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A Review on the Application of Nanotechnology in Food Processing and Packaging

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Abstract

Currently, nanotechnology is widely applied in various industrial fields and is rapidly emerging as a promising future technology. In food industries, nanotechnology is used to enhance food quality and safety. Numerous cutting-edge studies on the advantages of nanotechnology have been conducted in the fields of food processing, food ingredients and additives, food packaging, and food engineering for optimal health. The market for these areas of research has grown steadily, and is expected to continue to do so. Because of this, R&D for nanotechnology that can be used effectively in food industries is being performed by several companies, as well as in academic research institutions around the world. This review describes the recent global R&D trends that have been in progress for two key areas: food processing and food packaging.

Key words: nanotechnology, food processing, food packaging

Introduction

The term nanotechnology describes a scientific technique that is used to produce and utilize materials with structures that are less than 100 nanometers (nm). These structures can be applied in various areas and have been shown to produce a synergistic effect when used in combination with existing technologies. Because of this, nanotechnology is quickly emerging as a promising new technology. Among the various applications of nanotechnology, food nanotechnology is fast becoming a widely used 21st century food engineering technique. This includes production, manufacturing, and distribution in the food industry. The global scale of the nanofood market is approximately 970 billion USD in 2010, and is expected to grow to more than 1 trillion USD in 2012 (Cientifica, 2008; Kuzma & VerHage, 2006). The food market for nanotechnology is anticipated to account for about 40% of the global food industry by 2015 (Miller, 2007).

Nanofood means food that is created using nanotechnology techniques or tools during cultivation, production, processing, or packaging and this term is not limited to only foods modified at the atomic level or food produced by nanomachines (Joseph & Morrison, 2006; Cho, 2007). In general, nanofood is related to the improvement of food color and flavor, prolongation of shelf life and preservation, detection of germs and antibacterial characteristics, and intelligent packaging materials. In addition, nanofood includes not only the processed food category but also entire areas from cultivation to packaging. The application of nanotechnology in the cultivation and production process of food is becoming more prominent in the agricultural industry along with other important aspects of agriculture such as environment-friendly agriculture and environmental conservation.

Nanofood can be categorized generally into 5 areas: agro-products, food processing, food ingredients and addictives, food packaging, and food engineering. Robinson and Morrison (2009) further classified nanofood into 3 areas: food cultivation and production, which includes all methods and techniques used during the cultivation and production processes of food and food materials; food processing, which includes all methods and techniques used to modify unprocessed food materials into a consumer product, and food packaging, which includes all techniques used during packaging and distribution of processed and produced foods (Robinson & Morrison, 2009; Moraru et al.,

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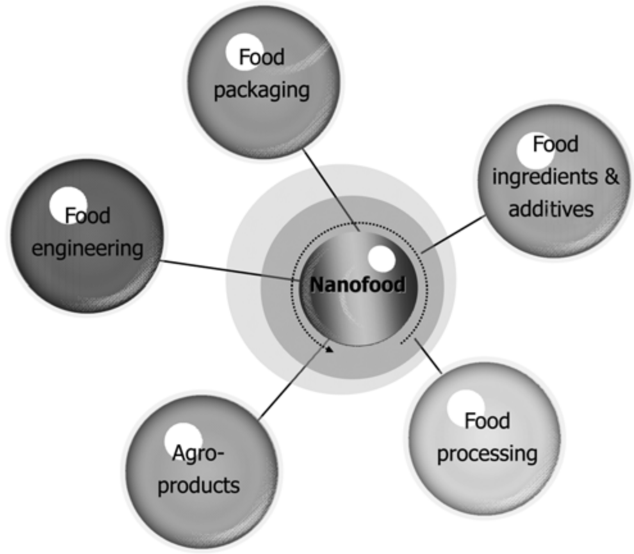

Fig. 1. Areas of the nanofood industry.

2009).

