JOURNAL OF KOREA SOCIETY OF PACKAGING
SCIENCE & TECHNOLOGY. Vol. 13, No. 1, 9~18 (2007)

Application of Nanotechnology in Food Packaging

Jong-Whan Rhim

Department of Food Engineering, Mokpo National University, 61 Dorimri, Chungkyemyon, Muangun, Jeonnam 534-729, Republic of Korea

Abstract Nanocomposite has been considered as an emerging technology in developing a novel food packaging materials. Polymer nanocomposites exhibit markedly improved packaging properties due to their nanometer size dispersion. These improvements include increased barrier properties pertaining to gases such as oxygen, carbon dioxide, and water vapor, as well as to UV rays, and increased mechanical properties such as strength, stiffness, dimensional stability, and heat resistance. Additionally, biologically active ingredients can be added to impart the desired functional properties to the resulting packaging materials. New packaging materials created with this technology demonstrate an increased shelf life with maintaining high quality of the product. Nanotechnology offers big benefits for packaging. Nanocomposite technology paves the way for packaging innovation in the flexible and rigid packaging applications, offering enhanced properties such as greater barrier protection, increased shelf life and lighter-weight materials.

Key words Nanotechnology, Nanocomposite, Food packaging, Antimicrobial, Active packaging.

Introduction

Nanotechnology is now recognized as one of the most promising areas for technological development in the 21st century. Nanotechnology is related with the creation of useful/functional materials, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, and biological) at that length scale. In terms of dimensions, one nanometer (nm) is a billionth of a meter (m) or one thousandth of a micrometer (μm), which in turn is one thousandth of a millimeter (mm) (Fig. 1). To give an idea of size on a human scale, an ordinary sheet of paper is about 100,000 nm thick, a single human hair is about 80,000 nm thick, and to compare a nanoaprticle with a football would be like comparing the football to the earth. One nanometer is ten times the diameter of a hydrogen atom and a bacterial cell like *E. coli* may be up to a few thousand nanometers in size. When a material or system is reduced in size, at some characteristic size of smaller than 100 nm, they begin to be influenced by quantum physics, and change the material or system completely in nature to have unique and novel functional properties.

The potential benefits of nanotechnology have been recognized by many industries, and commercial products are already being manufactured, such as in the microelectronics, aerospace, and pharmaceutical industries (Sinha Ray and Okamoto, 2003; Via and Gianelis, 1997; Gianelis, 1996). Nanotechnology also has great potential application in food packaging. Among the various existing nanotechnologies, the one that has attracted more attention in the field of packaging is in the polymer nanocomposites to improve

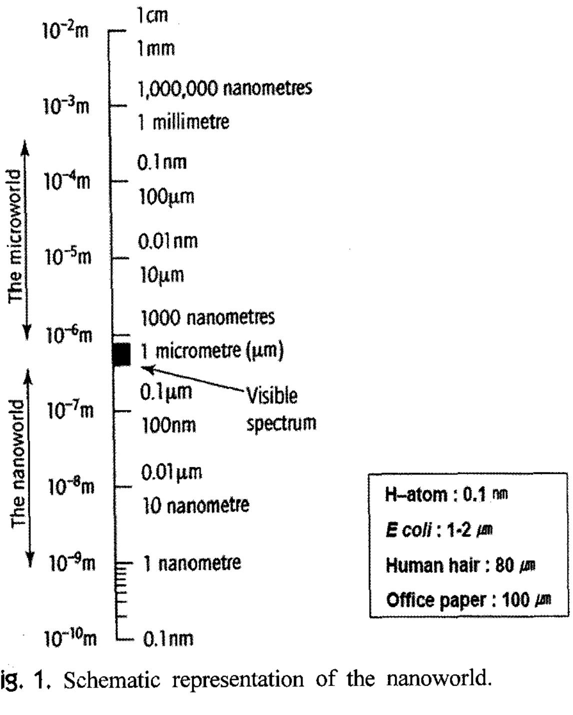

Fig. 1. Schematic representation of the nanoworld.

---

†Corresponding Author : Jong-Whan Rhim
Dept. of Food Engineering, Mokpo National University, 61 Dorimri, Chungkyemyon, Muangun, Jeonnam 534-729, Republic of Korea
E-mail : <jwrhim@mokpo.ac.kr>

properties of existing materials or develop new materials with unique properties. A polymer nanocomposite is the hybrid material consisting of a polymer matrix reinforced with a fiber, platelet, or particle having one dimension on the nanometer scale (Pandey et al., 2005). Owing to the nanometer-size particles dispersed in the polymer matrix, these nanocomposites exhibit markedly improved mechanical, thermal, optical and physicochemical properties when compared with the pure polymer or conventional (microscopic) composites. Improvements can include, for example, increased moduli, strength and heat resistance, decreased gas permeability and flammability with very low filler loading, typically 5 wt% or lower (Alexandre and Dubois, 2000).

Polymer Nanocomposite

Polymer-clay nanocomposites are a class of hybrid materials composed of organic polymer materials and nano-scale clay fillers (Gianelis, 1996; Lagaly, 1999). Among the nano-scale clays, Montmorillonite (MMT) is of particular interest and has been studied widely (Sinha Ray and Okamoto, 2003). MMT is a clay mineral consisting of stacked silicate sheets with a high aspect ratio (ratio of length to thickness) and a plate-like morphology. This high aspect ratio (100-1,500) with high surface area (700-800 m^2/g) and platelet thickness of 1 nm plays an important role for the enhancement of mechanical and physical properties of composite materials (Uyama et al., 2003). The large aspect ratio of the clay nanolayers with their impermeability results in increased tortuosity factors and, therefore, in delays in the diffusion of penetrants through packaging materials.

