Nanotechnology: A Brief Literature Review

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Contents

Introduction

Developments during the past decade in biochemistry, physical chemistry, microscopy, and engineering have resulted in a tremendous upsurge of interest in the properties of very small particles and their possible applications in a wide variety of products. Technological innovations have enabled the manipulation of tiny structures called dendrimers, quantum dots, nanoshells, nanotubes, and buckyballs (fullerenes). Currently available products marketed using the term "nanotechnology" include transparent sunscreens, stain-resistant clothing, self-cleaning glass, paints, sports equipment, and numerous applications in electronics. More than 200 consumer products marketed as "nanotechnology-based" are now on the market (www.nanotechproject.org/index.php?id=44). Medical researchers are using nanotechnology to devise more effective and efficient methods of delivering medications to specific tissues, such as in cancer chemotherapy. Researchers in universities and in food production and processing companies are now investigating possible applications for producing safer, more nutritious, and more appealing foods using nanotechnology.

What is nanotechnology? The National Nanotechnology Initiative of NSF defines nanotechnology as "the understanding and control of matter at dimensions of roughly 1 to 100 nanometers (nm), where unique phenomena enable novel applications" (www.nano.gov/html/facts/whatIsNano.html). For reference, recall that the diameter of DNA is about 2–12 nm while that of a red blood cell is 2,500 nm and a strand of human hair is 60,000 to 120,000 nm thick! A material may have different magnetic, electrical, optical, mechanical and chemical properties at various size scales. For example, physical properties of carbon change significantly when atoms of this element form nanotubes. Whereas elemental carbon is a poor conductor of electricity and not particularly strong (except for diamonds, which are formed under high pressure), aggregates of carbon nanotubes are many times stronger than steel wire and can carry more electricity than a copper wire. Carbon atoms can also be arranged to form nanostructures (fullerenes or buckyballs) that are similar to geodesic domes. Nanotubes may be used to hold hydrogen for fuel cells and buckyballs may be used to contain other useful compounds, such as drugs.

Other biological and chemical properties of nanoparticles may also differ from the macro form of these substances. This has given rise to some safety questions/concerns for production workers and consumers. Will these nanoparticles be taken up more readily through the lungs and digestive system, be disseminated more widely in the body, and be more difficult to excrete? Will they be metabolized faster and present challenges in dosing? Will composite materials containing nanoparticles shed these particles into the environment as they age and start to degrade, and what will be the fate and ecological consequences of dispersion of nanoparticles in the environment? These concerns along with questions on regulation and labeling are under consideration by universities and the government. Proponents of nanotechnology are reviewing the concerns and difficulties that arose when genetically engineered crops were introduced, hoping to anticipate and address some of the safety, societal and ethical issues that may arise, before they become contentious. Ultimately, the success of nanotechnology will be based on the acceptance of these products which will be based on functional improvements, costs, and safety.

What are the prospects for nanotechnology in the food industry? Nanoparticles in foods have traditionally been manipulated by food chemists when controlled processes of heating and cooling create nanostructures that maintain emulsions (e.g., sauces, margarine) and foams (e.g., on beer). However, new technical methods developed during the past decade have enabled manipulation of structures at the atomic level and the more specific and controlled production of novel materials and devices. Nanoparticles of carotenoids, for example, can be dispersed in water and this may improve their bioavailability. Nanoparticles of synthetic lycopene have undergone toxicity tests and may be used in the U.S. Nanoparticles may be used to encapsulate nutrients or other substances in foods, thereby improving their nutritional value or sensory attributes.

Other potential applications include "smart packaging" that could sense and indicate when food is beginning to spoil and packaging that will better control gas diffusion. Nanotechnology may also produce sensitive biosensors that can detect the presence of pathogens and toxins in foods and food processing establishments. Nanoparticles may also be used in cleaning and disinfection of surfaces and equipment. Innovations in other fields, that are not specifically food related, will likely also be applicable to the food industry. Improvements in construction materials for floors, walls, and machines as well as new devices and techniques in electronics, medicine, wastewater treatment, and other areas will impact agriculture and food processing by improving safety and efficiency.