Since late 2000, the active application of nanotechnology to food processing and packaging have increased the value of food. Industrial nanotechnology applications in these two areas are expected to increase by more than 50% every year. In terms of packaging, industrial applications of nanotechnology are in progress with a focus on conventional active packaging to prolong the shelf life or improve flavor, and this area of nanotechnology is expected to grow by Compound Annual Growth Rate (GAGR) 57.52% after 2007 and reach approximately 2.7 billion USD in 2012 (Table 1). Meanwhile, smart packaging, which involves tagging, monitoring, and tracking and tracing functions for the detection of food spoilage and contamination by microbes and chemical changes, the detection of the nutrient contents through a built-in sensor and for sending signals, has also been applied recently. Smart packaging that applies the cutting edge IT-NT technology has steadily increased since 2007, and its growth is expected to reach 130%. This area of nanotechnology is expected to be about 200 million USD in 2012.

This review describes the global research trends that have been recently increasing in two key areas of the three major nanofood areas: food processing and food packaging.

Food Processing

The food processing area in nanofood refers to the application of nanotechnology to any of the processes conducted on agricultural products, such as food materials and raw materials that are modified and processed into consumer products. The applicable nanotechnologies for food processing are edible nano coating, nanofiltration, and nanoemulsion. Nano coating is a technique that blocks direct contact with oxygen and moisture by coating existing food with a very thin layer of material that has a nano-scale thickness in order to prolong food shelf life as well as to generate an appealing aesthetic look. Nano filtration is a technique that is used to remove harmful or offending contents by extracting or filtrating various flavors, scents, and other selective components from the food. Since filtration of the inner components at the nano level can be achieved, various flavors, scents, and other components can be extracted and removed. Nanoemulsion is a microscopic oil-water drop emulsion that have diameters ranging from 100-500 nm. Since its size is extremely small, it has excellent penetrability and absorption capabilities; thus, various nutrients with high concentrations can be delivered successfully into the human body (Augustin & Sanguansri, 2009; Farhang, 2009).

Another area of nanotechnology used for food processing is

Table 1. Value of nanotechnology in the food industry **(Unit: M USD)**

	2007	2008	2009	2010	2011	2012	CAGR (%)
Active packaging	282	413	600	981	1,632	2,735	57.52
Smart packaging	3	4	11	28	74	195	130.45
Food processing	10	15	21	35	58	97	56.87

Source: Nanotechnology Opportunity Report, 3rd Ed., Cientifica (2008)

Table 2. Potential nanotechnology applications in the food industry

	Driver	Technology
Food processing	"fast-good-safe" food processing at nanoscale	nanocoatings, nanofiltration techniques, nanoemulsion
Food packaging	value added packaging cost, sustainability, convenience, safety and quality	nanosensor, antibacterial nanoparticles, nanoclay for plastic composites

nanoparticles. In this application, particles with nano structures are added to food products to improve the flavor and texture of the food material and to prolong shelf life. For example, nanoparticles such as vitamins, minerals (iron, magnesium, zinc, etc.), probiotics, bioactive peptides, antioxidants, plant sterols, and beans are added to dairy products, cereals, bread, and beverages to enhance the existing properties of the food. Nanoparticles (TiO_2, SiO_2, etc.) are also intentionally added to many foods as a processing supplement to improve liquidity, color, and stability, or to prolong shelf life during food processing, as well as the transfer function of several nutrients (Miller & Senjen, 2008). For instance, alumino-silicate is usually used in granular or powdered processed foods as an anti-caking agent, and anatase titanium dioxide is used for confectionery, cheese, and other sources as a common food whitener and brightener. In addition, the use of nano capsules, which contains active ingredients and nutraceuticals, is increasing. These have been recently added to micro encapsulated food; however, these are produced in nano capsules, which are thousands of times smaller, in order to improve their effectiveness. The success of introducing nutraceuticals using this approach depends on the bioavailability of the capsule, and the nano size or nano encapsulated active ingredients has been shown to improve the bioavailability, solubility, and effectiveness compared with a micro encapsulated active ingredient (Cientifica, 2008).

Nanocoatings

Nano edible coatings are used for meat, cheese, fruits, vegetables, confectionery products, bread, and fast food to prolong shelf life by forming barriers against moisture or gas/oxygen exchange even after the packing material is opened. They are also used as coloring agents, flavoring agents, antioxidants, enzymes, and anti-browning agents.