Homogeneous dispersion of the clay layers in the polymer matrix is crucial to fully exploit the properties of nanocomposite. Sometimes, the hydrophilic nature of the MMT surface impedes its homogeneous dispersion in an organic polymer phase (Sinha Ray and Okamoto, 2003, Alexandre and Dubois, 2000). To make the clay compatible with organic polymers, the clay's polarity must be modified to be more organophillic to interact successfully with polymers. One way to modify clay is by exchanging organic ammonium cations for inorganic cations from the clay's surface. Such modified clays are commonly referred to as organoclays. The organoclays play an important role for producing the nanocomposite. Surface modification may either enhance the interaction between the clay and the polymer, making it more suitably mixed, or it may favor the intercalation of the polymer chain by dictating the gallery spacing (Kumar et al., 2003; Su and Wilkie, 2003).

Preparation of nanocomposites

The nanocomposites are usually prepared by three different methods, i.e., i) *In-situ* polymerization, ii) solvent intercalation/exfoliation, and iii) melt intercalation/exfoliation method, and their properties have been found to be dependent on the preparation method (Shen et al., 2002; Artzi et al., 2002; Wan et al., 2003; Suh et al., 2000). *In-situ* polymerization involves the combination of clay and monomer, followed by the polymerization of the monomer, which ideally locks the exfoliated clay particles in the resulting polymer matrix. In solution intercalation, the clay is first swollen in a solvent and the polymer (intercalant) is dissolved in the solvent. Both solutions are then combined, and the polymer chains intercalate and displace the solvent within the interlayer of the clay (Shen et al., 2002). In melt intercalation, the clay and polymer are added together above the melting temperature of the polymer; they may be held at this temperature for a period of time, put under shear, or other conditions to encourage intercalation and exfoliation of the clay. Of these, melt intercalation is the most appealing approach because of its versatility, its compatibility with current polymer processing equipment such as extrusion and injection molding, and its environmentally benign character due to the absence of solvents (Shen et al., 2002). In addition, the melt intercalation method allows the use of polymers which were previously not suitable for *in situ* polymerization or solution intercalation.

Characterization of nanocomposites

When the layered silicate clays are mixed with a polymer, three types of composites are commonly obtained: i) immiscible tactoid, ii) intercalated, and iii) exfoliated structures (Fig. 2). In immiscible tactoids, complete clay particles are dispersed within the polymer matrix and the layers do not separate. The mixture of polymer and the silicate clays are microscale composites, and the clay only serves as conventional filler. Intercalation and exfoliation produce two ideal nanoscale composites. In an intercalated nanocomposite often a single polymer chain will be driven between the clay silicate layers, but the system still remains quite well ordered in a stacked type of arrangement. In an exfoliated nanocomposite the silicate layers are completely delaminated from each other and are well dispersed.

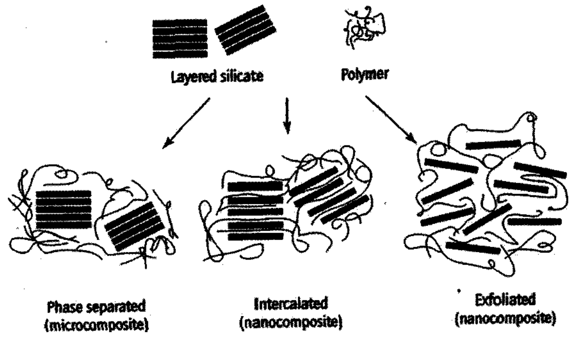

Fig. 2. Types of composite structure of polymer-layered silicate clay materials.

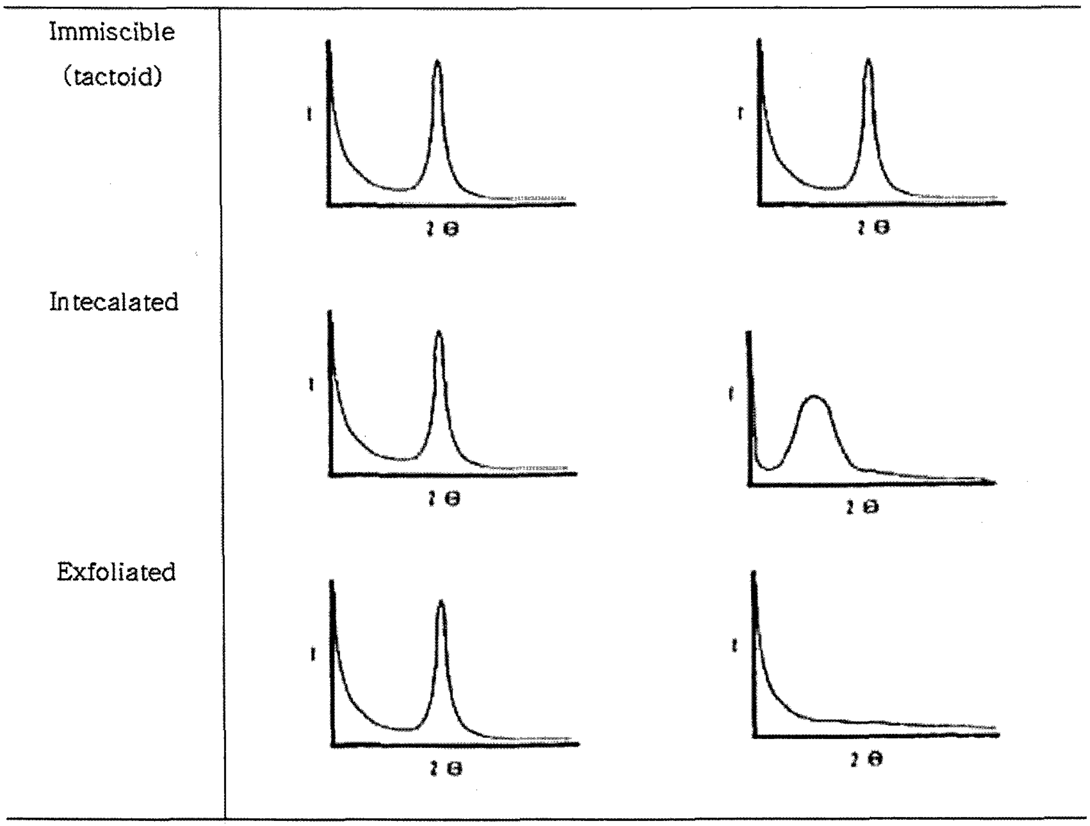

Fig. 3. Schematic representation of the X-ray diffraction patterns for various types of nanocomposite structures.

