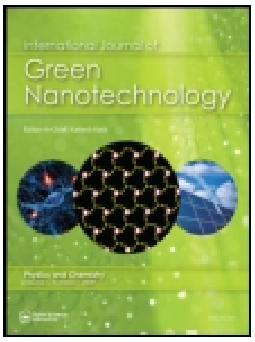

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R. Ravichandran

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R. Ravichandran

ABSTRACT. Nanoscience and nanotechnology are new frontiers of this century and food nanotechnology is an emerging technology. Their applications to the agriculture and food sector are relatively recent compared with their use in drug delivery and pharmaceuticals. Many scientists and engineers have recognized well the potential of nanotechnology to lead all the food industries in the 21st century. Even though successful applications of nanotechnology to foods are still limited, some basic concepts based on nanoscale have been established well. In food engineering field, two major applications related to nanotechnology, that is, food nanosensing and food nanostructured ingredients are being expected. In the former field, better food quality and safety evaluation can be achieved by using nanotechnology. Advances in technologies, such as DNA microarrays, microelectromechanical systems, and microfluidics, will enable the realization of the potential of nanotechnology for food applications. In the latter, food processing can be largely improved in the aspects of smart delivery of nutrients, bioseparation of proteins, rapid sampling of biological and chemical contaminants, nanoencapsulation of nutraceuticals, solubilization, delivery, and color in food systems; these being some of the emerging topics of nanotechnology for food and agriculture. Meanwhile, food nanotechnology as a new technology is requiring reviews of potentially adverse effects as well as many positive effects. In this review, we intended to cover some of the developments in nanotechnology and their applicability to food and nutraceuticals systems. It presents some of the nanoscale-sized structures that are uniquely relevant to the food industry, the different food manufacturing techniques that could benefit from nanotechnology, and nanotechnology's applicability to the formulation and storage of food, together with identifying the outstanding challenges.

KEYWORDS. food, food packaging, food processing, nanotechnology, nanosensors, nutraceuticals

INTRODUCTION

At one billionth of a meter, a nanometer is miniscule—much too small for the human eye to see. And for most humans, anything measuring 100 nm or less may be impossible to comprehend as significant. For this reason, it would seem illogical that structures measuring 1–100 nm would not only exist but would also have implications and applications that could be essential to humankind.[1] Nonetheless, scientists have embarked on a field of science

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R. Ravichandran is affiliated with the Regional Institute of Education (NCERT), Bhopal, India.
Address correspondence to R. Ravichandran, Regional Institute of Education (NCERT), Bhopal 462 013, India. E-mail: ravincert@gmail.com

that could literally fit on a person's fingernail: *nanotechnology*, a derivative of chemistry, engineering, physics, and microfabrication techniques.[2]

Nanoscience and nanotechnology are concerned with the understanding and rational manipulation of materials at the atomic and molecular levels, generally with structures of less than 100 nm in size. Scientifically, nanoscience is defined as the study of phenomena and the manipulation of materials at the atomic, molecular, and macromolecular scales, where the properties differ from those at a larger scale and have unique novel functional applications. Nanotechnology is defined as the design, production, and application of structures, devices, and systems through control of the size and shape of the material at the nanometer (10^{-9} of a meter) scale where unique phenomena enable novel applications.[3]

Nanoscience and nanotechnology have already been applied in various fields, such as computer electronics, communication, energy production, medicine, and the food industry. The nanoscale devices are often manufactured with the view to imitate the nanodevices found in nature and include proteins, DNA, membranes, and other natural biomolecules.[4,5] Nanotechnology based on highly reactive particles of sizes less than 100 nanometer is predicted to be central to developing and using new electronics and energy technologies during the present century.[6] Properties of nanoparticles are not governed by the same physical laws as larger particles but by quantum mechanics. Their physical and chemical properties such as color, solubility, strengths, chemical reactivity, and toxicity can be quite different. Engineered nanoparticles are used in hundreds of commercial products that are marketed today, which include transparent sun screens, light diffracting cosmetics, penetration enhanced moisturizers, stain- and odor-repellent fabrics, dirt-repellent coatings, long-lasting paints and varnishes, and many others. A nanometer (nm)-sized particle measures one billionth of a meter and one can imagine how small it is when a human hair measures 80,000 nm! A DNA strand is 2.5 nm wide whereas a protein chain is 5 nm in diameter.

Because applications with structural features on the nanoscale level have physical, chemical, and biological properties that are substantially different from their macroscopic counterparts, nanotechnology can be beneficial on various levels.[7] Research in biology, chemistry, engineering, and physics drives the development and exploration of the nanotechnology field. Consequently, certain industries such as microelectronics, aerospace, and pharmaceuticals have already begun manufacturing commercial products of nanoscale size. Even though the food industry is just beginning to explore its applications, nanotechnology exhibits great potential.[8] Food undergoes a variety of postharvest and processing-induced modifications that affect its biological and biochemical makeup, so nanotechnology developments in the fields of biology and biochemistry could eventually also influence the food industry.[9] Ideally, systems with structural features in the nanometer length range could affect aspects from food safety to molecular synthesis.[10]

Designing and producing food by shaping molecules and atoms is the future of the food industry worldwide.[11] On the one side, further breakthroughs in crop DNA decoding and analyzing enable the industries to predict, control, and improve the agricultural production. On the other side, with technology of manipulating the molecules and the atoms of food, the future food industry has a powerful method to design food with much more capability and precision, lower costs, and sustainability.[12] Meanwhile, the combination of DNA and nanotechnology research generates the new nutrition delivery system, which brings the active agents more precisely and efficiently to the wanted parts of the human bodies and cells. Functional food will benefit firstly from the new technologies, followed by standard food, nutraceuticals, and others.[13]

Food technology is regarded as one of the industry sectors where nanotechnology will play an important role in the future.[14] It is commonly distinguished between two forms of nanofood applications: food additives (nano inside) and food packaging (nano outside). Nanoscale food additives may for example be used to influence product shelf life, texture, flavor, nutrient composition, or even detect food pathogens and provide functions as food quality indicators. In the context of food packaging, nanotechnologies are mainly considered to be of use to increase product shelf life, indicate spoilt ingredients, or generally increase product quality, e.g., by preventing gas flow across product packaging.[15]

For food applications, nanotechnology can be applied by two different approaches, either "bottom up" or "top down."[1,2] The top-down approach is achieved basically by means of a physical processing of the food materials, such as grinding and milling. For example, dry-milling technology can be used to obtain wheat flour of fine size that has a high water-binding capacity.[16] This technology has been used to improve antioxidant activity in green tea powder.[17] As the powder size of green tea is reduced to 1000 nm by dry milling, the high ratio of nutrient digestion and absorption resulted in an increase in the activity of an oxygen-eliminating enzyme.[17] By contrast, self-assembly and self-organization are concepts derived from biology that have inspired a bottom-up food nanotechnology. The organization of casein micelles or starch and the folding of globular proteins and protein aggregates are examples of self-assembly structures that create stable entities. Self-organization on the nanometer scale can be achieved by setting a balance between the different noncovalent forces.[18]

The electron microscope and, more recently, the development of tools such as probe microscopes have provided unparalleled opportunities for understanding heterogeneous food structure at the submolecular level.[19] This has provided new solutions to previously intractable problems in food science and offers new approaches to the rational selection of raw materials, or the processing of such materials to enhance the quality of food products. This ability to use nanoscience to improve the quality of materials through understanding and refining their nanoscale structures is an example of a form of nanotechnology that has been called incremental nanotechnology.[20] When the reduction in size of structures leads to step changes in properties that provide radical new solutions to problems and new commercial opportunities, these types of applications are considered to be examples of what has been termed evolutionary nanotechnology.[20]

The prospect of the use of products of evolutionary nanotechnology in the food area is the area that has engendered most debate. The concern is that if changing the size of materials can lead to radical, albeit useful, properties, can we be sure how size will affect other properties and, in particular, the potential toxicity of such materials?[21] Although the products of nanotechnology intended for food consumption are likely to be classified as novel products and require testing and clearance, there are concerns, particularly in the area of food contact materials, that there could be inadvertent release and ingestion of nanoparticles of undetermined toxicity.[22] Such concerns need to be addressed because the ultimate success of products based on nanotechnology will depend on consumer acceptance. The recent explosion in the general availability of nanoproducts makes it almost certain that nanotechnology will have both direct and indirect impacts on the food industry.