This review will summarize recent scientific articles and government publications that address the uses of nanotechnology with some emphasis on food production and processing. Technological methods that differentiate nanotechnology from traditional food chemistry will be briefly described and societal implications and risk analysis issues will be discussed. This is not an exhaustive review of the literature but is intended to provide some basic information on nanotechnology and a description of the variety of applications being developed particularly by researchers in the biological sciences.

Technology

Synthesis and Assembly of Nanomaterials

Nanomaterials are, of course, abundant in nature as living organisms operate basically at a nanoscale level. Nanotechnologists seek to produce and utilize both novel nanomaterials and some natural nanomaterials in larger quantties and within a more consistent size range. Numerous techniques are used to fabricate different nanomaterials. Nanoparticles can be produced from larger structures (top down) by use of ultrafine grinders, lasers, and vaporization followed by cooling.

For complex particles, nanotechnologists generally prefer to synthesize nanostructures by a bottom-up approach by arranging molecules to form complex structures with new and useful properties.

Solvent extraction/evaporation. Nanoparticles of some organic polymers can be fabricated by solution in a solvent such as dichloromethane followed by sonication, evaporation, filtration, and freeze-drying (*55*).

Crystallization. Hydroxyapatite-aspartic acid (or -glutamic acid) crystals were synthesized in the presence of solutions containing different amounts of the amino acids (*9*).

Self-assembly. Manipulation of physical and chemical conditions such as pH, temperature, and solute concentrations can induce self-assembly of molecules to form fibrous nanostructures (*9;21*). Vesicles, called polymerosomes, that may be useful for encapsulation, can also be self assembled by slow evaporation of an organic solvent (*32*).

Layer-by-layer deposition. Platforms for bilayer membranes that can be used for protein analysis, can be fabricated by layering of sodium silicate and poly(allylamine hydrochloride) on gold followed by calcination in a furnace. Lipid bilayers can fuse to the silicate layer and be used to detect specific proteins (*35*).

Microbial synthesis. Living cells have been harnessed to produce nanoparticles, for example, silver nanoparticles produced extracellularly by the fungus *Aspergillus fumigatus* (*7*). Gold and silver nanoparticles can also be produced by other fungi and a number of bacterial species (*8*).

Biomass reactions. Gold nanorods and nanoparticles with other shapes were produced by incubation of dead oat stalks with an acidic aqueous solution of gold ions (AuIII) (*1*). Some living plants are also known to take up and sequester heavy metals (to prevent being poisoned by these metals) and these plants may also be useful in producing nanoparticles of metals (*8*).

Measurement, Characterization, Manipulation

High resolution electron microscopy and scanning probe microscopy can produce direct images of nanostructures and with the aid of computer controlled probes can be used to manipulate nanomaterials. Other instruments provide information on nanostructures based on their physical properties such as the scanning tunnelling microscope, which detects electronic structure and properties, magnetic force spectroscopy, which produces images of magnetic domains, and magnetic resonance microscopes, which detect nuclear or electron spin resonance. Cantilever probes and optical tweezers can manipulate nanoparticles. A variety of computer programs have been developed to simulate and model formation and interactions of nanomaterials (*38*)**.**

Applications

General Overview

Although the number of commercially available "nanotechnology-based" products is still relatively small, over 230 have been listed by the Project on Emerging Technologies (`http://www.nanotechproject.org/index.php?id=44`), and a tremendous amount of research is occurring in university, government and research laboratories. Nanotechnology is enabling the development of sensitive biosensor materials that can detect the presence of very small amounts of toxins, pathogens, volatile compounds, and various organic compounds present in body fluids or environmental samples. These will be useful in many areas, including detection of toxins, pathogens, and spoilage in foods and food-processing facilities, localization and monitoring of diseases in humans, detection of bioterrorism agents, detection of environmental toxins and assessing effectiveness of remediation processes**.**

Nanotechnology will also have useful applications in the fields of nutrition and nutritional supplements. Biosensors may detect the presence of chemicals indicating deficiencies of nutrients even before any recognizable symptoms appear, and nanomaterials may be used to deliver specific amounts of nutrients directly to tissues and cells that need them (*13;19;41;49*).