The structure of polymer nanocomposites is generally characterized by X-ray diffraction (XRD) and transmission electron microscope (TEM). XRD is used to identify intercalated structures by determination of the interlayer spacing. Intercalation of the polymer chains increases the interlayer spacing and according to Bragg's law, it should cause a shift of the diffraction peak towards lower angle. However, if the spacing between the layers becomes too large, those diffraction peaks will disappear in the X-ray diffractograms, which implies complete exfoliation of the layered silicates in the polymer matrix (Fig. 3). In this case, TEM is used to identify the exfoliated silicate layers.

Properties of Nanocomposites

1. Mechanical Properties

Formation of nanocomposite with organoclays has shown pronounced improvement in the mechanical properties of various polymers substantially even with a low level of filler loading. Such advantage of nanocomposite was first demonstrated by a group at the Toyota Research Center in Japan with nylon/silicate nanocomposite (Gianelis, 1998; Usuki et al., 1993). Properties of nylon and nylon/clay nanocomposites containing 4% silicate are summarized in Table 1. This result shows that mechanical properties of nylon such as tensile strength, tensile modulus and heat distortion temperature (HDT), enhanced profoundly through compositing with nanoclay. Tensile modulus and tensile strength increased by 91% and 55%, respectively and HDT was raised by 2.2-fold. Note the significant reduction in water adsorption for the nanocomposite. It has been frequently observed that mechanical properties of polymer/clay nanocomposites are strongly dependent on filler content (Huang and Yu, 2006). For example, by adding 2% nanoclay to a nylon-6 nanocomposite increased tensile strength by 49%, however, adding 6% nanoclay dramatically increased the tensile strength by 98% (Ling et al., 2004). The enhancement in mechanical

Table 1. Properties of nylon-6 and nylon-6/clay nanocomposite

Property	Nylon-6	nylon-6/clay nanocomposite
Tensile modulus (GPa)	1.1	2.1
Tensile strength (MPa)	69	107
Heat distortion temp. (°C)	65	145
Impact strength (kJ/m^2)	2.3	2.8
Water adsorption (%)	0.87	0.51
Coeff. of thermal expansion	13×10^{-5}	6.3×10^{-5}

properties of polymer nanocomposites is attributed to the high rigidity and aspect ratio together with the good affinity between polymer and organoclay.

2. Barrier Properties

Polymer nanocomposites have excellent barrier properties against gases (*e.g.*, oxygen and carbon dioxide) and water vapor. Studies have shown that such reduction in permeability strongly depends on the aspect ratio of clay platelets, with high ratios dramatically enhancing gaseous barrier properties. Yano *et al.* (1997) prepared polyimide/clay nanocomposite films with four different sizes of clay minerals such as hectorite, saponite, MMT, and synthetic mica in order to investigate the effect of the aspect ratio on the barrier properties of the hybrids. They found that, at constant clay content (2 wt%), the relative permeability coefficient decreased exponentially on increasing the length of the clay (Fig. 4). Yano *et al.* (1993) also showed that gas permeability including water vapor permeability and oxygen gas permeability of polyimids/clay nanocomopsite films decreased exponentially with increase in clay content from 0 to 8 wt%. Generally, the best gas barrier properties would be obtained in polymer nanocomposites with fully exfoliated clay minerals with large aspect ratio.

The increase in gas barrier properties of nanocomposite films is believed to be due to the presence of ordered dispersed silicate layers with large aspect ratios in the polymer matrix which are impermeable to water molecules (Yano et al., 1997; Cussler et al., 1998). This forces gas traveling through the film to follow a tortuous path through the polymer matrix surrounding the silicate particles (Fig. 5), thereby increasing the effective path length for diffusion.

3. Degradation Properties

Another interesting property is the significantly improved biodegradability of nanocomposites made from organoclay

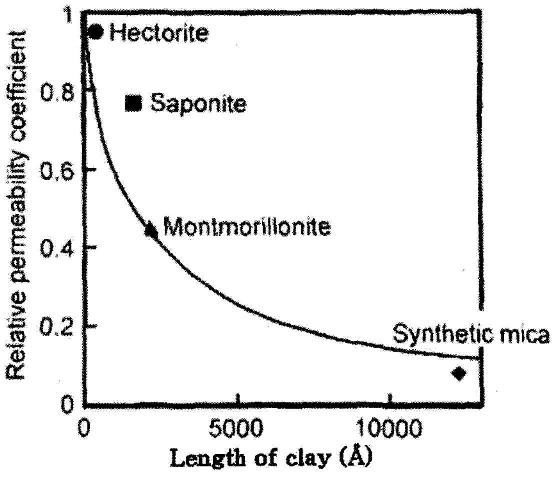

Fig. 4. Effect of clay length on relative permeability coefficient of nanocomposite films.

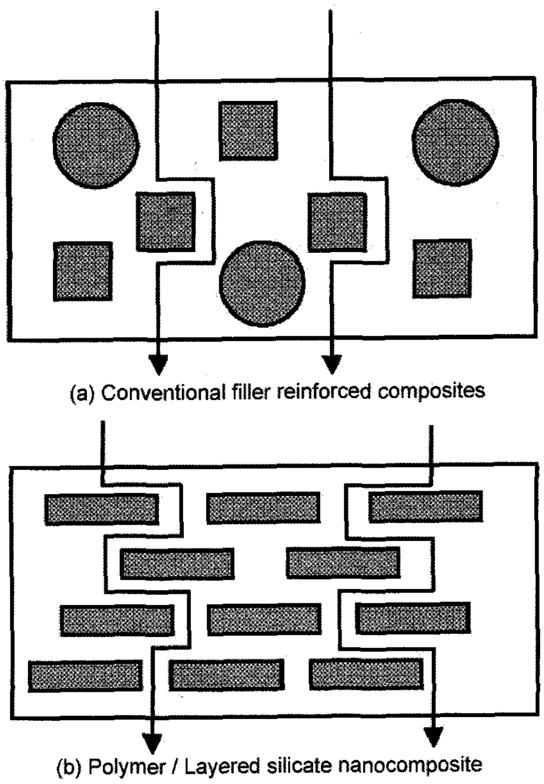

Fig. 5. Schematic illustration of formation of "tortuous path" in nanocomposite. (A) conventional filler reinforced composites, (B) polymer/layered silicate nanocomposites.

