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REVIEW PAPER

Nanotechnology for the Food and Bioprocessing Industries

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Abstract Several complex set of engineering and scientific challenges in the food and bioprocessing industries for manufacturing high quality and safe food through efficient and sustainable means can be solved through nanotechnology. Bacteria identification and food quality monitoring using biosensors; intelligent, active, and smart food packaging systems; and nanoencapsulation of bioactive food compounds are few examples of emerging applications of nanotechnology for the food industry. We review the background about the potential of nanotechnology, provide an overview of the current and future applications of nanotechnology relevant to food and bioprocessing industry, and identify the societal implications for successful implementation of nanotechnology.

Keywords Nanotechnology · Food · Bioprocessing · Nanosensors · Antimicrobial packaging · Nanoencapsulation

Introduction

Nanotechnology is generally defined as the design, production, and application of structures, devices, and systems through control of the size and shape of the material at the 10^{-9} of a meter scale. The National Nanotechnology Initiative (Arlington, VA, USA) defines nanotechnology as 'the understanding and control of matter at dimensions of roughly 1-100 nm, where unique phenomena enable novel applications'.

Nanotechnology is truly an interdisciplinary field that stretches across a whole spectrum of science including physics, chemistry, and biology as well as engineering including micro-fabrication techniques. The physical, chemical, and biological properties of structures and systems at nanoscale are substantially different than the macro-scale counterparts due to the interactions of individual atoms and molecules thereby offering unique and novel functional applications. As the size of the particles gets reduced to nanoscale range, there is an immense increase in the surface to volume ratio which increases reactivity and changes the mechanical, electrical, and optical properties of the particles.

The food and bioprocessing industry is facing enormous challenges for developing and implementing systems that can produce high quality, safe foods as well as feeds while also being efficient, environmentally acceptable, and sustainable (Manufuture 2006). To answer these complex set of engineering and scientific challenges, innovation is needed for new processes, products, and tools in the food industry. Nanotechnology is gaining momentum and becoming a worldwide important tool for the food and bioprocessing industry in meeting the foreseeable increasing world demand that will result from population growth and increasing incomes in developing countries. Nanotechnology can possibly improve production processes to provide products with better characteristics and new functionalities in the food and bioprocessing industry (Roco 2002).

Total global investment in nanotechnologies in the year 2004 was US $7 billion (European Commission 2004). The annual value of nanotechnology related products for the years 2011–2015 has been estimated to be $1 trillion (Roco and Bainbridge 2001). The nanofood market is expected to surge from US $7 billion in 2006 to US $20.4 billion in 2010 (Helmut Kaiser Consultancy 2004). In the year 2006, there were about 400 agricultural and food companies around the world actively pursuing nanotechnology research

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and development and this number is expected to increase to more than 1,000 by 2015 (Joseph and Morrison 2006).

The term ‘nanofood’ describes food which has been cultivated, produced, processed, or packaged using nanotechnology techniques or tools, or to which manufactured nanomaterials have been added (Joseph and Morrison 2006). To communicate the merits of nanotechnology in food applications and to avoid misunderstanding and confusion, a new definition of nanotechnology for food applications is essential (Kampers 2007).

Nanotechnology has potential applications in all aspects of food chain including storage, quality monitoring, food processing, and food packaging. Nanotechnology applications in the food industry range from intelligent packaging to creation of on-demand interactive food that allows consumers to modify food, depending on the nutritional needs and tastes.

The objective of this review is to provide a background on agri-food nanotechnology and an up-to-date account of known and possible futuristic applications of nanotechnology in the food and bioprocessing industry. The brand and the company names mentioned in the manuscript here are for the purpose of information only and not intended as an act of promotion or endorsement.

Food Quality Monitoring

Quality assurance in food and bioprocessing industry is of utmost importance because consumers demand safe and wholesome food as well as governments impose stringent regulations to ensure food safety and feed hygiene. Sensors or detection systems for rapid detection of spoilage of product components, for quality control, and for abuse detection at source and during production chain is possible through nanotechnology.

Nanosensors

Nanosensors can provide quality assurance by tracking microbes, toxins, and contaminants throughout food processing chain through data capture for automatic control functions and documentation. Nanotechnology also enables to implement low cost nanosensors in food packaging to monitor the quality of food during various stages of the logistic process to guarantee product quality up until consumption.