Currently Available and Potential Applications in Food Production and Processing

Food packaging. Improvements in characteristics of food packaging materials, such as strength, barrier properties, antimicrobial properties, and stability to heat and cold, are being developed using nanocomposite materials. Incorporation of nanoparticles of clay into an ethylene-vinyl alcohol copolymer and into a poly(lactic acid) biopolymer was found to increase barrier properties to oxygen. Electron microscopy shows that there is a strong adhesion between the clay nanoparticles and the polymer matrix and that there are exfoliated layers of clay that enhance the tortuosity factor thereby impeding the diffusion of gases through the composite membrane. This type of packaging may extend shelf life of food products (*30*). Polymer-silicate nanocomposites have also been reported to have improved gas barrier properties, mechanical strength, and thermal stability (*11;26;43*).

Other nanotechnology applications in packaging include sensors that can detect food deterioration, nanoclay-nylon coatings and silicon oxide barriers for glass bottles that impede gas diffusion, metallized films, antimicrobials incorporated in packaging, smarter bar codes, and improved pigments, inks, and adhesives.

Food processing. Some food processing methods utilize enzymes to alter food components to improve flavor, nutritional value or other characteristics. Immobilization of these enzymes on nanoparticles may aid in dispersion through food matrices and enhance their activity. Nano-silicon dioxide particles with reactive aldehyde groups were contructed and found to covalently bind to a porcine triacylglycerol lipase. These particles effectively hydrolyzed olive oil and were determined to have good stability, adaptability, and reusability (*3*).

Cleaning and disinfection. Titanium dioxide, in the presence of UV light, generates reactive species such as hydroxyl and superoxide radicals that cause degradation of organic compounds and, potentially, bacteria. However, this reaction is not very efficient as most of the excited electrons in titanium dioxide recombine and do not produce radicals. Deposition of silver on nanoparticles of titanium dioxide significantly increases its bacteriocidal effects against *E. coli* (*28*) while titanium dioxide combined with carbon nanotubes has enhanced disinfectant properties against *Bacillus cereus* spores (*29*). Silver-doped titanium dioxide nanoparticles also inactivated *B. cereus* spores on aluminum and polyester surfaces (*51*) and destroyed airborne bacteria and molds when incorporated into an air filter (*52*).

Silver itself is known to have antibacterial effects, and nanoparticles of silver stabilized with SDS or PVP effectively inhibited growth of *E. coli* and *Staphylococcus aureus* (*15*). Surfaces in some refrigerators and food storage containers contain nanoparticles of silver which reportedly prevent growth of pathogens and spoilage bacteria.

Sensors. Improved biosensor technology may be used to detect gases present in packaged foods as a measure of integrity of the packaging material, compounds released during food spoilage or deterioration, and the presence of pathogens or toxins in foods. Such sensors could be incorporated into packaging to alert consumers, producers, and distributers as to the safety status of foods or could be used to detect pathogens in processing plants. Recent developments in nanobiosensors have been reviewed. (*2;14;23*).

Numerous recent research papers describe detection methods for bacteria, viruses, toxins or other organic compounds based on nanotechnological methods and devices. A few examples which may be relevant to food safety and processing are described here.

Immunosensing of *Staphylococcus* enterotoxin B (SEB) in milk was achieved using poly(dimethylsiloxane) (PDMS) chips with reinforced, supported, fluid bilayer membranes. Antibodies to SEB were attached to the bilayer membrane in PDMS channels to form a biosensor with a detection limit of 0.5 ng/mL (*16*).

An immunomagnetic bead sandwich assay using universal G-liposomal nanovesicles in an array-based system was developed to simultaneously detect *E. coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes*. In mixed cultures, limits of detection were 3.1 x 10^3, 7.8 x 10^4, and 7.9 x 10^5, respectively (*12*).