OPPORTUNITIES

The nanoscale is not new to the food and beverage sector, with various phenomena already witnessed and exploited in nutraceutical and functional food formulation, manufacturing, and processing.[23] Colloid science, for example, has been applied to food materials for a long time. An array of food and beverages contain components that are nanoscale in size and in processing (dairy for example), the manipulation of naturally occurring nanoparticles is involved. However, it is only recently that novel applications have come under investigation for new functionalities and efficient delivery mechanisms for food and beverages.[24] New tools and processes are allowing researchers greater understanding of areas such as the mechanisms of targeted delivery that will potentially lead to smart delivery for both optimization of human health and novel physical, visual, and sensory effects.[25] Potential applications include food that can alter its color, flavor, or nutrients to suit each consumer's preference or health requirements; filters that can take out toxins or modify flavors by sifting through certain molecules based on their shape instead of size; and packaging that can detect when its contents are spoiling, and change color to warn consumers.[26] The understanding of food materials and food processing at the nanoscale is important in order to create new and improved food products.

How about a butter with low fat but tasting and feeling like natural butter? Nanotechnology bluffs believe it is possible in future using this powerful technique. Similarly one can make milk taste like cola beverage so that youngsters will have less inhibition in consuming nutritious milk. Foods can be enriched with fruits and vegetables through nanotechnology to deliver higher nutrient density in such foods. Nanoscale food components can be encapsulated and mixed with other foods in novel combinations.[27] This technology is also seems to be useful in dissolving additives, such as vitamins, minerals, antioxidants, phytochemicals, nutritious oils, that are not normally soluble. Nanoparticles can make many products clear that otherwise are opaque or translucent.[28] Nanoadhesive properties can bind to harmful matters in the gastrointestinal (GI) tract and remove them without any harm. Pure silver colloid liquid, reduced to 1 nm size with atomic particles, is highly bactericidal, capable of achieving 99.9% kill against 650 species of microorganisms within 6 min, whereas a normal antibiotic is effective only against 5–6 species. There are containers being offered with coatings of nanosilver particles that can be used for storage of foods safely without spoilage. Use of nanotechnology as a sensor to detect food spoilage within a packet of processed food is fraught with great significance in our fight against pathogenic microorganisms.[29]

Promising applications combining nanotechnologies and food are also expected to result from new encapsulation technologies. Such nanoencapsulation systems can be used to add additional nutrients without changing a product's flavor or quality.[30] This might enable producers to integrate nutrients that are not naturally occurring, or that so far could not be integrated due to reasons of chemistry. The advantages of such encapsulation systems also encompass extended shelf life, protection of the encapsulated ingredients from the surrounding medium and undesired interaction during food processing, as well as delivery of certain contents to a specific target site within the body.[31] Although such opportunities appear to be very promising at a first glance, they may also bring new risks into play.

The natural tendency for food biopolymers to self-assemble into larger structures can be used to fabricate coatings, barriers, and interfacial structures with controlled properties. Nanocomposites are already available as packaging or in coatings on plastic bottles to control gas diffusion and prolong the lifetime of various products. Nanotechnology is already being used worldwide to produce antimicrobial food contact materials commercially available as packaging, or as coatings on an ever-increasing number of products such as food containers, chopping boards, and refrigerators.[32] There is currently research on 'smart' surfaces that could, for example, detect bacterial contamination and react to combat infection. Although many of these materials contain nanoparticles, they are generally regarded as safe, provided their use does not lead to the release and ingestion of these particles.[33] Concern has been expressed over the long-term fate and disposal of these materials, which might then lead to release of nanoparticles into the environment. These types of concerns have led to debate on the labeling, approval, traceability, and regulation of these materials.[34]

Potential application areas include[35]:

- Organic nanoadditives
- Inorganic nanoadditives
- Food with nanoparticles
- Nanosensors for food quality control and smart packaging
- Nanocoating and nanofilms for kitchenware and foodstuffs

- Antimicrobial, hygiene coatings
- Detection of pathogens in food and beverages
- Self-sanitizing surfaces
- Polymeric films for food packaging with high antibacterial properties
- Nanoscale freshness indicators
- Nanoemulsions for fat reduction

POTENTIAL FOOD APPLICATIONS

All organisms represent a consolidation of various nanoscale-sized objects. Atoms and molecules combine to form dynamic structures and systems that are the building blocks of every organism's existence. For humans, cell membranes, hormones, and DNA are examples of vital structures that measure in the nanometer range. In fact, every living organism on earth exists because of the presence and interaction of various nanostructures.[36] Even food molecules such as carbohydrates, proteins, and fats are the results of nanoscale-level mergers between sugars, amino acids, and fatty acids.[37]

As it applies to the food industry, nanotechnology involves using biological molecules such as sugars or proteins as target-recognition groups for nanostructures that could be used, for example, as biosensors on foods.[38] Such biosensors could serve as detectors of food pathogens and other contaminants and as devices to track food products. Nanotechnology may also be useful in encapsulation systems for protection against environmental factors. In addition, it can be used in the design of food ingredients such as flavors and antioxidants.[39] The goal is to improve the functionality of such ingredients while minimizing their concentration. As the infusion of novel ingredients into foods gains popularity,[40] greater exploration of delivery and controlled-release systems for nutraceuticals will occur.[41]

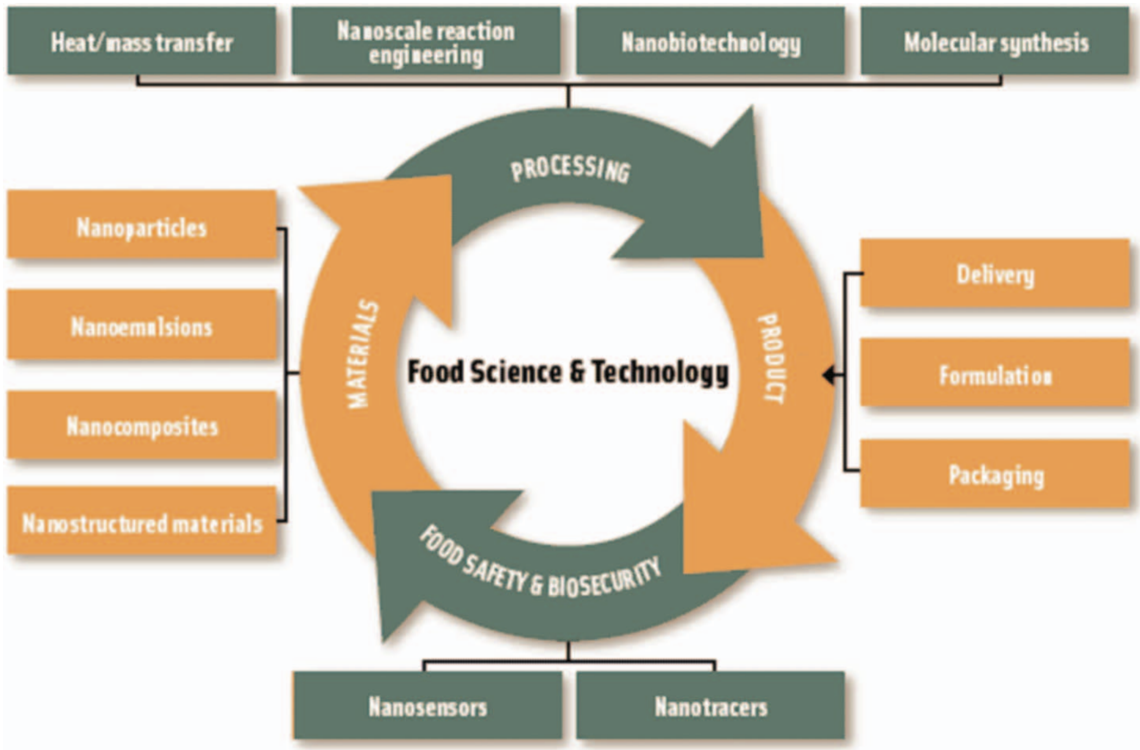
Although nanotechnology can potentially be useful in all areas of food production and processing, many of the methods are either too expensive or too impractical to implement on a commercial scale. For this reason, nanoscale techniques are most cost-effective in the following areas of the food industry: development of new functional materials, food formulations, food processing at microscale and nanoscale levels, product development, and storage.[42] This article mainly focuses on the nanoscale applications within these areas that have a greater chance of commercial viability now and in the near future. The spectrum of nanotechnology applications in food science and technology is given in Figure 1.