and biodegradable polymers. Study on the biodegradability of nanocomposites based on poly(ε-caprolactone) (PCL) showed on improved biodegradability over pure PCL (Zeng et al., 2005). Such an improved biodegradability of PCL in clay-based nanocomposites may be attributed to catalytic role of the organoclay in the biodegradation mechanism. Sinha Ray *et al.* (2002, 2003a,b) reported that the biodegradability of PLA nanocomposite made from organoclay is significantly enhanced. They attributed such a behavior to the presence of terminal hydroxylated edge groups in the clay layers.

4. Other Properties

Polymer nanocomposites also show significant improvement in other polymer properties useful for packaging application. For example, they have the transparency similar to pristine polymer materials because the clay platelets with about one nanometer thickness are well distributed through the polymer matrix. Thus, such clay platelets with size less than the wavelength of visible light do not hinder light's passage. Interestingly, the evenly distributed clay platelets well intercalated or exfoliated through the polymer matrix have a function of preventing transmission of UV light. Nanocomposite packaging materials with such optical properties (*i.e.*, transparency and UV-barrier properties) can be utilized for transparent packaging materials or transparent barrier packaging films or coatings. Some examples include wrapping films and beverage containers, such as processed meats, cheese, confectionery, cereals, fruit juice and dairy products, high barrier beer and carbonated drinks bottles, multi-layer films and containers, and barrier films and paper coatings.

Antimicrobial Activity

As one of the innovative active packaging methods, packaging films with antimicrobial activities have been receiving considerable attention as a potential application for a variety of foods including meat, fish, poultry, bread, cheese, fruits and vegetables (Cha and Chinnan, 2004; Cagri et al., 2004; Labuza and Breene, 1989; Han and Floros, 1997). An innovative antimicrobial nanocomposite films have been developed by endowing antimicrobial function to nanocomposite films (Del Nobile, 2004; Rhim et al., 2006; Wang et al., 2006). Rhim *et al.* (2006) prepared chitosan-based nanocomposite films using a solvent casting method to test the effect of nanoclay or particles such as Cloisite 30B, Na-MMT, Nano-silver, and Ag-Ion on the mechanical and water vapor barrier properties as well as antimicrobial activities of the resulting films. Chitosan film solution was prepared by dissolving 2% chitosan (wt/vol) in a 1% acetic acid solution with 25% of glycerol (w/w, relative to chitosan on a dry basis). In addition, four types of nanocomposite films were prepared by using 5% of each type of nanoparticle (w/w, relative to chitosan on a dry basis). Antimicrobial activity of the nanocomposite films was tested against two Gram positive bacteria, *S. aureus* and *L. monocytogenes*, and two Gram negative bacteria, *S. typhimurium* and *E. coli* O157:H7 using both disk method and total colony count method. Results of disk method (Table 2) indicated no clear microbial inhibition zone with chitosan/Na-MMT nanocomposite films, while Nano-silver- and Ag-Ion-incorporated nanocomposite films exhibited distinctive microbial inhibition zones against both Gram-positive and Gram-negative bacteria. Interestingly, Cloisite 30B-incorporated nanocomposite films exhibited antimicrobial activity against Gram-positive bacteria, *S. aureus* and *L. monocytogenes*. This result was confirmed with the total colony count method as shown in Fig. 6. Since silver ions are well known to have antimicrobial activity against wide range of microorganisms (Siragusa and Dickson, 1992), it was expected that silver-containing nanocomposite films exhibit antimicrobial action. However, the antimicrobial activity of Cloisite 30B-incorporated nanocomposite films has observed for the first time. Rhim *et al.* (2006) attributed this to the antimicrobial activity of the quarternary ammonium group in the silicate layer incorporated to the organoclay (Cloisite 30B) through organophilic modification. The effectiveness of such quarternary ammonium group for disrupting bacterial cell membranes and causing cell lysis has been well known (Kim et al., 1997; Gottenbos et al., 2002; Kim et al., 2003; Wang et al., 2006). All of these results indicate a high potential for antimicrobial bio-nanocomposite films with improved mechanical and barrier properties for use in active packaging applications.

Food Packaging Applications

The use of proper packaging materials and methods to minimize food losses and provide safe and wholesome food products has always been the focus of food packaging. In addition, consumer trends for better quality, fresh-like, and convenient food products have intensified during the last decades. Due to the improved performance in the properties of packaging materials such as i) gas, oxygen, water vapor, etc. barrier properties, ii) high mechanical strength, iii) thermal stability, iv) chemical stability, v) recyclability, vi) dimensional stability, vii) heat resistance, viii) good optical clarity, as well as ix) developing active antimicrobial and antifungal surfaces, and x) sensing and signaling microbiological and biochemical changes, food packaging has been one of the most concentrated nanotechnology development.

The enhanced gas barrier properties of nanocomposites make them attractive and useful in food packaging applications, both flexible and rigid. The use of nanocomposite

Table 2. Antimicrobial activity[1] of the chitosan nanocomposite films as observed by an agar diffusion assay on plate medium[2]

Test Organisms	Film Type					
	Neat Chitosan	Na-MMT	Cloisite 30B	Nano-silver	Ag-Ion$_5$ [3]	Ag-Ion$_{20}$ [3]
S. aureus ATCC-14458	-	-	++	+	+	+
L. monocytogenes ATCC-19111	-	-	+	+	+	++
S. typhimurium ATCC-14028	-	-	-	+	+	++
E. coli O157:H7 ATCC-11775	-	-	-	+	+	++

[1] - : no inhibition; + : clear zone of 6-8 mm; ++ : clear zone of 8-10 mm.