An electrochemical glucose biosensor, with detection and quantification limits of 0.035 and 0.107 mM, respectively, was nanofabricated by layer-by-layer self-assembly of polyelectrolytes on an electrode platform. Multi-walled carbon nanotubes dispersed in the perfluorosulfonated polymer, Nafion, were deposited on a glassy carbon electrode followed by adsorption of a chitosan derivative as a polycation and glucose oxidase as a biorecognition element. Glucose in solution was detected by changes in current (*39*).

Liposome nanovesicles have been devised to detect peanut allergenic proteins in chocolate (*53*) and pathogens (*17*).

Current and Potential Applications in Other Fields

Medicine. Nanoscience and nanotechnological methods are spurring the development of more sophisticated tools for detecting diseases, such as cancer and atherosclerosis, at early stages, delivering drugs to specific sites in the body, and performing neurosurgery.

Applications of nanotechnology in diagnosis of disease are developing rapidly. Two targets associated with atherosclerosis, fibrin and tissue factor, can be detected by MRI using paramagnetic nanoparticles targeted to these proteins and by use of targeted echogenic liposomes that alternate lipid bilayers with an aqueous fluid and produce an ultrasound signal (*54*). Nanoparticles of superparamagnetic iron oxide can also be used to visualize brain tumors using MRI (*34*). Specific nanoparticles can also be combined with nanowires, nanotubes, nanocantilevers, and microarrays to produce integrated and automated detection systems (*31*).

Nanoparticles may also aid in delivering drugs directly to tissue targets. Among applications under development are: (*a*) nanoparticles specific for smooth muscle cells that are loaded with paclitaxel or fumigallin that inhibit plaque development on artery walls (*54*) and poly(lactide)-tocopheryl polyethylene glycol succinate particles to efficiently deliver the cancer drug, paclitaxel (*55*); (*b*) "stealth" nanoparticles that circumvent the blood-brain barrier and deliver drugs to attack brain tumors (*34*); and (*c*) RNA nanoparticles containing siRNA (small interfering RNA) and folate for treatment of nasopharyngeal carcinoma. Cells of this cancer type contain a large number of folate receptors on their surface membranes. These nanoparticles would bind to the membranes and and bring the siRNA into the cells (*22*).

Restorative materials that aid in healing or replace damaged body parts may also be improved by nanotechnology. Nanoparticles of quaternary ammonium polyethylimine have been incorporated in composite resins used in dentistry to replace hard tissues. Such resins exerted antibacterial effects against *Streptococcus mutans* for at least one month and did not diminish the structural integrity of the resin (*6*). Nanocrystals of hydroxyapatite-aspartic acid (or -glutamic acid) have been found to interact with osteoblasts and enhance their activity in mineralization reactions. These composites may be useful in treatment of osteoporosis and other bone diseases (*9*). Nanofibers of a peptide amphiphile have been used to construct a scaffold that attached mesenchymal stem cells and enhanced their proliferation and differentiation. This system may also be useful for tissue repair (*9*).

In a procedure called "nano neuro knitting," one research group described the use of SAPNS (self-assembling peptide nanofiber scaffolds) to repair a severed optic nerve tract in hamsters. Regeneration of axons (elongated parts of nerve cells) after traumatic injury or a stroke is very difficult because of the formation of scar tissue, gaps in nervous tissue caused by phagocytosis of damaged cells, and the inability of many adult neurons to initiate axonal growth. SAPNS are self-assembling peptides with alternating positive and negative L-amino acids that form interwoven nanofibers (about 10 nm in diameter) that form a highly hydrated scaffolds in human body fluids, culture media, and even saline solutions. This scaffolding bridges the damaged tissue providing a framework for the partial regrowth and connection of nerve cells. Approximately 80% of nerves were regenerated in both adult and young animals in the best cases and some regrowth was evident after only 24 hours (*18*).

Nanotechnological tools may also shed light on many normal and pathological physiological processes. Lipoproteins, for example are of critical importance to human health and yet we don't yet understand why small dense LDL are so atherogenic while small HDL are so effective in reverse cholesterol transport. Nanoscience will improve our understanding of basic science and potentially lead to useful interventions (*20*). Size and shape of cells are affected by many factors, among them the nanotopography of substrates they contact. Experimental work defining these important nanofeatures may aid in tissue engineering and development of prosthetic devices (*44;46*).