Owing to the greater surface area of nanoparticles per mass unit, they are expected to be more biologically active than larger-sized particles of the same chemical composition. This offers several perspectives for food applications. Nanoparticles can, for instance, be used as bioactive compounds in functional foods.[43] Bioactive compounds that can be found naturally in certain foods have physiological benefits and might help to reduce the risk of certain diseases, including cancer. By reducing particle size, nanotechnology can contribute to improve the properties of bioactive compounds, such as delivery properties, solubility, prolonged residence time in the gastrointestinal tract, and efficient absorption through cells.[44] Omega-3 and omega-6 fatty acids, probiotics, prebiotics, vitamins, and minerals have found their applications in food nanotechnology as bioactive compounds.[45] In the food industry, several novel applications of nanotechnologies have become apparent, including the use of nanoparticles, such as micelles, liposomes, nanoemulsions, biopolymeric nanoparticles, and cubosomes, as well as the development of nanosensors, which are aimed at ensuring food safety.[46–49]

Nanodispersions and Nanocapsules

As the fundamental components of foods, functional ingredients such as vitamins, antimicrobials, antioxidants, flavorings, and preservatives come in various molecular and physical forms. Because they are rarely used in their purest form, functional ingredients are usually part of a delivery system. A delivery system has numerous functions, only one of which is to transport a functional ingredient to its desired site. Besides being compatible with food product attributes such as taste, texture, and shelf life,

FIGURE 1. Nanotechnology applications in food science and technology.



other functions of a delivery system include protecting an ingredient from chemical or biological degradation, such as oxidation, and controlling the functional ingredient's rate of release under specific environmental conditions. Because they can effectively perform all these tasks, nanodispersions and nanocapsules are ideal mechanisms for delivery of functional ingredients. These types of nanostructures include association colloids, nanoemulsions, and biopolymeric nanoparticles.

Association Colloids

Surfactant micelles, vesicles, bilayers, reverse micelles, and liquid crystals are all examples of association colloids. A *colloid* is a stable system of a substance containing small particles dispersed throughout. An *association colloid* is a colloid whose particles are made up of even smaller molecules. Used for many years to deliver polar, nonpolar, and amphiphilic functional ingredients,[50–53] association colloids range in size from 5 to 100 nm and are usually transparent solutions. The major disadvantages to association colloids are that they may compromise the flavor of the ingredients and can spontaneously dissociate if diluted.

Nanoemulsions

An *emulsion* is a mixture of two or more liquids (such as oil and water) that do not easily combine. Therefore, a nanoemulsion is an emulsion in which the diameters of the dispersed droplets measure 500 nm or less. Nanoemulsions can encapsulate functional ingredients within their droplets, which can facilitate a reduction in chemical degradation.[54] In fact, different types of nanoemulsions with more complex properties—such as nanostructured multiple emulsions or nanostructured multilayer emulsions—offer multiple encapsulating abilities from a single delivery system that can carry several functional components. In structures such as these, a functional component encased within one component of a multiple emulsion system could be released in response to a specific environmental trigger.

Biopolymeric Nanoparticles

Food-grade biopolymers such as proteins or polysaccharides can be used to produce nanometer-sized particles.[55–57] Using aggregative (net attraction) or segregative (net repulsion) interactions, a single biopolymer separates into smaller nanoparticles. The nanoparticles can then be used to encapsulate functional ingredients and release them in response to distinct environmental triggers. One of the most common components of many biodegradable biopolymeric nanoparticles is polylactic acid (PLA). Widely available from a number of manufacturers, PLA is often used to encapsulate and deliver drugs, vaccines, and proteins, but it has limitations: it is quickly removed from the bloodstream, remaining isolated in the liver and kidneys. Because its purpose as a nanoparticleis to deliver active components to other areas of the body, PLA needs an associative compound such as polyethylene glycol to be successful in this regard.[58]

Nanolaminates

Besides nanodispersions and nanocapsules, another nanoscale technique is commercially viable for the food industry: nanolaminates. Consisting of two or more layers of material with nanometer dimensions, a nanolaminate is an extremely thin food-grade film (1–100 nm/layer) that has physically bonded or chemically bonded dimensions.

Because of its advantages in the preparation of edible films, a nanolaminate has a number of important food industry applications. Edible films are present on a wide variety of foods: fruits, vegetables, meats, chocolate, candies, baked goods, and French fries.[59–62] Such films protect foods from moisture, lipids, and gases, or they can improve the textural properties of foods and serve as carriers of colors, flavors, antioxidants, nutrients, and antimicrobials.

Currently, edible nanolaminates are constructed from polysaccharides, proteins, and lipids. Although polysaccharide- and protein-based films are good barriers against oxygen and carbon dioxide, they are poor at protecting against moisture. On the other hand, lipid-based nanolaminates are good at protecting food from moisture, but they offer limited resistance to gases and have poor mechanical strength.[63] Because not polysaccharides, proteins, or lipids can provide all of the desired properties in an edible coating, researchers are trying to identify additives that can improve them, such as polyols. For now, coating foods with nanolaminates involves either dipping them into a series of solutions containing substances that would adsorb to a food's surface or spraying substances onto the food surface.[64]

While there are various methods that can cause adsorption, it is commonly a result of an electrostatic attraction between substances that have opposite charges. The degree of a substance's adsorption depends on the nature of the food's surface as well as the nature of the adsorbing substance. Different adsorbing substances can constitute different layers of a nanolaminate; examples are polyelectrolytes (proteins and polysaccharides), charged lipids, and colloidal particles. Consequently, different nanolaminates could include various functional agents such as antimicrobials, anti-browning agents, antioxidants, enzymes, flavors, and colors.

Nanofibers and Nanotubes

Two applications of nanotechnology that are in the early stages of having an impact on the food industry are nanofibers and nanotubes. Because nanofibers are usually not composed of food-grade substances, nanofibers have only a few potential applications in the food industry.

Produced by a manufacturing technique using electrostatic force, nanofibers have small diameters ranging in size from 10 to 1000 nm, which makes them ideal for serving as a platform for bacterial cultures. In addition, nanofibers could also serve as the structural matrix for artificial foods and environmentally friendly food-packaging material. As advances continue in the area of producing nanofibers from food-grade materials, their use will likely increase.

As with nanofibers, the use of nanotubes has predominantly been for nonfood applications.

Carbon nanotubes are popularly used as low-resistance conductors and catalytic reaction vessels. Under appropriate environmental conditions, however, certain globular milk proteins can self-assemble into similarly structured nanotubes.[65–68]

Nanostructures in Food

Food proteins are often globular structures 1–10 nm in size. Most polysaccharides (carbohydrates) and lipids (fats) are linear polymers with thicknesses less than nanometers, the functionality of many raw materials and the successful processing of foods arise from the presence, modification, and generation of forms of self-assembled nanostructures.[69] Examples include the planer assemblies of cellulose fibrils in plant cell walls, the crystalline structures in starch, and processed starch-based foods that determine gelatinization and influence the nutritional benefits during digestion, the fibrous structures that control the melting, setting, and texture of gels, and the two-dimensional (2D) nanostructure formed at oil-water and air-water interfaces that control the stability of food foams and emulsions.[70]

Understanding the nature of nanostructures in foods allows for better selection of raw materials and enhanced food quality through processing. Techniques such as electron microscopy and the newer probe microscopies, such as atomic force microscopy (AFM), have begun to reveal the nature of these structures, allowing rational selection, modification and processing of raw materials.[71]

For example, the creation of foams (e.g., the head on a glass of beer) or emulsions (e.g., sauces, creams, yoghurts, butter, margarine) involves generating gas bubbles, or droplets of fat or oil, in a liquid medium. This requires the production of an air-water or oil-water interface and the molecules present at this interface determine its stability. These structures are one molecule thick and are examples of 2D nanostructures. A source of instability in most foods is the presence of mixtures of proteins and other small molecules such as surfactants (soap-like molecules or lipids) at the interface.[72] AFM has allowed these interactions to be visualized and understood and has led to generic strategies for improving the stability of the protein networks that can be applied widely in the baking, brewing, and dairy industries. This form of incremental nanotechnology is likely to lead to continued improvement in food quality, but is unlikely to require modifications to food regulation or labeling. Novel raw materials with new molecular structures and properties, identified through nanoscience, would require clearance for use in foods.