Nano edible coating means to coat food with an extremely thin membrane, which has a thickness of approximately 5 nm. This technology has been applied to meat, cheese, fruits, vegetables, confectionery products, bread, and fast food. Since it plays a large role in blocking direct contact from air or moisture, it not only prolongs shelf life but also maintains the flavor and scent of the food long after the package has been opened. Sono-Tek Corp., a US company, announced in 2007 a new way to develop antibacterial nano edible coating techniques, in which the nanocoating can be used to directly coat bread (Weiss et al., 2006; ElAmin, 2007).

Mars, Inc, another US company, developed a nano mineral coating using nanoparticles such as TiO_2, SiO_2 and has filed a patent. This coating creates a barrier that protects the coated food from oxygen or moisture so that the shelf life can be prolonged. The application of this coating technology prevented hard candies from becoming sticky, cookies from spoiling, and cereals from becoming stale in milk. In the filed patent, the optimal thickness of the coating was reported to be 0.5-20 nm. Though the coating can be produced from any mineral, materials such as SiO_2 or TiO_2 (which have been already approved by the FDA) are recommended for use. The company has already enhanced several products, including M&Ms, Twix, and Skittles, by coating these candies with a mineral nano film (Cientifica, 2008).

Nanofiltration Techniques

Micro holes that can pass only certain types of desirable molecules can be generated by using nanofiltration techniques that control and process the membrane surface. This nanofiltration technique can be used to exclusively remove desirable molecules, bacteria, or viruses. In particular, the nanofiltration technique has the ability to make potable water safe for consumption by removing various germs and contaminants from the water. Furthermore, this technique is highly economical and is therefore widely used in developing countries where potable water is insufficient and unsafe (Iyer, 2009; Cotriss, 2004).

The University of Wales (UK) is currently studying the potential of using nanofiltration to extract the color and flavor of food. For example, even though beetroot is a well-known coloring agent that is often used in salad, it has a minute soil taste and some consumers have an aversion to it. However, the nanofiltration technique has been used to filter the color and remove the flavor. In another experiment, researchers changed red wine to white wine using nanofiltration, and made a pH indicator (a substitute for phenolphthalein known as a potential carcinogen) by extracting pigments from red cabbages and onions. Nanofiltration and nano concentration processes are safe and inexpensive, and produce minimal phase changes and heat, and do not result in chemical extraction. Several researchers are currently applying nanofiltration to milky whey. In this case, nanofiltration removes moisture before the spray dry step, which reduces the cost of the spray dry process. In addition, nanofiltration can be used to change lactose into another saccharide for consumers who are lactose intolerant (Cientifica, 2008).

Kraft‘s NanoteK Consortium (US company) is currently studying the ‘Smart’ aspects of nanofiltration, which produces allergy-inducing molecules left in the capsule and creates appropriate molecules. In addition, a study on nanofiltration that involves releasing the proper amounts of calcium molecules for patients who have osteoporosis is currently in progress (Pazour, 2009).

The University of Nebraska-Lincoln (US) is developing a filter paper that removes caffeine from coffee during the brewing using the nanofiltration technique. The objective of this technique is to maintain the original coffee taste while selectively removing caffeine. This novel approach will allow one to brew coffee at various caffeine concentrations by simply controlling the number of filters and filter papers. The caffeine molecule footprints are made on the filter surface in molecular imprinting processes; thus, caffeine molecules are filtered and the rest are eliminated when coffee passes through the filter. The production of these footprints may be generated from the caffeine containing liquid by mixing cellulose and silica (Cientifica, 2008).

Nanoemulsion/Encapsulation

Emulsion is the mixture of two or more liquids that are typically immiscible; for example: water and oil. In nanoemulsion, small liquid drops with diameters of less than 500 nm are mixed into an emulsion type suspension. Nanoemulsion maintains the specific functional contents in these small liquid drops through encapsulation and can thereby reduce degradation. In addition, because nanoemulsion can create encapsulation through multiple phases, it can deliver functional contents with different types of more complex characteristics (Tarver, 2006; Silberglitt et al., 2006)

Nestle and Unilever are developing nanoemulsion-based low-fat ice cream that maintains flavor but reduces fat content. Nano additives for nutrient enhancement are also used to enhance the vitamin and mineral content in some processed foods and to increase production time for processed meat (Joseph & Morrison, 2006).