[2] Culture medium: TSA(tryptic soy agar, Difco Lab.), incubation temperature: 37°C.

[3] Ag-Ion$_5$, Ag-Ion$_{20}$: Ag-Ion concentration, 5 and 20% (w/w of chitosan), respectively.

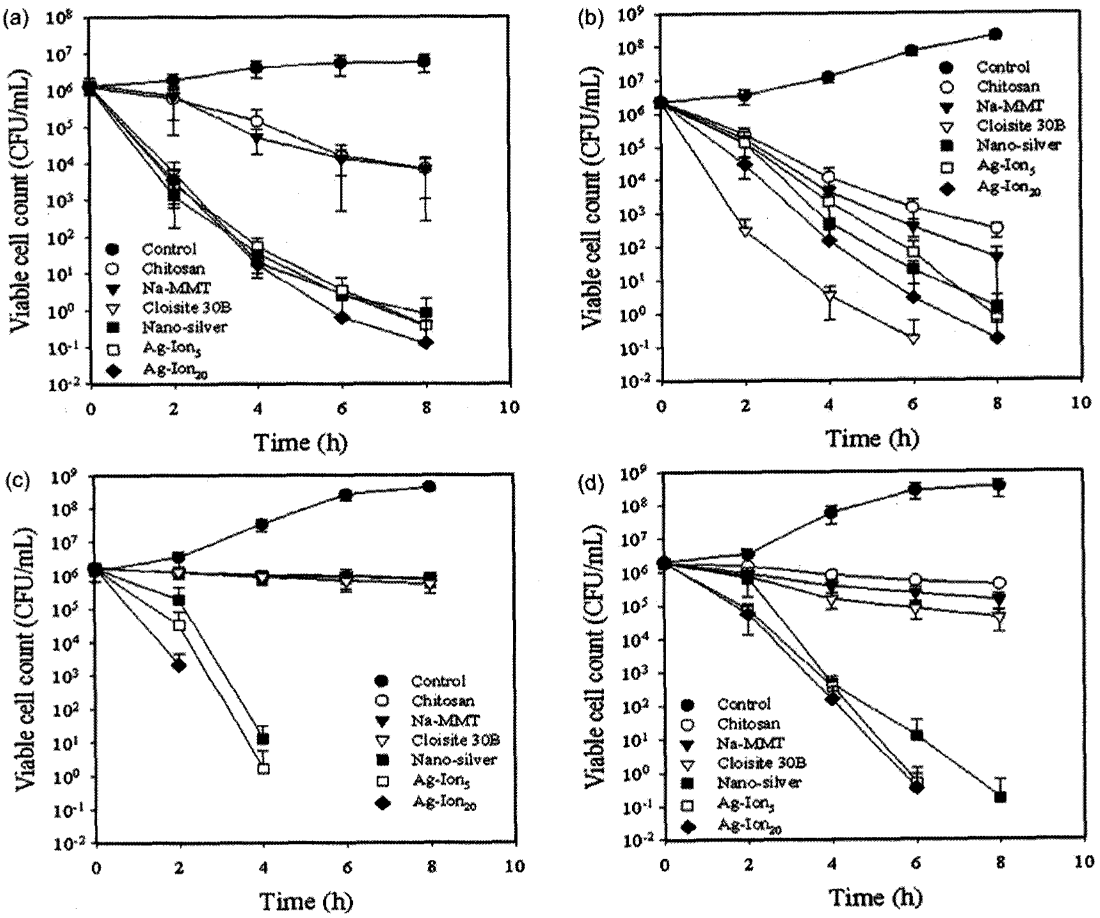

Fig. 6. Antimicrobial activity of chitosan-based nanocomposite films against (A) *S. aureus*, (B) *L. monocytogenes*, (C) *S. typhimurium*, and (D) *E. coli* O157:H7.

formulations is expected to considerably enhance the shelf-life of many types of food. Specific examples include packaging for processed meats, cheese, confectionery, cereals and boil-in-bag foods, also extrusion-coating applications in association with paperboard for fruit juice and dairy products, together with co-extrusion processes for the manufacture of beer and carbonated drinks bottles.

The dominant property improvement is a higher quality shelf life. This improvement can lead to lower weight packages because less material is needed to obtain the same or even better barrier properties. This, in turn, can lead to reduced package cost. Improved shelf life and lower packaging cost are the reasons why nanotechnology is being pursued in consumer packaging. Nanocomposite consumer packaging applications versus property improvements are summarized in Table 3 (Nanocor, 2004).

Rigid Packaging Application

For many foods and beverages the most important and challenging factor for limiting shelf life is the package's resistance to gas intrusion, exemplified by oxygen and water vapor. For other situations it is retention of gases, CO_2 for example, and aromas. The migration of CO_2 out of carbonated beverage bottles can reduce shelf life by allowing the beverage to become flat. Oxygen migrating into beer bottles reacts with the beer to make it stale. In either case the solution is providing barrier to the movement of molecules through the plastic matrix comprising the package.

Nanocomposites that enhance barrier properties are already commercially available. Nylon 6 nanocomposites are being developed by a number of companies, including Honeywell, Bayer, Ube America, and Mitsubishi Gas Chemical, for high barrier packaging. The beer industry is one of the largest business areas exploring the use of polymers enhanced with the nanocomposites, in an effort to complement and/or replace costly and fragile glass.