Nanoparticles in Foods

Up to now, most of the research on nanotechnology focused on the electronics, medicine, and automation sector. The knowledge gained from these sectors could be adapted for the use of food and agriculture products, such as for applications in food safety (e.g., detecting pesticides and microorganisms), in environmental protection (e.g., water purification), and in delivery of nutrients ("Conventional and Nano-Based Water Technologies," available at http://www.merid.org/nano/waterpaper/).[43,73–75] The area that has led to most debate on nanotechnology and food is the incidental or deliberate introduction of manufactured nanoparticles into food materials. This debate largely concerns the risk and benefits, given the lack of knowledge on the potential bioaccumulation and possible toxicity of nanoparticles. The report on 'Nanofoods' from the Helmut Kaiser Consultancy (2004) estimates an increasing growth in the development of food-related nanoproducts and patent applications.[76]

Food Contact Materials

Various additives or ingredients are approved for use in food contact materials. The types of materials approved and the regulations on their use will vary for different countries. If the materials do not partition into foods, then there should be little concern over the safety of their use in food contact applications. Should some degree of partitioning occur, then the limitations on their use are based on an acceptable daily uptake (ADI) for these additives or ingredients. The inclusion of nanoparticles in food contact materials can be used to generate novel types of packaging materials and containers. Nanoparticles of pigments such as TiO_2 become transparent but retain their ultraviolet (UV) absorption characteristics. This suggests applications in transparent wraps, films, or plastic containers where absorption of UV radiation needs to be avoided. Layered composites containing nanoparticles (such as nanoclays) are being used to generate long path lengths through materials to reduce gas diffusion and prolong the shelf life of products. At present, any regulation of the use of additives or ingredients does not appear to take into account the size of the material and how this could affect ADI values. Thus, technically, it may be possible for a supplier to sell nanoparticles of food-approved ingredients or additives as approved for use in food contact applications.[77] Ultimately, however, there must be an obligation that the final products that use these food contact materials are safe.

Foods

Worldwide commercial foods and food supplements containing added nanoparticles are becoming available. A major growth area appears to be the development of "nanoceuticals" and food supplements.[78] The general approach is to develop nanosized carriers or nanosized materials, in order to improve the absorption and, hence, potentially the bioavailability of added materials such as vitamins, phytochemicals, nutrients, or minerals. The materials can be incorporated into solid foods, delivered as liquids in drinks, or even sprayed directly on to mucosal surfaces. The important issues are whether the carriers and the encapsulated products are normally absorbed, digested, and metabolized. If they are, then the interest is in whether the absorption and metabolism remains the same for the nanoform of the material, and whether there could be new issues related to enhanced levels of absorption: the aim of encapsulation will be to optimize rather than just increase bioavailability. There are added concerns for materials such as minerals that are normally largely excreted: will the nanoform lead to enhanced bioaccumulation, reduced excretion, and thus a need to establish new ADIs for these materials in the nanoform?

The number of food-related nanoproducts is increasing rapidly, and examples include

- nanoparticles of carotenoids that can be dispersed in water, allowing them to be added to fruit drinks providing improved bioavailability;
- a synthetic lycopene has been affirmed GRAS ("generally recognized as safe") under US Food and Drug Administration (FDA) procedures;
- nanosized micellar systems containing canola oil that are claimed to provide delivery systems for a range of materials such as vitamins, minerals, or phytochemicals;
- a wide range of nanoceutical products containing nanocages or nanoclusters that act as delivery vehicles, e.g., a chocolate drink claimed to be sufficiently sweet without added sugar or sweeteners;
- nano-based mineral supplements, e.g., a Chinese nanotea claimed to improve selenium uptake by one order of magnitude;
- patented "nanodrop" delivery systems, designed to administer encapsulated materials, such as vitamins, transmucosally, rather than through conventional delivery systems such as pills, liquids, or capsules; and
- an increasingly large number of mineral supplements such as nanosilver or nanogold.

Indirect Food Applications of Nanotechnology

Computing and Communications

Silicon chips have been made by nanotechnology for over 20 years, and have led to advances in electronics, computing, and communications. Continued incremental advances in these areas and the growing sophistication of communication devices will continue to influence the way consumers shop. New types of labeling, possibly based on polymer light-emitting diodes, offer new ways to store, display, and interrogate information on packaging. This will allow individuals to access more information about the source, history, and storage of specific foods, their nutritional characteristics, and their suitability to their genetic makeup and lifestyle.

Material Science

Techniques such as microfluidics and, in the future, nanofluidics will allow small factories or laboratories to be constructed on chips. Coupled with the ability to interrogate increasingly sophisticated databases, such advances should enhance authentication, and improve the safety of foods.

Nanosensors

In addition, food preservation is also of great importance for the food industry. Food spoilages can be detected with so-called nanosensors, for example, an array of thousands of nanoparticles designed to fluoresce in different colors on contact with food pathogens. Taking into account the crucial importance of time in food microbiology, the main aim of nanosensors is to reduce the time for pathogen detection from days to hours or even minutes.[79] Such nanosensors could be placed directly into the packaging material, where they would serve as "electronic tongue" or "noses" by detecting chemicals released during food spoilage.[80,81] Other types of nanosensors are based on microfluidics devices[82] and can also be used to detect pathogens efficiently in real time and with high sensitivity. A major advantage of microfluidic sensors is their miniature format and their ability to detect compounds of interest rapidly in only microliters of required sample volumes, which has already led to widespread applications in medical, biological, and chemical analysis.[83,84]

Silicon-based microfluidic systems have proven popular in the so-called laboratory-on-a-chip technology.[85] Recently, Bodor et al. have used several food additives, including benzoate, sorbate, *p*-hydroxybenzoic acid esters, and glutamate, to evaluate the performance of different types of electrophoresis methods within a chip setup and found that, for different additives, different detection methods proved to be optimal.[86] In the food-analysis market, devices produced with the so-called nanoelectromechanical system (NEMS) technology are already in use and these systems contain moving parts ranging from nano- to millimeter scale, which might serve as developing tools in food preservation. They can control the storage environment and act as active "sell by" devices. A digital transform spectrometer (DTS) produced by Polychromix (Wilmington, MA, USA) uses NEMS systems technology to detect trans-fat content in foods.[87] NEMS could be used in food quality-control devices because they consist of advanced transducers for specific detection of chemical and biochemical signals. The use of so-called micro- and nanotechnologies (MNTs) have several advantages for food technology, such as portable instrumentation with quick response, low costs, and smart communication through various frequency levels. In the area of food safety and quality, MNTs are particularly suitable because they are able to detect and monitor any adulteration in packaging and storage conditions.[88]

Nanocantilevers are another innovative class of biosensors. Their detection principle is based on their ability to detect biological-binding interactions, such as between antigen and antibody, enzyme and substrate or cofactor, and receptor and ligand, through physical and/or electromechanical signaling.[89] They consist of tiny pieces of silicon-based materials that have the capability of recognizing proteins and detecting pathogenic bacteria and viruses.[90] Nanocantilever devices have already had tremendous success in studies of molecular interactions and in the detection of contaminant chemicals, toxins, and antibiotic residues in food products.[91] Pathogen detection is based on their ability to vibrate at various frequencies in dependence on the biomass of the pathogenic organisms. A European Union–funded project called Bio-Finger developed a nanocantilever device that could be used for the diagnosis of cancer and to detect pathogens in food and water based on the sensing of ligand–receptor interactions.[92] The silicon surface of nanocantilevers can be modified to attach antibodies, resulting in a change of the resonant frequency depending on the attached mass. Gfeller et al. were able to detect *Escherichia coli*, which is an indicator of fecal pollution of water and food products, with the help of acantilever coated with agarose.[93]

Food Packaging

Novel food packaging technology is by far the most promising benefit of nanotechnology in the food industry in the near future. Companies are already producing packaging materials based on nanotechnology that are extending the life of food and drinks and improving food safety. Food packaging and monitoring are a major focus of food industry–related nanotechology research and development (R&D).[94]

While the nanofood industry struggles with public concerns over safety, the food packaging industry is moving full-speed ahead with nanotechnology products. Leading the way is active or 'smart' packaging that promises to improve food safety and quality and optimizes product shelf life. Numerous companies and universities are developing packaging that would be able to alert if the packaged food becomes contaminated, respond to a change in environmental conditions, and self-repair holes and tears.

Worldwide sales of nanotechnology products to the food and beverage packaging sector increased from US$150 million in 2002 to US$860 million in 2004 and are expected to reach to US$20.4 billion by 2010.[95] However, despite the increased marketing efforts in the nanotechnology sector, research into nanotechnology of food and food-related products is only just beginning to develop.[43] Some examples of the use of nanotechnology in food products are cooking oils that contain nutraceuticals within nanocapsules, nanoencapsulated flavor enhancers, and nanoparticles that have the ability to selectively bind and remove chemicals from food ("Nanotechnology in agriculture and food," available at http://www.nanoforum.org). The main reasons for the late incorporation of food into the nanotechnology sector are issues associated with the possible labeling of the food products and consumer-health aspects.