Grain quality monitoring nanosensors (Fig. 1), that are being developed by researchers at the Canadian Wheat Board Centre for Grain Storage Research, University of Manitoba, Canada; use conducting polymer nanoparticles (Neethirajan et al. 2009a), which respond to analytes and volatiles in food storage environment and thereby detect the source and the type of spoilage. The advantage of this sensor system is that thousands of nanoparticles can be placed on a single sensor to accurately detect the presence of insects or fungus inside stored grain bulk in bins. Because of the miniaturization and low power requirement, the nanosensors can be fabricated small and light weight (Neethirajan and Jayas 2007) and can be deployed and distributed into the crevices of grain bulk, where the stored product pests often hide.

Ruengruglikit et al. (2004) have developed an electronic tongue for inclusion in food packaging that consists of an array of nanosensors that are extremely sensitive to gases released by food as it spoils, causing the sensor strip to change color as a result, giving a clear visible signal of whether the food is fresh or not.

Bacteria Identification

Horner et al. (2006) have developed an analytical technology called reflective interferometry, using nanotechnology which provides specific, rapid, and label-free optical detection of biomolecules in complex mixtures. This new platform technology has provided food quality assurance by detecting *Escherichia coli* (*E. coli*) bacteria in a food sample by measuring and detecting light scattering by cell mitochondria. This sensor works on the principle that a protein of a known and characterized bacterium set on a silicon chip can bind with any other *E. coli* bacteria present in the food sample. This binding will result in a nanosized light scattering detectable by analysis of digital images.

A biosensor developed by Fu et al. (2008) uses fluorescent dye particles attached to anti-salmonella antibodies on a silicon/gold nanorod array. When the salmonella bacteria present in the food is being tested, the nanosized dye particles on the sensor become visible. Unlike the time-consuming conventional lab tests that are based on bacterial cultures, this biosensor can detect the salmonella in food instantly.

Campylobacter jejuni are bacteria which cause abdominal cramps and diarrhea in humans. The campylobacter infections can be traced to poultry meat products which have been contaminated with intestinal contents during processing. To address this food safety problem, Stutzenberger et al. (2007) have developed a novel strategy that employs bioactive nanoparticles in the chicken feed specifically designed to bind to the biomolecular structures on the surfaces of campylobacters. The feed enriched by antibiotic-functioning nanocarbohydrate particles binds with the bacterium’s surface to remove it through the bird’s feces.

Agromicron Ltd, Hong Kong has developed a low cost Nano Bioluminescent Spray (Plexus Institute 2006), which can react with the pathogen strain on food and produce a visual glow for easy detection. The spray is made of nanoparticles and would work based on its reactivity with the bacteria. The higher the number of connections between

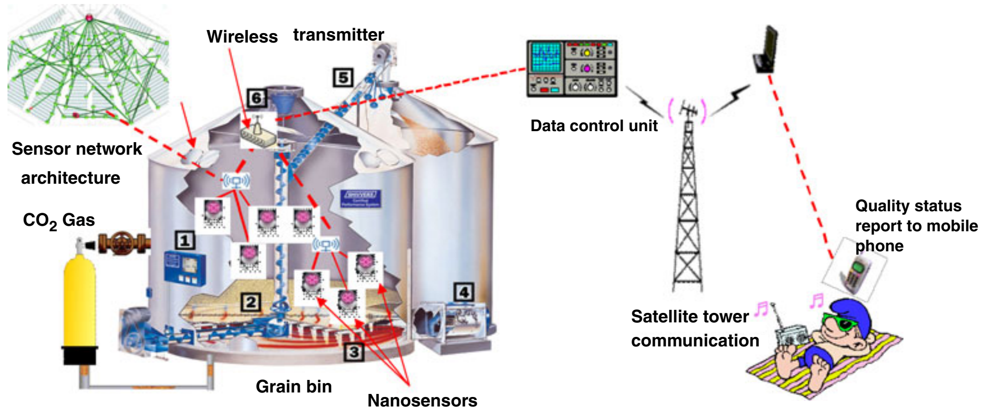

Fig. 1 Example of a futuristic wireless nanosensor network for grain quality monitoring. *1* Control panel, *2* grain auger, *3* air plenum, *4* fan, *5* auger to transfer grain, if needed, *6* wireless transmitter

bacteria and molecules, the more intense the glow produced by the particles. This spray can identify a broad range of food-related pathogens, such as Salmonella and *E. coli*. Cheng et al. (2009) demonstrated rapid detection of *E. coli* in food using biofunctional magnetic nanoparticles (about 20 nm in diameter) in combination with adenosine triphosphate bioluminescence. Zhao et al. (2004) developed an ultrasensitive immunoassay for in situ pathogen quantification in spiked ground beef samples using antibody-conjugated silica fluorescent nanoparticles (about 60 nm in diameter).