Honeywell produces three versions of their nylon-6 nanocomposite Aegis^{TM}: OX, HFX and CDSE for the high oxygen barrier of plastic beer bottles, hot-fill bottles, and carbonated soft drink bottle applications, respectively. Studies show that Nylon-6 nanocomposites can achieve on oxygen transmission rate (OTR) almost four times lower than unfilled nylon-6 (Brody, 2003). In the case of Aegis^{TM} OX, which is an oxygen-scavenging nylon formulated for the high oxygen barrier demands of plastic beer bottles, Hon-

Table 3. Nanocomposite consumer packaging applications versus property improvements

	IMPROVED SHELE LIFE	COST REDUCTION	HOT STRENGTH	ODOR CONTROL	VITAMIN PRESERVATION	FLAVOR SCALPING	IMPROVED PRINTABLTY	CHEMICAL RESISTANCE
BOTTLES								
JUICE	○				○	○		
SOFT DRINKS	○							
CATCHUP	○	○						
BEER	○					○		
VEGETABLE OIL	○							
BAGS & PACKS								
FATTY SNACKS	○							
SMOKED MEAT	○			○				
CHEESE	○	○		○				
BOIL-IN-BAG		○	○					
DOG FOOD	○			○	○			
ELECTRONICS		○						○
FILMS								
FRESH MEATS	○	○						
VACUUM PACK CHEESE	○	○		○				
CARTONS								
JUICE	○	○			○	○		
MISC								
SOUP LIDS			○				○	
STAND UP POUCHES		○					○	
MICROWAVE TRAYS	○		○					
SAUSAGE CASINGS		○						
AEROSOL CAN LINERS		○						
BUBBLE RAP		○						○
ANIT FREEZE CONTAINERS		○						
CIGARETTE WRAPPERS	○		○					

eywell claims this nanocomposte PET bottles bring a 100-fold reduction in OTR versus nylon 6, taking oxygen ingress to near-zero level (Fig. 7). In the Aegis™ OX beer bottle, the nanolayers act as the passive barrier and nylon specific oxygen scavenger acts as the active agent as shown in Fig. 8. This beer bottles provides a shelf life of 6-12 months-comparable to glass bottles. In addition, Aegis OX demonstarates excellent resistance to delamination, it can be processed easily, has excellent clarity, is recyclable, and cost competitive. Aegis OX is currently used in a three-layer PET bottle where it is the core layer for a 1.6-liter Hite Pitcher beer in Korea.

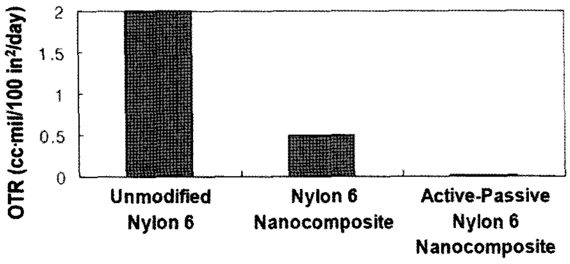

Fig. 7. Oxygen transfer rate (OTP) of Nylon 6 and Nylon 6-based nanocomposite packaging materials.

Imperm®, produced by Mitsubishi Gas Chemical Company, has similar results when added to a multiplayer PET structure under the trade name of M9 (Inperm, 2004). It is currently being used as the core of a three-layer 16 ounce

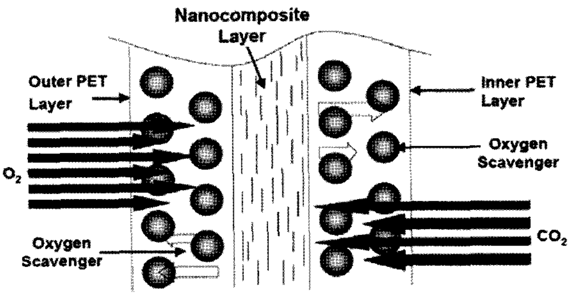

Fig. 8. Schematic representation of passive-active barrier of a three-layer plastic beer bottle of polyamide-based nanocomposite and PET.

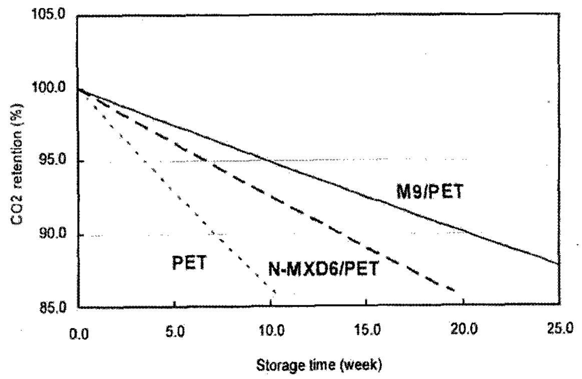

Fig. 9. Comparison of CO_2 retention of various types of PET beer bottles.

non-pasteurized PET beer bottle and is said to have 100-fold lower OTR than that of straight PET. It also adheres to PET without tie layers and retains sufficient clarity to meet requirements for the amber bottle. They were able to extend the shelf life of a 28 gram weight PET bottle from 14 weeks to 21 weeks by using the standard N-MXD6 with a five percent barrier layer of M9 due to its high carbon dioxide barrier (Fig. 9). The cut-off is at 90 percent CO_2 retention.

Another example of consumer packaging for exploring nanotechnology is a multilayer ketchup bottle experiencing difficulties in processing ethylene vinyl alcohol (EVOH) as a barrier layer, which lead to an unacceptable number of bottle rejects. The bottle producer replaced the EVOH with Nanocor's M9 material, melt-compounded in the plastic resin used to extrusion blow the bottle. This lowered rejects by 71% while maintaining the barrier properties and the same cost. The need for tie layers in the structure was also eliminated (Moore, 2004).