Smart Packaging and Active Packaging

One of the most promising innovations in smart packaging is the use of nanotechnology to develop antimicrobial packaging. Packaging that incorporates nanomaterials can be "smart," which means that it can respond to environmental conditions or repair itself or alert a consumer to contamination and/or the presence of pathogens.[96] Scientists at big name companies including Kraft, Bayer, and Kodak, as well as numerous universities and smaller companies, are developing a range of smart packaging materials that will absorb oxygen, detect food pathogens, and alert consumers of spoiled food. These smart packages, which will be able to detect public health pathogens such as *Salmonella* and *E. coli*, are expected to be available within the next few years. According to industry analysts, the current US market for "active, controlled and smart" packaging for foods and beverages is an estimated $38 billion—and will surpass $54 billion by 2015. The following examples illustrate nanoscale applications for food and beverage packaging.

Similar technology is being developed for the US Government as a means of detecting possible terrorist attacks on the US food supply. Scientists in The Netherlands are taking smart packaging a step further with nanopackaging that will not only be able to sense when food is beginning to spoil, but will release a preservative to extend the life of that food. Because of their ability to improve safety and extend the life of food, these nanopackaging solutions are some of the most exciting innovations in the food industry today. However, other less dramatic (but far more practical) developments in nanopackaging are already in use around the world.[96–98]

Using Clay Nanoparticles to Improve Plastic Packaging for Food Products

Chemical giant Bayer produces a transparent plastic film (called Durethan) containing nanoparticles of clay. The nanoparticles are dispersed throughout the plastic and are able to block oxygen, carbon dioxide, and moisture from reaching fresh meats or other foods. The nanoclay also makes the plastic lighter, stronger, and more heat-resistant. Clay nanocomposites are being used in plastic bottles to extend the shelf life of beer and make plastic bottles nearly shatter proof. Embedded nanocrystals in plastic create a molecular barrier that helps prevent the escape of oxygen. The technology currently keeps beer fresh for 6 months, but developers at several companies are already working on a bottle that will extend shelf life to 18 months. Several large beer makers, including South Korea's Hite Brewery and Miller Brewing Company, are already using the technology.

How Creating a Molecular Barrier by Embedding Nanocrystals in Plastic Can Improve Packaging

Until recently, industry's quest to package beer in plastic bottles (for cheaper transport) was unsuccessful because of spoilage and flavor problems. Today, Nanocor, a subsidiary of Amcol International Corp., is producing nanocomposites for use in plastic beer bottles that give the brew a 6-month shelf life. By embedding nanocrystals in plastic, researchers have created a molecular barrier that helps prevent the escape of oxygen. Nanocor and Southern Clay Products are now working on a plastic beer bottle that may increase shelf life to 18 months.

Using Nanotechnology Methods to Develop Antimicrobial Packaging and "Active Packaging"

Kodak, best known for producing camera film, is using nanotechology to develop antimicrobial packaging for food products that will be commercially available in 2010. Kodak is also developing other 'active packaging,' which absorbs oxygen, thereby keeping food fresh.[99]

Embedded Sensors in Food Packaging and "Electronic Tongue" Technology

Scientists at Kraft, as well as at Rutgers University and the University of Connecticut, are working on nanoparticle films and other packaging with embedded sensors that will detect food pathogens. Called 'electronic tongue' technology, the sensors can detect substances in parts per trillion and would trigger a color change in the packaging to alert the consumer if a food has become contaminated or if it has begun to spoil.

Using a Nanotechnology Bioswitch in "Release on Command" Food Packaging

Researchers in The Netherlands are going one further step to develop intelligent packaging that will release a preservative if the food within begins to spoil. This "release on command" preservative packaging is operated by means of a bioswitch developed through nanotechnology.

Using Food Packaging Sensors in Defence and Security Applications

Developing small sensors to detect foodborne pathogens will not just extend the reach of industrial agriculture and large-scale food processing. In the view of the US military, it's a national security priority. With present technologies, testing for microbial food contamination takes 2 to 7 days and the sensors that have been developed to date are too big to be transported easily. Several groups of researchers in the United States are developing biosensors that can detect pathogens quickly and easily, reasoning that "super sensors" would play a crucial role in the event of a terrorist attack on the food supply. With US Department of Agriculture (USDA) and National Science Foundation funding, researchers at Purdue University are working to produce a hand-held sensor capable of detecting a specific bacteria instantaneously from any sample. They've created a start-up company called BioVitesse.[100]

Problems That Sensors and "Smart Packaging" Will Not Address

Although devices capable of detecting foodborne pathogens could be useful in monitoring the food supply, sensors and "smart packaging" will not address the root problems inherent in industrial food production that result in contaminated foods: faster meat (dis)assembly lines, increased mechanization, a shrinking labor force of low-wage workers, fewer inspectors, the lack of corporate and government accountability, and the great distances between food producers, processors, and consumers. Just as it has become the consumer's responsibility to make sure meat has been cooked long enough to ensure that pathogens have been killed, consumers will soon be expected to act as their own meat inspectors so that industry can continue to trim safety overhead costs and increase profits.[101]

THE CAUTIOUS STEP

Despite the obvious enthusiasm for nanoscale science and its applications to food engineering and processing, the food and beverage industry is generally conservative and cautious when talking about the future of nanotechnology and food. Most industry representatives decline to provide specific details about the level of funding and industry partners. Same with scientists at giant food and beverage corporations (Kraft and Nestlé), as well as university researchers and representatives from small nanotechnology start-ups. After witnessing widespread rejection of genetically modified foods, the food industry may be especially skittish about owning up to R&D on "atomically modified" food products.

In fact, there are no worldwide accepted rules or regulations for nanotechnology. In a survey performed by Israel and the United States in March 2006, it was found that over 200 manufacturers currently market products identified as "nanoproducts." Approximately 60 of these products were for "health and fitness" and 9% were for "food and beverage" products.[43] Despite the lack of unifying nanotechnology guidelines, manufacturers nevertheless have to deal with existing general regulations for food products and the introduction of a new nanoingredient can be difficult and time-consuming. For this reason, most expected nanoapplications in the food market will probably occur in food packaging and only few in actual food products.

THE SAFETY ISSUES

It is important to note that nanomaterials, owing to their increased contact surface area, might have toxic effects in the body that are not apparent in the bulk materials.[102] In addition, there might be potential and unforeseen risks for their use in food-packaging materials. Despite this lack of regulation and risk knowledge, a handful of food and nutrition products that contain nanoscale additives are already being sold, such as iron in nutritional drink mixes, micelles that carry vitamins, minerals, and phytochemicals in oil, and zinc oxide in breakfast cereals. Nanoclays have also found use in plastic beer bottles.

Although consumer will be thrilled at the enormous range of exciting food products emerging by application of nanotechnology, like any other new technologies, serious questions about safety will be an issue requiring attention by the industry as well as the policy makers. The GRAS list of additives universally accepted will have to be reexamined when used at nanoscale level. Rats breathing nanoparticles showed a tendency to collect them in the brain and the lungs, increasing the biomarkers for inflammation and stress response. Toxicity is one issue that will be uppermost in the minds of the consumer and because nanoparticles are more reactive, more mobile, and likely to be more toxic, this concern must be addressed. There is strong possibility that nanoparticles in the body can result in increased oxidative stress that, in turn, can generate free radicals, leading to DNA mutation, cancer, and possible fatality. It is also not fully understood whether enhancing the bioavailability of certain nutrients or food additives might negatively affect human health.[103] Irradiation technology has taken more than 5 decades of research and safety assessment before becoming acceptable in a limited way. Nanotechnology also will have to wait till all safety issues are resolved.

REGULATIONS

In the United States, the US Food and Drug Administration (FDA) require manufacturers to demonstrate that the food ingredients and food products are not harmful to health, yet this regulation does not "specifically" cover nanoparticles, which could become harmful only in nanosized applications. Thus no special regulations exist for the use of nanotechnology in the food industry[104]. In contrast, the European Union has recommended special regulations that have yet to be accepted and enforced. The FDA says that it regulates "products, not technologies." Nevertheless, FDA expects that many products of nanotechnology will come under the jurisdiction of many of its centers; thus, the Office of Combination Products will likely absorb any relevant responsibilities.[105]

Because FDA regulates on a product-by-product basis, it emphasizes that many products that are already under regulation contain particles in the nanoscale range. Accordingly, "particle size is not the issue," and any new materials will be subjected to the customary battery of safety tests.