Aquanova Co., a German company, has developed a nanotechnology-based carrier system to encapsulate vitamin C & E, coenzyme Q10, isoflavone, flavonoid, cartenoid, phyto-extract, essential oil, preservatives, coloring agens, and other active ingredients using 30nm micelles. In particular, this technique uses CoQ10 for fat reduction and Alpha-lipoic acid for satiety. These micelles have been sold under the brand name NovaSol since 2006, and the carrier system improves the effect of the active ingredients and bioavailability (Miller & Senjen, 2008).

The top-selling product at George Weston Foods Co. in Australia is called ‘Tip Top-up’ bread. The bread contains microcapsules of tuna fish oil (140-180 μm, product name: Nu-Mega Driphorm), a source of omega 3 fatty acids (Nu-mega 2007). Since the tuna fish oil is in microcapsules, consumers don’t detect the taste of the oil during consumption. The microcapsules are designed to break open only when they have reached the stomach. However, companies like Aquanova and Zymes offer 30-40 nm nanocapsules of omega 3, which are 4,000 times smaller than Nu-Mega. The same technology is also used in yogurt and baby food. (Chaudhry et al., 2008).

The Israeli company Nutralease, which was established by researchers at the Hebrew University in Jerusalem, utilizes NSSL (Nano-sized Self-assembled Liquid Structures) technology to deliver nutrients to cells. The particles are expanded micelles (hollow spheres made from fats, with an aqueous interior) with a diameter of approximately 30 nm. The nutrients, which are contained within the aqueous interior, include lycopene, beta-carotene, lutein, phytoserol, CoQ10, and DHA/EPA. The nutralease particles allow these compounds to enter the bloodstream from the gut more easily, thus increasing their bioavailability. The technology has already been adopted and marketed by Shemen Industries (Israel) to deliver Canola Activa oil, which it claims reduces cholesterol intake in the body by 14% (Cientifica, 2008).

Biodelivery Sciences International, a US company, has developed Nanocochleates and has filed a patent for this technology. Nanocochleates are 50 nm coiled nanoparticles induced from beans and calcium and can be used to deliver pharmaceuticals and nutrients (vitamins, lycopene, and omega fatty acids) directly to cells. Nanocochleates have specific features that can mix omega 3 fatty acids into cakes, muffins, pasta, soup, or cookies without affecting the color or taste of the food (Chaudhry et al., 2008).

In addition, Salvona Technologies Inc. has created a multi-component delivery system called ‘MutiSal’. This system successfully releases multiple ingredients (water and fat soluble ingredients) that don't normally mix well. It increases the stability and bioavailability of a broad range of nutrients and other components, controls their release system, and prolongs the release time in the mouth to enhance taste. After making hydrophobic nanospheres with diameters of approximately 0.01-0.5 micron, the nanospheres are encapsulated in a water or pH sensitive microsphere with a diameter of 20-50 microns, which are equally dispersed in the sphere. When the microsphere contacts moisture (saliva), it dissolves and releases nanospheres and other components. Various components can be mixed in both or either the hydrophobic nanosphere matrix or a water sensitive microsphere matrix (Robinson & Morrison, 2009; Shefer, 2008).

In 2002, BASF developed a nano sized synthetic cartenoid (a red pigment in carrots or tomatoes that acts as an antioxidant) called lycopene, which is a food additive, and obtained GRAS (Generally Recognized as Safe) Approval for its sales from the FDA in the US. BASF markets lycopene to major food and beverage companies around the world and this capsulated synthetic nano cartenoid is added to lemonade, fruit juice, and margarine (Robinson & Morrison, 2009; Sanguansri & Augustin, 2006; Shelke, 2005; Hodge et al., 2007).