Flexible Packaging Application

Nanocomposites would ease the transition between current packaging with metal layers and glass containers to flexible pouches or rigid plastic structures. Many current structures require multiple layers, which render the packaging un-recyclable, but in the facing of global recycling issues, nanocomposite polymers would help to reduce packaging waste and would allow recycling efforts. Waste reduction is a very pressing issue in the world and the U.S. military is a good example of how nanocomposite polymers can positively impact the environment. Since 2002, the U.S. army Natick Soldier Center has been conducting extensive research into the use of no-foil polymer nanocomposites structures for military rations-Meals, Ready-to-Eat (MRE's). The goal is to reduce the amount of solid waste associated with the current packaging as well as reducing costs through material savings. More than 14,000 tons of MRE packaging waste is generated each year because of the foil layer, which causes main problem to recycle the waste pouch after use. One Army ration created 1.04 pounds of waste, while a Navy ration creates 3.6 pounds of solid waste (SERDP, 2003). In addition, the current MRE packages, which are three to four-layer retortable pouches with a foil layer, do not meet the rigorous standards of the military. MRE packaging needs to withstand the following conditions: air-droppable, a minimum three year shelf life at 80°F and six months at 100°F (Culhane, 2005). Nanocomosite polymers with higher barrier properties will extend shelf life and provide greater product protection for military rations. According to U.S. Army research, costs of the future nanocomposite structures are estimated to be 10-30% less than the current pouches. Expected savings comes from less material cost, improved manufacturability with more automation, and less waste handling costs. Overall cost savings are estimated at $1-3 million (U.S. Army, 2004). The technology developed in the military rations can be easily adopted by the consumer packaging of related food items.

Other Applications

Active packaging is a type of packaging that changes the condition of the packaging to extend shelf-life or improve safety or sensory properties while maintaining quality of the food (Vermeiren et al., 1999). A variety of active packaging technologies have been developed to provide better quality, wholesome and safe foods and also to limit package-related environmental pollution and disposal problems (Ozdemir and Floros, 2004). An example of an active packaging is a programmable barrier that controls the atmosphere inside a package.

Self-cleaning glass is another example for using nanotechnology. Asahi Glass and Pilkington Glass are manufacturing it by embedding the glass with titanium dioxide nanoparticles, which in the presence of light, react with dirt and grease and break down the smudges into a pool that will roll off the glass (Ewels, 2004). In addition, self-cleaning surfaces that destroy bacteria, isolate pathogens, or fluoresce under certain conditions are under development (Ragauskas, 2004). It is expected that nanotechnology will bring an explosion of new materials and technologies that will impact the packaging industry.

Conclusions

Nanocomposites of nanoclay and packaging polymer exhibited increased mechanical and gas barrier properties and decreased water sensitivity without sacrificing transparency or biodegradability. Such property improvements are generally attained at low nanoclay content (less than 5%) compared to that of conventional fillers (in the range of 10 to 50%). For these reasons, nanocomposites are far lighter in weight than conventional composite materials, making them competitive with other materials for specific applications such as in packaging. Nanocomposite packaging appears to have a very bright future for a wide range of applications in the food industry including innovative active food packaging with bio-functional properties.

Research continues into other types of nanofillers, allowing new nanocomposite structure with different, improved properties that will further advance nanocomposite uses in many diverse packaging applications. The novel properties that nanotechnology can bring to materials such as self cleaning coating and the cheap sensor application for detecting spoilage seem to offer more potential in food and drink packaging. The use of nanocapsules to reveal tampering or for sensors to show when food has spoiled has the greatest attraction.

Polymer nanocomposites are a new generation of polymers emerging on the packaging market and are the future for the global packaging industry.

References

1. Alexandre M, Dubois P. Polymer-layered silicate nanocomposites: preparation, properties and use of a new class of materials. *Mater. Sci. Eng.* 28: 1~63 (2000).
2. Artzi N, Nir Y, Narkis M, Siegmann A. Melt blending of ethylene vinyl alcohol copolymer/clay nanocomposites: Effect of the clay type and processing conditions. *J. Polym. Sci.: Part B: Polym. Phys.* 40: 1741~1753 (2002).
3. Brody, A. "Nano, Nano" Food packaging technology. *Food Technol.* 57(12): 52~54 (2003).
4. Cha DS, Chinnan MS. Biopolymer-based antimicrobial packaging: A review. Crit. Rev. *Food Sci. Nutrit.* 44: 223~237 (2004).
5. Cagri A, Ustunol Z, Ryser ET. Antimicrobial edible films and coatings. *J. Food Protect.* 67: 833~848 (2004).
6. Cussler EL, Highes SE, Ward WJ, Aris R. Barrier membranes. *J. Mem. Sci.* 38: 161~174 (1998).
7. Del Nobile MA, Cannaris M, Altieri C, Sinigaglia M, Favia P, Iacoviello G, D'Agostino R. Effect of Ag-containing nanocomposite active packaging system on survival of Alicyclobacillus acidoterrestris. *J Food Sci.* 69: E379~E383 (004).
8. Ewel C. Nanotechnology and Packaging. Advantage Magazine (on-line), February 2004, Available: www.fmi.org/advantage.archives =23706&nan?_4306.html.
9. Giannelis EP Polymer layered silicate nanocomposites. *Adv. Mater.* 8: 29~35 (1996).
10. Giannelis EP Polymer-layered silicate nanocomposites: synthesis, properties and applications. Appl. Organmetal. *Chem.* 12: 675~680 (1998).
11. Gottenbos B, Van der Mei HC, Klatter F, Nieuwenhuis P, Busscher HJ. In vitro and in vivo antimicrobial activity of covalently coupled quartemary ammonium silane coatings on silicone rubber. *Biomaterials* 23: 1417~1423 (2002).
12. Han JH. Antimicrobial food packaging. *Food Technol.* 54(3): 56~65 (2000).
13. Imperm 103. (2004). Retrived on February 18, 2007 from http://www.gasbarriertechnologies.com/imperm103.html.
14. Kim, CH, Choi JW, Chun HJ, Choi SK. Synthesis of chitosan derivatives with quartemary ammonium salt and their antibacterial activity. *Polym. Bull.* 38: 387~393 (1997).
12. Kim JY, Lee JK, Lee TS, Park WH. Synthesis of chitooligosacharide derivative with quartemary ammonium group and its antimicrobial activity against *Streptococcus mutans. Int. J. Biol. Macromol.* 32: 23~27 (2003).
13. Kumar S, Jog JP, Natarajan U. Preparation and characterization of poly(methylmethacrylate)-clay nanocomposites via melt intercalation: The effect of organoclay on the structure and thermal properties. *J. Appl. Polym. Sci.* 89: 1186~1194 (2003).
14. Labuza TP, Breene WM. Applications of active packaging for improvement of shel-life and nutritional quality of fresh and extended shelf-life foods. *J. Food Proc. Preserv.* 13: 1~69 (1989).
15. Lagaly G. Introduction: from clay mineral-polymer interactions to clay mineral-polymer nanocomposites. *Appl. Clay Sci.* 15: 1~9 (1999).
16. Ling Y, Omachinski S, Logsdon J, Whan Cho J, Lan T. (2004). Nano-effect in *In Situ* Nylon-6 nanocomposites. Retrieved on February 28, 2007 from http://www.nanocor.com/tech_papers /antec2001.asp.
17. Moore G. Commercial applications. pp. 9-57. In "Nanotechnology in Packaging", Pira International Ltd., Leatherhead, UK (2004).
18. Nanocor (2004). Commercial applications. Retrieved on February 16, 2007, from http://www.nanocor.com/app_pkg.asp.
19. Ozdemir M, Floros JD. Active food packaging technology. Crit. Rev. *Food Sci. Nutr.* 44: 185~193 (2004).
20. Pandey JK, Kumar AP, Misra M, Mohanty AK, Drzal LT, Singh RP. Recent advances in biodegradable nanocomposites. *J. Nanosci. Nanotechnol.* 5: 497~526 (2005).
21. Polymer Nanocomposite Technology Brief. pp. 1-2 available from: http://ip.research.sc.edu/PDF/Polymer%20Nanocomposite%20Technology%20Brief%20v1.pdf *Accessed Dec.* 27, 2006.
22. Ragauskas, AJ. Big opportunities with tiny technology. Pulp & Papers, may 2004. Available: http://www.paperloop.com/db_area/archive/p_p_mag/2004/0005/comment.html.
23. Rhim JW, Hong SI, Park HM, Ng PKW. Preparation and characterization of chitosan-based nanocomposite films with antimicrobial activity. *J. Agricul. Food Chem.* 54: 5814~5822 (2006).
24. Shen Z, Simon GP, Cheng YB. Comparison of solution intercalation and melt intercalation of polymer-clay nanocomposites. *Polymer,* 43: 4251~4260 (2002).
25. Sinha Ray S, Okamoto M. Polymer/layered silicate nanocomposites: a review from preparation to processing. *Prog. Polym. Sci.* 28(11): 1539~1641 (2003).
26. Sinha Ray S, Yamad K, Okamoto M, Ueda K. Biodegradable polylactide/montmorillonite nanocomposites. *J. Nanosci. Nanotechnol.* 3: 503~510 (2003a).
27. Sinha Ray S, Yamada K, Okamoto M, Ueda K. New polylactide-layered silicate nanocomposites. 2. Concurrent improve-