The Institute of Food Science and Technology (IFST), a United Kingdom–based independent professional body for food scientists and technologists, has a different view of nanotechnology. In its report,[106] the organization says that size matters and recommends that nanoparticles be treated as potentially harmful until testing proves otherwise. Still, it is the European Commission's intention to apply existing food laws to food products using nanotechnology. Consequently, the European Commission says that the technology will likely require some modification for it to adhere to existing laws.

Commissioned by the UK to assess the potential effects of nanotechnology, the Royal Society and the Royal Academy of Engineering recommend indicating nanoparticles in the lists of ingredients. The UK government agrees that the inclusion of nanoparticles on ingredient labels is necessary for consumers to make informed decisions; thus, updated ingredient labeling requirements will be necessary.[107] The UK government plans to consult with its EU partners to determine whether IFST's recommendation to scrutinize nanoparticle ingredients for safety is valid.

TA-Swiss, the Swiss center for technology assessment, has recently analyzed the situation concerning nanotechnologies and food in Switzerland,[108] considering in particular food additives that have been used in Switzerland for many years (e.g., carotenoids, micelles, and silicon dioxide). Although according to the TA-Swiss study, there are no indications at this time that nanoparticles are used in Switzerland that have been shown to be dangerous to human health, in most cases no specific tests have been conducted to clarify possible new risks depending on particle size. Similar to any other industry sector, the current lack of methodologies and guidelines on how to assess potential risks emanating from certain substances at the nanoscale complicates risk assessment in the food sector.

The regulatory system for food additives in Switzerland sticks to the so-called "positive principle." Food additives may only be used if they have been tested and appear on a positive list, identifiable by an E-number. In Switzerland, silicon dioxide (E 551), iron oxide (E172), titanium dioxide (E 171), silver (E 174), gold (E 175), and aluminium (E 173) are registered and on the positive list of food additives. These substances may be used in certain foods according to the standard of "Good Production Practice."[109] Most food additives on the positive list, however, have only been used and tested in the macroscale form so far. Because particle size is not a relevant criterion to distinguish substances in safety tests (yet), the nanoscale form of these substances is implicitly admitted too. This problem also exists concerning, e.g., chemicals legislation or information disclosure obligations through material safety data sheets.

An emerging trend in food packaging makes use of silver's antibacterial properties by implementing silver nanoparticles into food containers. Using fresh strawberries, the test series clearly demonstrated that the silver-coated food container reduced mould growth. Critics, however, argue that it is not yet clearly understood whether and how nanoparticles might pass out of the packaging into the food, and what effects they might exhibit once they have been ingested.

Even if such nanosilver applications might not be available at this time in Switzerland's stores, with the possibility to globally order goods over the Internet, products with less stringent or different safety standards are readily available to consumers. Particularly in the food sector, it will be of utmost importance to deal with the mentioned safety issues in an early phase in order to avoid harsh consumer (over)reactions.

There are several generic issues related to regulation, labeling, and approval of nanoproducts:

- In the UK the Royal Society and the Royal Academy of Engineering produced a report on nanotechnology. They identified a lack of knowledge on the bioaccumulation and toxicity of nanoparticles. Based on this they suggested caution in the use of nanoparticles in consumer products until more information was available on their safety.

- Although regulatory authorities agree with the need to be cautious in the use of new technologies such as nanotechnology, they anticipate that most applications of nanotechnology in food to be considered for approval will be safe and beneficial to the consumer. It is generally suggested that there is a need to evaluate new products on a case-by-case basis and then consider any necessary amendment of regulations. They reason that they could not ban a nanoproduct unless there was some evidence that the product was actually harmful. Such an approach to regulation could be perceived by consumers as a loophole that could allow industry to introduce products onto the market without adequate testing or approval. Given the ambiguity of the status of the use of nanoparticles of food-approved ingredients or additives in food or food contact materials, the authorities responsible for regulation should make clear statements about their use and that they consider that new products based on the use of added manufactured nanoparticles in food or food contact materials should be regarded as novel products, requiring evaluation and approval.
- The attitude to regulation, labeling and approval of products of food nanotechnology varies from country to country. However, nanoproducts are becoming widely available through the Internet. The lack of consistency in regulation, labeling, and approval of such products makes it difficult for consumers to exercise choice in a rational manner.
- Consumer attitudes are likely to be vital to the successful application of nanotechnology in the food industry. Given the lessons of the genetically modified (GM) debate in the UK and Europe, it is important that the benefits and risks of nanotechnology are openly discussed, and that it is important to consider the issue of labeling. In particular, the use of the term "nano" or related terms as part of the branding of a product is at present ill defined. It would be useful if regulators provided guidelines as to when such branding was appropriate and justified. Where the term "nano" is used, there should be a requirement that producers define how nanotechnology has been used in the development of the product, and why this process enhances the quality of the product.
- Special attention should be given to novel uses of nanoparticles as antimicrobial agents on surfaces such as cutting boards, refrigerators, or utensils. The key questions here are whether such materials are released on contact with food, whether they are ingested, and if they are, their impact on human health and the acceptable levels of intake of such materials on a daily basis. New applications such as the use of nanoparticles as antimicrobial agents in edible films and coatings are likely to arise in the future and will raise new issues on the ingestion, accumulation and safety of such products.
- There is a need for further research into the consequences of the ingestion of nanoparticles. There is a specific need for research on materials not normally adsorbed, digested, and metabolized on ingestion. For these materials the research should consider the effect of size on the bioaccumulation and toxicity of such particles, as well as the benefits and risks of any antimicrobial effects on the microbial ecology of the mouth and the gut.
- Consideration should be given to the consequences of the use of nanotechnology to enhance the bioavailabilty of nutrients. This should consider the safety of the products, the consequences of enhanced or altered metabolism, and also the need for labeling, regulation, and testing of health claims for such food supplements.
- Where the safety data or ADIs for manufactured nanoparticles of food-approved ingredients or additives differs from that

of the bulk materials, then there may be a need for selective or distinctive labeling of these nanoproducts.

PUBLIC AND ACTIVIST CONCERNS

Public perception of nanotechnology is another important factor that will affect the realization of nanotechnology approaches in the food industry, as seen in the example of genetically modified (GM) foods.[109–112] Similar to GM foods, consumers cannot directly judge the benefits of a food derived from nanotechnology and any benefits need to be explained to the consumer. However, it is likely that some products engineered with nanotechnology will be accepted more easily by the public than others. A recent survey performed by Siegrist et al.[113] evaluated the public perception of different types of food materials, including an antibacterial food-packaging material, a nanocoating that protects tomatoes from humidity and oxygen, a bread containing nanocapules of omega-3 fatty acids, and a juice with vitamin A encapsulated in starch. The results obtained from 153 people showed that the nanotechnology-derived packaging was perceived as being more beneficial than the nanotechnology-engineered foods. These results also supported the hypothesis that nanotechnology inside a food is perceived as less acceptable than being on the outside (i.e., in the food packaging). However, there are social and ethical issues of using nanotechnology in the food sector that must be considered. Currently, the potential risks of nanomaterials to human health and to the environment are unknown.[102] The 2006 report of the Institute of Food Science and Technologists mentions that "size matters" and recommends the use of nanoparticles in the food sector only after safety has been proven following vigorous testing. Special attention should also be given to consumer attitudes towards food nanotechnology. Taking lessons from the GM arguments across European countries, it is crucial to discuss the benefits and risks of this highly promising technology. Governments should consider appropriate labeling and should also set down regulations that will help to increase consumer acceptability.

Because there is little government oversight in this area, says Craig Minowa, an environmental scientist for the Organic Consumers Association (OCA), the public may have little to say about it. "Products are not labeled, so consumers cannot choose to avoid them," he explains.[114]

The OCA, a grassroots nonprofit public interest organization based in the United States, is one of many vocal organizations calling for government regulation on nanofoods, at least until more safety testing is completed. These organizations argue that a lack of evidence of harm is not the same as reasonable certainty of safety, which is what food companies must demonstrate to the US Food and Drug Administration (FDA) before introducing a new food additive.

"The OCA is focusing its efforts on educating the public about the potential risks of nanofoods and putting pressure on government agencies to increase oversight," says Minowa, adding that ever-tightening federal budgets, at least in the United States, will make the latter a huge challenge. "There's a lack of consumer understanding, a lack of government oversight, and a lack of labeling," says Minowa. "Combine these with a lack of testing and you have an equation for serious problems."