In food systems, there are several types of nanoparticulates such as emulsion, liposome and biopolymeric particles. Nano emulsion and nano-liposome technology is receiving a great deal of attention due to their ability to control the solubility and stability of healthy, functional food products. A research team at the Korea Food Research Institute modified various water-insoluble and instable phytochemicals to have stable or water-soluble properties. For example, the team made nanoemulsion of capsaicin using a surfactant that can be used in food, and nano-encapsulted phytosterols in multilamellar vesicles using ultrasonic waves and pressure (Choi et al., 2009; Kim et al., 2009; Lee et al., 2008).

Food Packaging

The nano packaging system can increases the barrier properties (mechanical, thermal, chemical, and microbial) of food packaging by adding nanoparticles to the packaging material or bottles that respond to environmental conditions (temperature, moisture, gas, and exposure to UV). This packaging approach maintains food safety and freshness by blocking germs and microbes, improves taste and scent, and prolongs shelf life (Doyle, 2006).

Nano packaging also allows for 'smart packaging,' which has tagging, monitoring, and tracking and tracing functions for detecting food spoilage and contamination by microbes and chemical changes, detecting the content of nutrients through a built-in sensor and for sending signals (Kim, 2008).

Use of Nanosensor

Nanosensors can be used in food packaging material to detect chemicals such as certain composites that are generated when food begins to spoil. When food starts spoiling, the packaging material will change color in order to signal its state to the consumer right away. This can be used to provide more accurate and safer food distribution systems than the currently used system, in which an expiration date is set by the manufacturer. The electronic tongue based nanosensor can also detect chemicals at a ppt (parts per trillion) level (Choi et al., 2007).

Purdue/Clemson University is presently studying a nanosensor developed by using fluorescent or magnetic nanoparticles with various colors. They found that it is possible to selectively attach nanoparticles to pathogens and small footprints of harmful pathogens can be detected using a portable sensor that adopts infrared light or magnetic material. The advantage of this system is that it quickly and accurately detects multiple bacteria and pathogens because hundreds or thousands of nanoparticles are contained in a single nanosensor (Cientifica, 2008).

EU researchers in the Good Food Project have crafted a portable nanosensor to detect chemicals, pathogens, and toxins in food. This sensor allows food to be analyzed for safety and quality at the farm or abattoir during transport, processing or at the packaging plant. The project is also developing a device using DNA biochips to identify pathogens. This technique can also be applied to determine the presence of different kinds of harmful bacteria in meat or fish, or fungi affecting fruit. Moreover, it can be used to detect the presence of pesticides on fruit and vegetables. The project also has plans to develop microarray sensors ("Good Food sensors") that can be used to monitor environmental conditions at the farm (Joseph & Morrison, 2006).

AgroMicron, an Australian company, has developed the NanoBioluminescence Detection Spray, which contains a luminescent protein that has been engineered to bind to the surface of microbes such as *Salmonella* and *E. coli.* The product, which will be marketed under the name BioMark, emits a visible glow when bound, thus allowing easy detection of contaminated food or beverages. The more the intense the glow is, the higher the bacterial contamination (Joseph & Morrison, 2006).

RFID (Radio Frequency Identification) technology was developed by the military more than 50 years ago, but has now found its way into numerous applications from food monitoring in stores to improving supply chain efficiency. The technology, which consists of microprocessors and an antenna that can transmit data to a wireless receiver, can be used to monitor an item from the warehouse to the consumer's hands. Unlike bar codes, which need to be scanned manually and read individually, Philips Semiconductors Co has made an RFID that is capable of reading hundreds of tags a second using nanotechnology. Retail chains like Wal-Mart, Home Depot, the Metro group, and Tesco have already tested this technology. Current RFID tags have become much smaller than previous RFID tags and can be printed on thin labels. The main drawback of this new technology is the increased production costs due to silicon manufacturing. With the fusion of nanotechnology and electronics, these tags should in the future become more economical, easier to implement and more efficient (Robinson & Morrison, 2009; Joseph & Morrison, 2006).

Strathclyde University (UK) is currently developing what is dubbed 'smart ink,' a product that consists of light absorption titanium dioxide (TiO_2) nanoparticles, to detect the presence of oxygen. When ink is exposed to UV light, its color will selectively change in response to oxygen. When activating the printed labels with the ink using UV just before shipping, the label becomes oxygen-sensitive. If the package is damaged or if air enters it, the color of the label changes. Nano-sized titanium dioxide is a semiconductor that makes electron-hole pairs, which performs chemical reactions by absorbing UV energy and delivering it to the particle surface. This technology can record what is occurring in the food, and secure food safety if the time-temperature ink combines with other bacteria detecting sensors (Cientifica, 2008).