ments of material properties, biodegradability and melt rheology. Polymer 44: 857~866 (2003b).

28. Sinha Ray S, Yamada K, Okamoto M, Ueda K. Polylactide-layered silicate nanocomposite: A novel biodegradable material. Nano Lett. 2: 1093~1096 (2002).
29. Siragusa GA,Dickson JS. Inhibition of *Listeria monocytogenes* on beef tissue by application of organic acids immobilized in a calcium alginate gel. *J. Food Sci.* 57: 293~296 (1992).
30. Su SP, Wilkie CA. Exfoliated poly(methylmethacrylate) and polystyrene nanocomposites occur when the clay cations containing vinyl monomer. *J. Polym. Sci.:Part A: Polym. Chem.* 41: 1124~1135 (2003).
31. Suh DJ, Lim YT, Park OO. The property and formation mechanism of unsaturated polyester-layered silicate nanocomposite depending on the fabrication methods. *Polymer*, 41: 8557~8563 (2000).
32. U.S. Army Soldier Systems Center-Natick. (2004). Nanotechnology applied to rationpackaging. Accessed on February 12, 2007 from the U.S. Army Soldiers Systems Center-Natick at http://www.natick.army.mil/about/pao/2004/04-21.htm
33. Usuki A, Kojima Y, Kawasumi M, Okada A, Fukushima Y, Kurauchi T, Kamigaito O. Synthesis of nylon 6-clay hybrid. *J. Mater. Res.* 8: 1179~1184 (1993).
34. Uyama H, Kuwabara M, Tsujimoto T, Nakano M, Usuki A, Kobayashi S. Green nanocompositefrom renewable resources: Plant oil-clay hybrid materials. *Chem. Mater.* 15: 2492~2494 (2003).
35. Vaia RA, Gianelis EP. Lattice Model of Polymer Melt Intercalation in Organically-Modified Layered Silicates. Macromolecules, 30: 7990-7999 (1997)Huang M, Yu J. Structure and properties of thermoplastic corn starch/montmorillonite biodegradable composites. *J. Appl. Polym. Sci.* 99: 170~176 (2006).
36. Vermeiren L, Devlieghere F, van Beest M, de Kruijf N, Debevere J. Developments in active packaging of foods. *Trends Food Sci. Technol.* 10: 77~86 (1999).
37. Wan C, Qiao X, Zhang Y, Zhang Y. Effect of different clay treatment on morphology and mechanical properties of PVC-clay nanocomposites. *Polym. Test.* 22: 453~461 (2003).
38. Wang X, Du Y, Yang J, Wang X, Shi X, Hu Y. Preparation, characterization and antimicrobial activity of chitosan/layered silicate nanocomposites. *Polymer* 47: 6738~6744 (2006).
39. Yano K, Usuki A, Okad A. Synthesis and properties of polyimide-clay hybrid films. *J. Polym. Sci.: Part A: Polym. Chem.* 35: 2289~2294 (1997).
40. Yano K, Usuki A, Okad A, Kurauchi T, Kamigaito O. Synthesis and properties of polyimide-clay hybrid. *J. Polym. Sci.: Part A: Polym. Chem.* 31: 2493~2498 (1993).
41. Zeng QH, Yu AB, Lu GQM, Paul DR. Clay-based polymer nanocomposites: Research and commercial development. *J. Nanosci. Nanotechnol.* 5; 1574~1592 (2005).