Although there is far less opposition to nanopackaging than there is to nanofoods, there are some who argue that the use of these devices will allow the food industry to further shirk their corporate responsibilities.

"While devices capable of detecting food-borne pathogens could be useful in monitoring the food supply, sensors and 'smart packaging' will not address the root problems inherent in industrial food production that result in contaminated foods: faster meat (dis)assembly lines, increased mechanization, a shrinking labor force of low-wage workers, fewer inspectors, the lack of corporate and government accountability, and the great distances between food producers, processors, and consumers," says the ETC Group, a conservation and sustainable advancement organization. "Just as it has become the consumer's responsibility to make sure meat has been cooked long enough to ensure that pathogens have been killed, consumers will soon be expected to act as their own meat inspectors so that industry can continue to trim safety overhead costs and increase profits."[115]

Interestingly enough, the US Environmental Protection Agency (EPA) declared on November 22, 2006, that it intends to regulate a large class of consumer items made with silver nanoparticles. The decision, which will affect not only washing machines but other consumer products such as odor-destroying shoe liners, food-storage containers, air fresheners, and a wide range of other products that contain nanosilver, marks a significant reversal in federal policy.

Nanosilver-containing consumer products that are applied to food packaging are not regulated by the EPA but by the FDA. The FDA is still considering whether it needs new rules for nanomaterials.

R&D AND MARKET ESTIMATES

A handful of food and nutrition products containing invisible nanoscale additives are already commercially available. Hundreds of companies are conducting research and development (R&D) on the use of nanotechnology to engineer, process, package, and deliver food and nutrients to our shopping baskets and our plates. Among them are giant food and beverage corporations, as well as tiny nanotechnology start-ups. In addition to a handful of nanofood products that are already on the market, over 135 applications of nanotechnology in food industries (primarily nutrition and cosmetics) are in various stages of development. According to Helmut Kaiser, more than 200 companies worldwide are engaged in nanotech research and development related to food. Among the 20 most active companies are 5 that rank among the world's 10 largest food and beverage corporations, Australia's leading food corporation, and Japan's largest seafood producer and processed food manufacturer. According to Jozef Kokini, the Director of the Center for Advanced Food Technology at Rutgers University (New Jersey, USA), "Every major food corporation has a program in nanotech or is looking to develop one." A report produced by Helmut Kaiser Consultancy, "Nanotechnology in Food and Food Processing Industry Worldwide," predicts that the nanofood market will surge from \$10 billion today to \$30.4 billion in 2015.[116]

NANOFOOD, HOW FAR WE ARE?

The potential benefits of nanofoods—foods produced using nanotechnology—are astonishing. Advocates of the technology promise improved food processing, packaging, and safety; enhanced flavor and nutrition; 'functional foods' where everyday foods carry medicines and supplements; and increased production and cost-effectiveness. In a world where thousands of people starve each day, increased production alone is enough to warrant worldwide support. For the past few years, the food industry has been investing millions of dollars in nanotechnology research and development. Some of the world's largest food manufacturers, including Nestlé, Altria, H.J. Heinz, and Unilever, are blazing the trail, while hundreds of smaller companies follow their lead. Yet, despite the potential benefits, compared with other nanotechnology arenas, nanofoods don't get a lot of publicity. The ongoing debate over nanofood safety and regulations has slowed the introduction of nanofood products, but research and development continue to thrive—though, interestingly, most of the larger companies are keeping their activities quiet (when you search for the term 'nano' or "nanotechnology" on the Web sites of Kraft, Nestlé, Heinz, and Altria, you get exactly zero results). Although the risks associated with nanotechnology in other areas, such as cosmetics and medicine, are equally blurry, it seems the difference is that the public is far less apt to jump on the nanotechnology bandwagon when it comes to their food supply.[117]

According to a definition in a recent report ("Nanotechnology in Agriculture and Food") food is "nanofood" when nanoparticles, nanotechnology techniques, or tools are used during cultivation, production, processing, or packaging of the food. It does not mean atomically modified food or food produced by nanomachines.

In the forefront of nanofood development is Kraft Foods, which took the industry's lead when it established the Nanotek Consortium, a collaboration of 15 universities and national research labs, in 2000. Kraft's focus is on 'interactive' foods and beverages. These products will be customized to fit the tastes and needs of consumers at an individual level. Possible products include drinks that change colors and flavors to foods that can recognize and adjust to a consumer's allergies or nutritional needs. Other large companies, such as Nestlé and Unilever, are exploring improved emulsifiers that will make food texture more uniform. These huge Western companies are responsible for the bulk of the food industry's research and development; however, the nanofood industry is truly a global phenomenon.[118]

In Australia, for instance, nanocapsules are used to add omega-3 fatty acids to one of the country's most popular brands of white bread. According to the manufacturer, nanocapsules of tuna fish oil added to Tip Top Bread provide valuable nutrients, whereas the encapsulation prevents the bread from tasting fishy. NutraLease, a start-up company of the Hebrew University of Jerusalem, has developed novel carriers for nutraceuticals in food systems. The nanosized self-assembled structured liquid (NSSL) technology allows for encapsulation of nutraceuticals, cosmeceuticals, and essential oils and drugs in food, pharmaceuticals, and cosmetics. Another advantage to the NSSL technology is that it allows the addition of insoluble compounds into food and cosmetics. One of the first products developed with this technology—a healthier version of canola oil—is already available to consumers in Israel.

In other parts of the world, nanotechnology efforts are focused on the agricultural side of food production. A joint effort among universities in India and Mexico is directed at developing nontoxic nanoscale herbicides. Researchers at Tamil Nadu Agricultural University in India and Monterrey Tech in Mexico are looking for ways to attack a weed's seed coating and prevent it from germinating.

The range of current nanofood research and development is as impressive as the industry's projected growth. Last August, UK-based Cientifica estimated that nanotechnologies in the food industry were currently valued at $410 million and would grow to $5.8 billion by 2015.[119] Figure 2 gives the nanotechnology applications in agriculture and food.

FUTURE FOR NANOFOOD?

"The food industry is more traditional than other sectors like IBM" (where nanotechnology can be applied), explains Gustavo Larsen, a professor of chemical engineering and a former consultant to Kraft. "My take is that there are good opportunities and it's often more feasible to realise these opportunities in the food sector. You can make nanoparticles and use them in foods—you don't have to assemble them first." When asked what he believes will be the first products of nanotechnology R&D related to food, Larsen said that consumers are likely to see packaging composed of nanoscale materials before novel food products. "I think the packaging is a safer bet," said Larsen.[120]

Nanotechnology can confer unique advantages on processed foods in many ways. Programmable foods, considered the ultimate dream of the consumer, will have designer food features built into it and a consumer can make a product of desired color, flavor, and nutrition using specially programmed microwave ovens. The trick is to formulate the food at the manufacturer's end with millions of nanoparticles of different colors, flavors, and nutrients and under the program in the oven set by the consumer based on his preferences, only selective particles are activated while others stay inert, giving the desired product profile. Nano-based polymers with silica-based nanoparticles sandwiched can enhance the properties of pressure-sensitive adhesive labels and create biodegradable properties in them. Enhanced solubility, improved bioavailability, facilitating controlled release and protecting the stability of micronutrients in food products, are other virtues of nanotechnology. The Government of India is setting up a National NanoScience and Technology Institute to develop nanofoods by using nanotechnology during cultivation, processing, and packaging of food, but it is not clear whether the declaration has any backing of the Government of India or whether any serious planning has really gone into the proposal.[121]

FIGURE 2. Nanotechnology applications in agriculture and food.