Food Packaging

The purpose of food packaging is to increase food shelf life by avoiding spoilage, bacteria, or the loss of food nutrient. Nanotechnology offers higher hopes in food packaging by promising longer shelf life, safer packaging, better traceability of food products, and healthier food. Polymer nanocomposite technology holds the key to future advances in flexible, intelligent, and active packaging. Intelligent, smart, and active packaging systems produced by nanotechnology would be able to repair the tears and leakages (self healing property), and respond to environmental conditions (e.g., change in temperature and moisture). Intelligent food packaging can sense when its contents are spoiling, and alert the consumer, while active packaging will release a preservative such as antimicrobials, flavors, colors, or nutritional supplements into the food when it begins to spoil. Nanotechnology can provide solutions for food packaging by modifying the permeation behavior of foils, increasing barrier properties (mechanical, chemical, and microbial), providing antimicrobial properties, and by improving heat-resistance properties (Brody 2003; Chaudhry et al. 2008).

Antimicrobial Packaging

Antimicrobial packaging systems are important for the food industry and the consumers because these systems can extend the product shelf life and maintain food safety by reducing the growth rate of microorganisms. Antimicrobial nanoparticle coatings in the matrix of the packaging material can reduce the development of bacteria on or near the food product, inhibiting the microbial growth on non-sterilized foods and maintain the sterility of pasteurized foods by preventing the post-contamination. Antimicrobial packaging systems include adding an antimicrobial nanoparticle sachet into the package, dispersing bioactive agents in the packaging; coating bioactive agents on the surface of the packaging material, or utilizing antimicrobial macromolecules with film forming properties or edible matrices (Coma 2008). The schematic of a typical antimicrobial coating nanopackaging film (120 μm thickness) based on research by Buonocore et al. (2005) is shown in Fig. 2.

Foods such as cheese, sliced meat, and bakery that are prone to spoiling on the surface can be protected by contact packaging imbued with antimicrobial nanoparticles. Antifungal active paper packaging developed by Rodriguez et al. (2008) incorporating cinnamon oil with solid wax paraffin using nanotechnology as an active coating was shown to be used as an effective packaging material for bakery products. Working with oregano oil and apple puree, Rojas-Grau et al. (2006) have created edible food films that are able to kill *E. coli* bacteria.

Antimicrobial nanoparticles that have been synthesized and tested for applications in antimicrobial packaging and food storage boxes include silver oxide nanoparticles (Sondi and Salopek-Sondi 2004), zinc oxide, and magnesium oxide nanoparticles (Jones et al. 2008) and nisin particles produced from the fermenation of a bacteria (Gadang et al. 2008).

CTC Nanotechnology GmbH, Merzig, Germany has manufactured and is selling a nanoscale dirt-repellent coating (CTC Nanotechnology 2009) to create self-cleaning surfaces for use in food packages and meat-processing plants. The technology concept is based on the sol-gel process where the nanoparticles are suspended in a fluid medium and by the action of nanohydrophobisation;