Use of Antibacterial Nanoparticles

Unlike packaging materials that are designed to release chemicals in response to microbial growth, moisture, or other changes, the packaging material itself contains antibacterial nanoparticles. Nanoparticles are general used as antibacterial packaging materials. They can be made of nano zinc oxide or nano chlorine dioxide. Magnesium oxide, copper oxide, titanium dioxide nanoparticles and a carbon nano tube are also expected to be used for food packaging in the future. They can be applied in accordance with food properties and strength of the packaging material (Kim, 2008; Robinson & Morrison, 2009).

Sharper Image, a US company, has created a food storage container called FresherLonger,™ which is made with antibacterial silver nanoparticles. FresherLonger containers keep fruit, vegetables, cheese, bread, and soup fresher up to four times longer than conventional containers. In the self-test, harmful bacteria, which typically grows within 24 hours, was reduced by 98%. Dokdo Co. (Korean company) has also developed a food storage container using silver nanoparticles. They report that their container displayed a 99% antibacterial effect and blocked harmful bacteria through a magnetic field and electromagnetic waves. The containers are considered 'high-strength' because they are not easily broken (even by a vehicle). In addition, SongSing Nano Technology Co. (Taiwan) has developed a nano plastic wrap using nano zinc oxide (ZnO), which blocks UV and infrared light and has excellent antibacterial effects. This nano plastic wrap can protect food effectively, even against fire, since it protects against high temperatures and is thus not easily burned or broken (Pazour, 2009; Dokdo, 2008).

DuPont Co. has released a titanium dioxide nanoparticle product called Light Stabilizer 210. When producing a container using this nanoparticle, UV light is blocked successfully so that shelf life can be prolonged. On the other hand, Rohm and Haas Co. has released an acrylic nanoparticle product called Paraloid BPM-500, which has great durability against lactic acid and is biodegradable by microbes. (Robinson & Morrison, 2009).

JR Nanotech (UK) produces nanosilver, in which the antibacterial material (silver nanoparticle) is coated with packaging materials. Nanosilver can be simply added to macromolecules or fluids. Furthermore, it can be widely used by the food industry, including in the work environment (ventilating filters, antibacterial paint, and floor mats), devices (knives, sprays, and wipes), by industrial workers (protective clothes, hair covers, and socks), and in food packaging (ready meal trays, food storage containers, and wraps) (Cientifica, 2008).

The University of Leeds in the UK has recently announced that nanoparticles made of magnesium oxide and zinc oxide are highly effective at destroying microorganisms. Since these would be much less expensive to manufacture than silver nanoparticles, this product could have tremendous applications in food packaging (Chaudhry et al., 2008).

Researchers at the University of Bonn in Germany are presently developing dirt repellent coatings for packages using the lotus effect. Abattoirs and meat processing plants in particular could benefit from such technology (Cientifica, 2008).

Nanoclay – Plastic Composites

Clay consists of multiple layers of complex metallic ores. Due to its relative abundance and low cost, clay has been generally used as a material in food storage containers. However, an understanding of the nanoparticles in clay and its ability to disperse ultra-fine layers within other materials has led to the production of lightweight, nanoclay polymers that would usually only be found in glass or expensive metals in the past. The generation of nanoclay composites is dependent on the separation of ultra-fine layers, a process known as exfoliation. These nanoclay composites can physically block liquid or gases that are different from air. Exfoliated clay (MMT, montmorillonite) nanoparticles are one of the most widely used nanoclay composites. Nanoclay used for plastic composites has very tiny irregular platelets with thicknesses of 1 nm and diameters of 100 nm. When these clay platelets are added to plastic, they effectively reduce oxygen flow speed so that they can dramatically reduce the ingress of oxygen to food packaging materials. Such nanoclay composites are mainly used for liquor bottles and films, which are sensitive to the ingress of oxygen. In addition, the use of nano clay as a material that can coat other materials, such as cardboard and metal, is currently being investigated (Robinson & Morrison, 2009).

