contain triclosan, an antimicrobial aromatic chloro-organic compound, which is also used in soaps, shampoos, and so on [72]. The use of triclosan for food-contact applications was allowed in EU countries by the SCF (Scientific Committee for Food) in the 10th additional list of monomers and additives for food contact materials (SCF, 2000), with a quantitative restriction on migration of 5 mg/kg of food. Nevertheless, the future use of triclosan is being currently questioned because of potential toxicological side effects and is being replaced by metal-based and natural-products–based antimicrobials.

In this respect, the EU has launched a new regulation [73] that legislates the use of antimicrobial products to come into contact with foods, which will trigger the implementation of antimicrobial plastics in packaging within Europe. A range of different antimicrobial plastics are being currently assessed by the EFSA for commercial implementation into food packaging applications in the EU area and in countries of influence. Nevertheless, although the use of antimicrobials in plastics in the food area is expected to grow over the next decade, the U.S. FDA regulations limiting the use of antimicrobials as additives in packaging with direct food and drug contact will restrict broader usage. Concerns regarding the migration of these substances into food will prevent regulatory approval for their use in packaging. Another drawback of many condensed antimicrobials is that they are effective only at the surface, and significant microbial activity often takes place below the surface. However, the significant media emphasis on health and hygiene matters and their role in the spread of infections is creating great opportunities for antimicrobial additives in packaging for personal care and pharmaceutical products.

In the academic literature, other examples of antimicrobial polymers are based on the following principles: thymol [74] and thymol in nanocomposites [75], chitosan and chitosan derivatives [76, 77], nisin [78], 2-nonanona [79], natamycin [80], cinnamon, rosemary, garlic essential oils, oregano and thyme [81–83], clove oils [84], carvacrol [85], lysozyme [86], and many others that can be found in previous work and recent literature reviews [87–90].

The incorporation of plant extracts and essential oils in different plastic systems, like adhesive layers, is without a doubt one of the most interesting areas of current research [88]. Some of these compounds also have antioxidant properties, which makes them very suitable for designing multifunctional plastic materials with greater stability for the contact products.

Of particular interest is also the biobased polymer chitosan. This system has been widely researched, but it has been only recently that the phenomenology of the polysaccharide and its biocide properties have been more clearly understood and adequate characterization methods put in place to optimize its biocide capacity in food packaging and coating applications [76, 91, 92] (see chapter 4).

Recent developments and optimization in nanofabrication by electrospinning of this biopolymer and others indicate that nanostructured fiber mats of biopolymers have very strong biocide properties [93].

Direct application of antimicrobial compounds onto the food surface can be inefficient because of their rapid diffusion within the bulk of food [94]. The incorporation of the above and other antimicrobial agents into the packaging

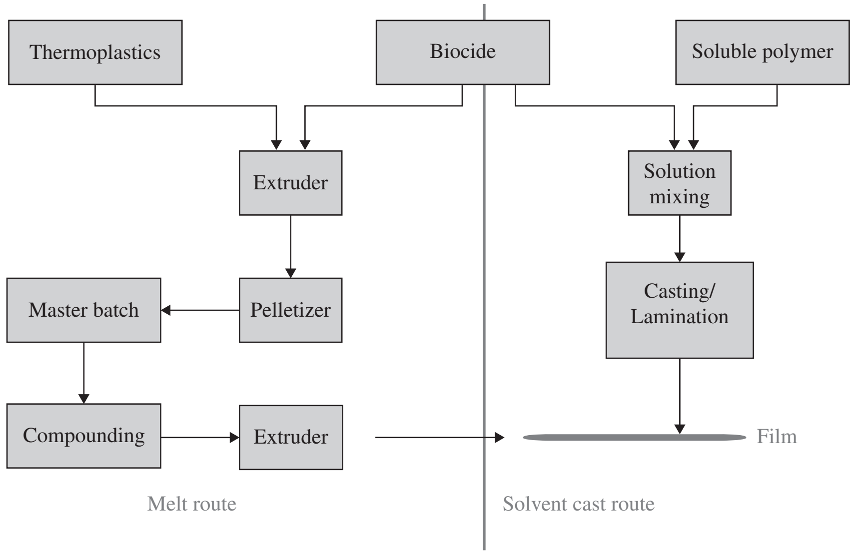

FIGURE 1.3 Schematics for the typical production of antimicrobial plastics via compounding or coating.

material, leading to antimicrobial films, could improve their activity maintaining an optimal effect during the whole storage period. According to Cooksey [61], there are three basic categories to form antimicrobial films: (1) the incorporation of volatile biocide substances into a sachet connected to the package, (2) the direct incorporation of the antimicrobial agent into the packaging film by, for instance, melt compounding routes (see Figure 1.3), and (3) coating of the packaging with a matrix that acts as a carrier for the antimicrobial agent (see Figure 1.3). For nonvolatile compounds that have an increased risk of losing their properties during the thermal polymer processing methods such as extrusion and injection moulding, the latter option seems to be the most appropriate method.

1.8 CONCLUSIONS

The incorporation of antimicrobials within plastic appliances and surfaces has attracted over the last few years a great deal of research and development attention because of widespread concerns at all levels in safety and hygiene. The reasons for incorporating biocides in plastics are to make plastic objects aseptic from a microbial contamination viewpoint, to render them antistaining or antifouling, to stabilize or fixate the biocides, and because of the particular mass transport properties of plastics, to procure control release of the biocides to tailor antimicrobial performance. It is clear that the future will bring a lot of new developments in the area with special focus on the use of bioplastics as matrixes, in the development of natural and biologically derived biocides, and in the application of nanotechnology tools for increased efficiency and specificity.

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