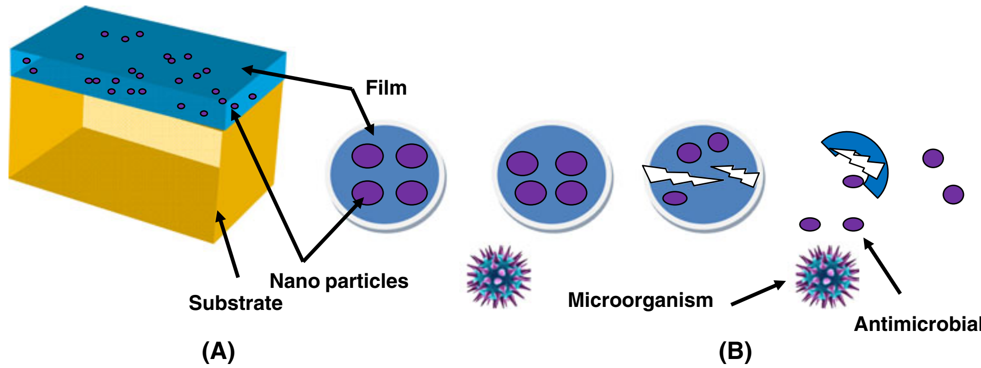

Fig. 2 **a** Schematic showing exploded view of a typical antimicrobial coating nanopackaging film; **b** Antimicrobial active packaging microorganisms hydrolyses starch based particles causing release of the antimicrobial lysozyme resulting in inhibitors of microbial growth (based on Buonocore et al. 2005)

the absorbency of the surfaces to be treated is eliminated so that they remain resistant to the environmental factors after cleaning. The added advantages of this product are that they are biodegradable and approved and certified for use with food.

Improved Food Storage

Oxygen inside food packaging is the main cause for food deterioration due to oxidation of fats and oils and growth of microorganisms. Also, oxygen accelerates the processes inside food packaging leading to discoloration, changes in texture, rancidity and off-odor, and flavor problems. Nanotechnology can effectively produce oxygen scavengers for sliced processed meat, beer, beverages, cooked pastas, and ready-to-eat snacks; moisture absorber sheets for fresh meat, poultry, and fish; and ethylene-scavenging bags for packaging of fruit and vegetables.

Active packaging films for selective control of oxygen transmission and aroma affecting enzymes has been developed based on the nanotechnology approach (Rivett and Speer 2009). The modification of the surface of nanosized materials by dispersing agents can act as substrates for the oxidoreductase enzymes. Oxygen absorbing sachets (Bioka Ltd, Finland; Sealed Air Corporation, USA; Constar International Inc, USA; Actipak, India) based on reactions catalyzed by food grade enzymes are also commercially available in the market.

Packaging film enriched with silicate nanoparticles produced by Bayer Polymers, Germany reduces the entrance of oxygen and other gasses, and the exit of moisture and can prevent the food from spoilage. Nanocor Inc, Chicago, IL, USA has developed a nanocomposite containing clay nanoparticles (Advantage Magazine 2004) for manufacturing polyethylene terephthalate bottles to ship beer, fruit juice, and soft drinks. The clay nanoparticles embedded in the plastic bottles stiffen the packaging, reducing gas permeability, and minimizes the loss of carbon dioxide from the beer and the ingress of oxygen to the bottle, keeping the beer fresher and increases the shelf life to more than six months.

Green Packaging

Natural biopolymer bio-nanocomposites-based packaging materials have great potential for enhancing food quality, safety, and stability as an innovative packaging and processing technology. Plantic Technologies Ltd, Altona, Australia has manufactured and is selling biodegradable and fully compostable bioplastics packaging (CSIRO 2006), made from organic corn starch using nanotechnology. Bio degradable bio-nanocomposites prepared from natural biopolymers such as starch and protein exhibited advantages as a food packaging material by providing enhanced organoleptic characteristics such as appearance, odor, and flavor (Zhao et al. 2008). The unique advantages of the natural biopolymer packaging are that these can handle particulate foods, can act as carriers for functionally active substances, and provide nutritional supplements (Rhim and Ng 2007).

Kriegel et al. (2009) have developed a methodology using electrospinning technique for making biodegradable green food packaging from chitin. Chitin is a natural polymer and a main component of lobster shells. The electrospinning technique involves dissolving chitin in a solvent and drawing it through a tiny hole with applied electricity to produce nanoslim fiber spins. These strong and naturally antimicrobial nanofibers were used for developing the green food packaging. BASF, Ludwigshafen, Germany; New Ice, Durango, USA; Archer Daniels Midland CO, Decatur, USA; Sharp Interpack, Aylesham, UK and RPC Group, Northamptonshire, UK (BASF 2009; Bordes et al. 2009; Coating & Converting Magazine 2008) have produced food packaging bags and sachets from biodegradable polylactic acid and polycaprolactone obtained from polymer nanocomposites of corn plant.