Agriculture	Food Processing	Food Packaging	Supplements
• Single molecule detection to determine enzyme substrate interactions • Nanocapsules for delivery of pesticides, fertilizer and other agrichemicals more efficiently • Delivery of growth hormones in a controlled fashion • Nanosensors for monitoring soil conditions and crop growth • Nanochips for identity preservation and tracking • Nanosensors for detection of animal and plant pathogens • Nanocapsules to deliver vaccines • Nanoparticles to deliver DNA to plants (targeted genetic engineering)	• Nunocapsules to improve bioavailability of neutraceuticals in standard ingredients such as cooking oils • Nanoencapsulated flavor enhancers • Nanotubes and nanoparticles as gelation and viscosifying agents • Nanocapsule infusion of plant based steroids to replaces meat's cholesterol • Nanoparticles to selectively bind and remove chemicals or pathogens from food • Nanoemulsions and particles for better availability and dispersion of nutrients	• Antibodies attached to fluorescent nanoparticles to detect chemicals or foodborne pathogens • Biodegradable nanosensors for temperature, moisture and time monitoring • Nanoclays and nanofilms as barrier materials to prevent spotlage and prevent oxygen absorption • Electrochemical nanosensors to delect ethylene • Antimicrobial and antifungal surface coatings with nanoparticles (silver, magnesium, zinc) • Lighter, stronger and more heat-resistant films with silicate nanoparticles • Modified permeation behavior of foils	• Nanosize powders to increase absorption of nutrients • Cellulose nanocrystal composite as drug carrier • Nanoencapsulation of neutraceuticals for better absorption, better stability of targeted delivery • Nanocochleates (coiled nanoparticles) to deliver nutrients more efficiently to cells without affeccting color or taste of food • Vitamin sprays dispersing active molecules into nanodroplets for belter absorption

During last 3 years, food industries have witnessed that the nanotechnoloy has been really integrated in a number of food and food-packaging products. There are now over 300 nanofood products available on the market worldwide. These exciting achievements have encouraged a large increase of R&D investments in nanofood. Today, the nanotechnology is no longer an empty buzzword, but an indispensable reality in the food industry. Any food company who wants to keep its leadership in food industries must begin to work with nanotechnology right now. The impact of nanotechnology is huge, ranging from basic food to food processing, from nutrition delivery to intelligent packaging. It is estimated that the nanotechnology and nano-bio-info convergence will influence over 40% of the food industries up to 2015. The risk for the food companies lies in NOT entering the nanotechnology, but entering too late.[122]

The nanofood market has been soaring from US$2.6 billion in 2006 to US$5.3 billion dollars in 2009 and is expected to reach US$20.4 billion in 2015. Nano-featured food packaging market will grow from US$ 1.1 billion 2009 to US$3.7 billion up to 2015. More than 400 companies around the world are today active in research and development and production. USA is the leader, followed by Japan and China. By 2015, Asia, with more than 50% of the world population, will become the biggest market for the nanofood, with China in the leading position.[123]

THE PROMISES

Nanotechnology is becoming increasingly important for the food sector. Promising results and applications are already being developed in the areas of food packaging and food safety. Nanotechnology has begun to find potential applications in the area of functional food by engineering biological molecules toward functions very different from those they have in nature, opening up a whole new area of research and development. Of course, there seems to be no limit to what food technologists are prepared to do to our food and nanotechnology will give them a whole new set of tools to go to new extremes. Many have taken critical view of food nanotechnology in the past. Today, though, we look at the potentially beneficial effects nanotechnology-enabled innovations could have on our foods and, subsequently, on our health.

According to a definition in a recent report ("Nanotechnology in Agriculture and Food"), food is *nanofood* when nanoparticles, nanotechnology techniques or tools are used during cultivation, production, processing, or packaging of the food. It does not mean atomically modified food or food produced by nanomachines.[124]

Because food and agricultural sciences are mostly concerned with biological systems, and much of biology is grounded in nanoscale phenomena, the National Institutes of Health provide a more detailed definition of nanotechnology with regard to biological systems: "Only those studies that use nanotechnology tools and concepts to study biology; that propose to engineer biological molecules toward functions very different from those they have in nature; or that manipulate biological systems by methods more precise than can be done by using molecular biological, synthetic chemical, or biochemical approaches that have been used for years in the biology research community are classified as nanotechnology projects."[125]

Below is an overview of what nanotechnology applications are currently being researched, tested, and in some cases already applied in food technology.

Let's start with where the benefits of this will be needed most: third world countries where food supply is often limited and the quality of available food leads to nutritional deficiencies and the quality of drinking water is a major contributor to disease. In a study by the University of Toronto Joint Centre for Bioethics from 2 years ago ("Nanotechnology and the Developing World"), a panel of international experts ranked the 10 nanotechnology applications in development worldwide with the greatest potential to aid the poor. Number two on the list was "agricultural productivity enhancement," number three was "water treatment and remediation," and number six was "food processing and storage."[126]

Apart from funky food that changes color and taste, and glows in the dark, food nanotechnology will also lead to beneficial health effects in overfed Western countries.

"The ancient Asian concept that 'food and medicine are one' has gradually also become accepted in Western countries," says Dr. Yun-Hwa Peggy Hsieh, a professor at Florida State University with a research interest in functional foods. "Foods no longer merely meet an individual's basic physical needs, but are also expected to contribute to their health and well being. Nutritional and epidemiological studies have provided strong evidence that many chronic diseases such as cardiovascular disease, diabetes, and cancer are linked to diet and the risks posed by these diet-related diseases can be reduced by the consumption of foods with extra measures of phytochemical antioxidants and with lowered fat content, especially saturated fat."[127]

In a recent article in *Asia Pacific Journal of Clinical Nutrition*, titled "Innovations in food technology for health," Hsieh and her colleague Jack Ofori look at a range of modern technologies applied in food production and agriculture and describe how nanotechnology is also beginning to find potential applications in this area.[128] Hsieh points out that federally funded nanotechnology research in food and agriculture is devoted primarily to the areas of food packaging and pathogen detection and that various innovative nanosensors for the detection of pathogenic bacteria have been developed. "Recent research, however, has begun to address the potential applications of nanotechnology for functional foods and nutraceuticals by applying the new concepts and engineering approaches involved in nanomaterials to target the delivery of bioactive compounds and micronutrients," she says. "Nanomaterials allow better encapsulation and release efficiency of the active food ingredients compared to traditional encapsulating agents, and the development of nanoemulsions, liposomes, micelles, biopolymer complexes, and cubosomes have led to improved properties for bioactive compounds protection, controlled delivery systems, food matrix integration, and masking undesired flavors."

Nanotechnology also has the potential to improve food processes that use enzymes to confer nutrition and health benefits. For example, enzymes are often added to food to hydrolyze antinutritive components and hence increase the bioavailability of essential nutrients such as minerals and vitamins. To make these enzymes highly active, long-lived, and cost-effective, nanomaterials can be used to provide superior enzyme-support systems due to their large surface-to-volume ratios compared to traditional macroscale support materials.

An article in the April 22 *New York Times* magazine, "You are what you grow," shows the frightening connection between low-cost, highly processed foods and obesity and bad health. Of course there is no substitute for eating healthy, natural foods; but if food nanotechnology could contribute to making processed foods less unhealthy, then this would be a tremendous success story for nanotechnology.[129]

The incorporation of nanomaterials into food packaging is expected to improve the barrier properties of packaging materials and should thereby help to reduce the use of valuable raw materials and the generation of waste. Edible nanolaminates could find applications in fresh fruits and vegetables, bakery products, and confectionery, where they might protect the food from moisture, lipids, gases, off-flavors, and odors. Natural biopolymers of nanosize scale, such as polysaccharides, can be used for the encapsulation of vitamins, prebiotics, and probiotics and for delivery systems of drugs or nutraceuticals. In the food sector, one of the most important problems is the time-consuming and laborious process of food quality-control analysis. Innovative devices and techniques are being developed that can facilitate the preparation of food samples and their precise and inexpensive analysis. From this point of view, the development of nanosensors to detect microorganisms and contaminants is a particularly promising application of food nanotechnology.

CONCLUSIONS

As developments in nanotechnology continue to emerge, its applicability to the food industry is sure to increase. Most aspects of incremental nanotechnology are likely to enhance product quality and choice and will be perceived as progressive changes in standard and accepted technology. There are a few issues, particularly regarding the accidental or deliberate use of nanoparticles in food, or food-contact materials, which may provoke consumer concern. It is particularly important to ensure that consumers are able to exercise choice in the use of the products of nanotechnology and that they have the information to assess the benefits and risks of such products. The success of these advancements will be dependent on consumer acceptance and the exploration of regulatory issues. Food producers and manufacturers could make great strides in food safety by using nanotechnology, and consumers would reap benefits as well. Many companies are conducting research in nanotechnology and its application to food products and as more of its functionalities become evident, the level of interest is certain to increase. Nanotechnology has already made inroads into the food industry and it is claimed that more than 300 foods have already been developed with this technology. The market value for nanofoods is estimated to increase to more than US$30 billion by 2015 and it is predicted that more than 40% of food products will be nanotechnology based by the year 2015. To maintain leadership in food and food-processing industry, one must work with nanotechnology and nano-bio-info in the future. The future belongs to new products and new processes with the goal to customize and personalize the products. Improving the safety and quality of food will be the first step. Designing and producing food by shaping molecules and atoms is the future of the food industry worldwide.

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