Honeywell (US) has developed 3 grades of nanoclays/nylon 6 resins (Aegis OX, HFX, and CSD). The resin "Aegis OX" is comprised of nylon composites that remove oxygen and responds to the oxygen barrier. It was initially created for use in fabricating better beer bottles. Nanoclays work as a passive barrier, while nylons operate as an active oxygen scavenger. Aegis OX offers a high oxygen barrier, easy processing, excellent delamination resistance, and clarity. Because it is specially mixed for superb oxygen protection in conjunction with superior delamination performances in hot-fill bottles, Aegis HFX has been used to increase oxygen delamination resistance in food. Ageis CDS provides delamination resistance and offers passive high carbon dioxide retention compared with the single layer PET used for carbonated soft drinks. In a plastic beer bottle, nano crystals mixed with nanocomposites are made using this material and a molecular barrier, which plays a key role in blocking oxygen release, is formed, thereby prolonging the shelf life of beer up to 26 weeks. This has been used since late 2003 in the 1.6-liter Hite Pitcher beer bottle from Hite Brewery Co. in South Korea (Robinson & Morrison, 2009; Pazour, 2009).

In association with Mitsubishi Gas Chemical Company Inc., Nanocor (US) has developed barrier PET bottles and films called "M9," which mixes nanoclay additives with Mitsubishi's MXD6 nylon. MXD6 is excellent as a barrier against harmful gases in food and beverages and is easy to process and allows for packaging with high clarity. Thus, it is superior to other barrier plastics. M9 increases standard MXD6's CO_2 and O_2 barriers to 50% and 75%, respectively, and has the same level of high clarity and delamination resistance as MXD6. It is currently used as a core material in 3-layer, 16 ounce unsterilized PET beer bottles (Maul, 2005; Cientifica, 2008).

Bayer, a German company, is currently developing nylon 6 nanocomposites, known as a hybrid system, using clays from Nanocor. The strength of these nanocomposites has increased two times, and the level of its gloss and clarity is similar to the level of expensive polyamide films, which have an optimal clarity. This new film, which contains nanoparticles, massively reduces the entrance of gases and the exit of moisture, thereby combining the advantage of EVOH and polyamide 6. Bayer's Durethan KU 2-2601 is an ideal material for paperboard plastic coatings, which can protect oxygen sensitive contents (e.g. orange juice) at a low cost (Joseph & Morrison, 2006).

In association with Nanocor, Inc, Voridan (US, a subsidiary of Eastman Chemical) has developed nanocomposites containing clay nanoparticles called Imperm. When this nanocomposite is used, the resulting bottle is both lighter and stronger than glass, and is less likely to shatter. The structure of the nanocomposite minimizes loss of carbon dioxide from beer and ingress of oxygen to the bottle, keeping the beer fresher and giving it a shelf life of up to six-months. The technology has been adopted by several companies, including the Miller Brewing Co. (Joseph & Morrison, 2006; Robinson & Morrison, 2009).

Conclusion

Here, we reviewed typical R&D trends and current examples for nano food processing and nano food packaging applications in three areas of nanofood. Since there is a wide range of potential applications of nanotechnology for food, there might be more applications that were not mentioned in this review. However, this review does provide a concise overview of the current trends of nanotechnology in the food industry.

Several countries, including the US, Japan, and the EU, are studying and investing extensively nanotechnology with the hope that it will emerge as the next generation of core technology. The investment for research and development is drastically increasing every year. Studies on nanotechnology in the food industry are one of the most active areas of research, in that it addresses many basic human needs. Around the globe, numerous companies and research institutions are expanding into this area in order to dominate the nanofood market.

Nanofood includes not only food made with simple materials or food processing but also food made with complex materials and involves the cultivation and manufacturing of agricultural products, processing, packaging, and distribution. Nanofood has the potential to become a novel area of production. It also presents an excellent opportunity that offers great advantages to agricultural engineers. However, further studies will be required for the development of eco-friendly pesticides and sustainable production, processing, and distribution using nanotechnology.

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