Tracking, Tracing, and Brand Protection

Nanotechnology can help food industries in providing authentication, and track and trace features of a food product for avoiding counterfeiting; preventing adulteration and diversion of products destined for a specific market. To help in the tracking and tracing, nanotechnology provides complex invisible nanobarcodes with batch information which can be encrypted directly onto the food products and packaging. This nanobarcode technology offers food safety by allowing the brand owners to monitor their supply chains without having to share company information to distributors and wholesalers.

Oxonica, Oxford, UK offers solutions for food product identification using a biological fingerprint combined with recorded quality characteristics in the form of nanobarcodes. The technology involves nanoparticles (Oxonica 2007) made up of gold, silver, and platinum varying in width, length, and amount to create stripes of different reflectivity. By altering the stripe orders, different codes can be created and be assigned for every food item providing brand and authenticity in tracing food batches.

NanoInk, Skokie, USA has developed a patterning technique called Dip Pen Nanolithography (Zhang et al. 2009) to encrypt information directly onto food products or pharmaceutical pills and on packaging. The technique involves using a scanning probe molecule-coated tip to deposit a chemically engineered ink material to create nanolithographic pattern onto the food surface. Authentix, Addison, USA has developed and is marketing nanoscale markers that can be incorporated into product packaging.

Nam et al. (2003) have made nanodisks of gold and nickel to encrypt information to be used as biological labels in applications such as DNA detection and as tags for tracking food products. The nanodisks were functionalized with dye molecules called chromophores that emit a unique light spectrum when illuminated with a laser beam.

Li et al. (2005) have created a nanobarcode detection system that fluoresces under ultraviolet light in a combination of color that can be read by a computer scanner. Food and biological samples containing various combinations of *E. coli*, anthrax, and tularemia bacteria, and Ebola and SARS viruses has been tested using this system and several pathogens were clearly distinguished simultaneously by different color codes.

Encapsulation and Delivery

The nanoencapsulation system offers numerous benefits (Shefer 2008) including ease of handling, enhanced stability, protection against oxidation, retention of volatile ingredients, taste masking, moisture-triggered controlled release, pH-triggered controlled release, consecutive delivery of multiple active ingredients, change in flavor character, long lasting organoleptic perception, and enhanced bioavailability and efficacy. Nanomaterials for food and bioprocessing applications can be produced from engineered plants or microbes and through the processing of waste materials such as stalks and other cellulosic materials (Robinson and Morrison 2009). Nanosilicas produced from plants can be used for encapsulating enzymes that in turn can be used for in vivo drug or nutrient release systems (Neethirajan et al. 2009).

Bioactive Compounds

Bioactive compounds are extra nutritional constituents that typically occur in small quantities in foods. Examples include beta-carotene from carrots, lycopene from tomato, beta-glucan from oats, omega-3 acid from salmon oil, conjugated linoleic acid from cheese, lactobacillus from yogurt, and isoflavones from soybeans. Nanotechnology has shown greater potential in improving the efficiency of delivery of nutraceuticals and bioactive compounds in functional foods to improve human health. Nanotechnology can enhance solubility, improve bioavailability, and protect the stability of micronutrients and bioactive compounds during processing, storage and distribution (Chen et al. 2006).

Nanocapsules have been used by George Weston Foods, Australia to mask the taste and odor of tuna fish oil (source of omega-3 fatty acids) which is integrated into bread. The nanocapsules break open only when they reach the stomach and hence the unpleasant fish oil taste can be avoided. Nanoencapsules has been used for the protection and controlled release of beneficial live probiotic species to promote healthy gut function. The viability of probiotic organisms including *Lactobacillus acidophilus*, *Lactobacillus casei*, *Lactobacillus rhamnosus*, and *Bifidobacterium* spp. within freeze dried yogurt can be improved by nanoencapsulation with calciumalginate (Kailasapathy and Rybka 1997). Nanoencapsulated Bifidobacteria with starch by spray coating exhibited an affordable and industrially convenient encapsulation process (O'Riordan et al. 2001).

The bioavailability of lycopene (antioxidant from tomato), can be increased by fortifying nanoparticles of lycopene in tomato juice, pasta sauce, and jam (Auweter et al. 1999). Milk protein, casein, was used to make nanosized micelles and has been employed as a vehicle for delivering sensitive health-promoting ingredients including vitamin D2 (Semo et al. 2007). Biopolymer zein (maize protein) nanofibers prepared by electrospinning technique (Fernandez et al. 2009) for encapsulating beta-carotene demonstrates the potential of nanotechnology in food and nutraceutical formulation and coatings, bioactive food packaging, and food processing industries.

Self-assembled nanotubes, developed from hydrolysed milk protein α-lactalbumin, offers a new naturally derived carrier for nanoencapsulation of nutrients, supplements, and pharmaceuticals (Graveland-Bikker and de Kruif 2006). Crystalline nanocochleates of about 50 nm in size derived from soya bean can protect micronutrients and antioxidants from degradation during manufacture and storage (Bio-Delivery Sciences International, Raleigh, NC, USA).

Interactive Foods

Nanotechnology helps to make interactive foods which can allow consumers to modify the food depending on their own nutritional needs or tastes. The concept of on-demand food states that thousands of nanocapsules containing flavor or color enhancers or added nutritional elements would remain dormant in the food and will only be released when triggered by the consumer (Dunn 2004).

Kraft, the leader in food industry, has established a consortium called 'Nanotek' to collaborate with universities and research laboratories in USA for developing interactive foods and nanoscale sensors (Forbes 2005). Development of foods capable of changing their color, flavor, or nutritional properties according to a person's dietary needs, allergies, or taste preferences is on the research agenda of Nestle and Kraft.

Nanotechnology can enable methods to make foods such as soft drinks, ice cream, chocolate, or chips to be marketed as 'health' foods by reducing fat, carbohydrate or calorie content or by increasing protein, fiber or vitamin content. Also, nanotechnology can aid in the production of stronger flavorings, colorings, and nutritional additives, and processing aids to increase the pace of manufacturing and to lower costs of ingredients and processing (Burdo 2005). Nanofilters and membranes can screen out or pass through certain molecules based on the shape and/or size to remove toxins or adjust flavors. Nestle and Unilever are reported to be developing a nanoemulsion based ice cream with a lower fat content that retains a fatty texture and flavor (Renton 2006).

Texture

The size and the structure of food influence the functionality of foods by providing the taste, texture, and stability properties that consumers want. Nanotechnology can play a vital role in controlling the size and structure of food to a greater extent. These include healthier foods (lower fat, lower salt) with desirable sensory properties; ingredients with improved properties; and the potential for removal of certain additives without loss of stability, for example in emulsions, and in smart-aids for processing foods to remove allergens such as peanut protein.

Scaling down the size of food molecules to nanosized crystals creates more particles for an overall greater surface area. Smaller particles improve food's spreadability and stability, and can aid in developing healthier low-fat food products. Multiple emulsions such as water-in-oil-in-water can distribute the lipids more evenly to reduce extra stabilizers and thickeners to achieve a desirable food texture (Garti and Benichou 2004). Bitter blockers (Senomyx, San Diego, USA) prepared from nanoscale assays (Wenner 2008) can activate the taste receptors of human tongue and can reduce the bitterness naturally inherent in some foods.

A photocatalytic process using nanogold particles (80-120 nm size) was developed by Lin et al. (2008) for shortening the aging period and enhancing the sensory quality of sorghum spirits. Contreras et al. (2009) showed that nanozinc can be potentially used to optimize conditions for surface enhancement of infrared absorption of food components. They were able to demonstrate that butter treated with nanozinc particles provided trans fat spectral information along with the degree and the unsaturation of the acyl groups. These results indicate the potential of nanomaterials in imaging to reveal useful information concerning food allergens, bioactive compounds, and microbial pathogens.

Table 1 Promising nanotechnology applications for food and bioprocessing industries

Technology	Description	Benefits
Nanostructures of food ingredients	Nanosized ingredients, additives	Improved texture, flavor, taste; Reduction in the amount of salt and sugar; enhanced bioavailability
Nanoencapsulaton of supplements based on micelles and liposomes	Delivery systems for supplements	Taste masking; protection from degradation during processing
Nanoparticle form of additives and supplements	Nano-engineered particulate additives	Antimicrobial; health benefits; enhanced bioavailability of nutrients
Improved and active nano-composites, intelligent and smart packaging	Food packaging	Improve flexibility, durability, temperature/moisture stability, barrier properties
Nutrient delivery	Enzymatic structure, modification, emulsion and foams	Targeted delivery of nutrients, increased bioavailability of nutrients
Membrane filtration	Effective separation of target material from food	Higher quality food products and fluids
Surface disinfectant	Engineering nanoparticles	Non-contaminated foods, protection from pathogens
Nanoparticle-based intelligent inks; reactive nanolayers	Nanolithography depositions	Traceability, authentication, prevention of adulteration

Safety and Societal Implications

The existing safety laws, safety testing methods, and the workplace health procedures are inadequate to measure the exposure and assess the risks posed by nanofoods, nanofood packaging, and nanobased chemicals, as summarized in Table 1. The nanomaterials used for manufacturing nanofoods and nanopackaging materials are not assessed as new chemicals and currently, the industries follow established guidelines in the safety assessments. Interaction of nanoparticles with living cells and the implications for industry and consumers is not yet understood completely. Regulations governing nanomaterial developments, verification of their safety, fate, and how to dispose them through remediation treatments need to be understood. Experimental studies and research tests should be performed to generate hazard and exposure data leading to risk assessments and to answer concerns about the possible toxicological effects of exposure to nanoparticles in the air pollution.

Acquiring evidence in the nanosafety area is fundamental for the development of proportionate controls and associated legislation. Being a very new technology, lack of data introduces potentially high uncertainty into assessments of environmental risk. The key areas of uncertainty must first be identified, and the strategic approach for addressing and managing these areas of uncertainty needs to be developed. A study from the USA (Monteiller et al. 2007) shows that toxicities of nanoparticles and large particles were similar when the dose was expressed in surface area. Hence, the complexity of the nanomaterials behavior in natural systems and the uncertainty introduced for hazard and exposure assessment can be answered by building on experiences with chemicals risk assessment. Toxicological assessment of nanomaterials in food applications by high content screening technique and Zebrafish model can provide valuable developmental toxicity information in terms of endpoint identification and mechanism elucidation (Donofrio 2006). Further research into human exposure to nanomaterials and their toxicology and biokinetics is needed.

A large number of initiatives have been established, 421 over the last few years, to address potential health and environmental safety issues associated with nanomaterials and nanotechnologies including European and American research projects and networks, International Risk Governance Council projects on nanotechnologies, and European and international standardization activities. Investigations into the health effects of inhaled nanotubes and the surface reactivity and free radical generating potential of nanomaterials are being carried out at National Nanotoxiciology Research Centre, UK. An international approach to regulate the risks from nanomaterials through Organization for Economic Co-operation and Development (OECD) has been developed. This has drawn research work into occupational exposure undertaken by the Health and Safety laboratories as part of multinational programs in the G8 countries (Canada, France, Germany, Italy, Japan, Russia, UK, and USA).

The toxicokinetic properties of engineered nanomaterials after oral exposure into the human body should be correlated with their physicochemical properties to determine whether these nanomaterials can be categorized based on appropriate dose metrics (European Food Safety Authority Report 2009).

Nanotechnology related terminology and nomenclature and validated measurement and characterization protocols in addressing the nanosafety issues to consider social and ethical concerns and demands are being undertaken by the British Standards Institution, International and European Committee for Standardization, and OECD.

Conclusions

Influenced by nanotechnology, the food and bioprocessing industry will see great advances with intelligent innovations in the upcoming years and will lead to improved food quality and safety. Nanotechnology has provided sensors and diagnostic devices with improved sensitivity and selectivity to monitor food processes and assure food quality measurements along the production lines. The brand protection and track and trace applications using nanotechnology is mostly confined to the research laboratories and is expected to grow exponentially. Nanotechnology will open up new possibilities in controlling structural changes in the food product and might permit decrease in the power consumption for food production and processing. Nanotechnology offers intriguing opportunities for research in food nanoscience and provides new chances for innovation with tremendous possibilities in bringing solutions for the food and bioprocessing industry. Knowledge gap in addressing and framing the regulations of nanotechnology usage for foods, food additives, and food packaging materials is underway through various regional and international agencies. The success of nanotechnology in the food and bioprocessing industry depends on the perception of consumers and societal acceptance.

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