Pollution abatement. Provision of sufficient clean water for human consumption, agriculture, and industrial processes is an ongoing and increasing challenge as a result of population growth, extended droughts, and numerous competing demands. Nanotechnology offers several possible novel, improved and efficient methods for purifying water.

Photocatalytic membranes have been produced and tested in a pilot plant for their efficacy in degrading triazine herbicides. Use of these compounds particularly in areas with sandy soils has contaminated underground aquifers with compounds such as atrazine. Composite membranes produced by nanotechnology and containing titanium dioxide, tributyl- and triisopropyl vanadate were exposed to sunlight resulting in the oxidation and destruction of atrazine in water at a concentration of 1 ppm (*5*). Other systems containing titanium dioxide nanoparticles have been reported to degrade PCBs and other organic pollutants in water (*42*).

Nanomaterials can also be used to adsorb or sequester pollutants and remove them from water. Sorbents are already widely used in water purification but nanosorbents can be much more effective because they have a much larger surface area as compared to conventional bulk particles. Various chemical groups can also be added to nanoparticles to improve their specificity in removing certain pollutants. Multiwalled carbon nanotubes have been found to adsorb three–four times the amount of heavy metals (copper, cadmium, and lead) as powdered or granular activated carbon. Chitosan nanoparticles containing tripolyphosphate adsorb even greater amounts of lead. Other nanosorbents have been devised to remove arsenic and chromium from water. Carbon nanotubes and nanoporous activated carbon fibers can effectively adsorb organic pollutants such as benzene and fullerenes can adsorb polycyclic aromatic compounds such as naphthalene (*42*).

Ultrafiltration and reverse osmosis are now used to remove impurities from water. Nanotechnology can enhance the effectiveness of these processes, and nanofiltration processes are being developed for desalination. Carbon nanotube filters can effectively remove bacteria and viruses from water, and other nanostructured membranes have been reported to remove organic pollutants, uranium, arsenic, and nitrates. Gram-positive and -negative bacteria can be killed by nanoparticles of silver compounds and magnesium oxide which disrupt bacterial cell membranes (*42*).

Dendritic polymers are highly branched macromolecules with a controlled composition and architecture. These polymers (1–20 nm in size) can act as soluble ligands for radionuclides, heavy metals, inorganic ions, and organic solutes. Metal-dendrimer complexes can be separated from the solution and the metals released by altering the pH. This would allow reuse of the polymers and recovery of the metals.

Dendritic polymers can also act as scaffolds to carry antimicrobial compounds (*42*).

Toxicology/Safety of Nanoparticles and Nanostructures

Overview

As yet the potential for nanomaterials to exert deleterious effects on humans or the environment is poorly understood but data on their possible effects is needed so that expanded development and use of nanotechnology can proceed. Promoters of nanotechnology are aware of the problems encountered by genetic engineers when the public suddenly became aware of genetically modified crops present in fields and in foods. Already there has been one reported rapid withdrawal of a nanotechnology-based product, Magic Nano, a spray-on ceramic sealant to repel dirt. Over 110 consumers in Europe reported respiratory symptoms after using the product and the product was pulled in March 2006 (*36*). There is a need to educate the public about these new technologies and to discuss their promise as well a potential safety issues and how these are being addressed.

Assessing the risk of using nanomaterials presents some unique challenges because there is little published research on which to base conclusions and recommendations. A preliminary framework has been developed to help determine what research is needed, how it can be integrated, and how the resulting information can be incorporated into decisions about safety (*33*). Thirteen experts with competence in a variety of relevant fields were interviewed to establish a list of factors affecting the potential human health risks and ecological risks of nanoparticles. Information was sorted into an influence diagram with relationships that the experts hypothesized would affect safety assessment. This framework can help prioritize experiments necessary to determine safety of nanoparticles. As research results are obtained, they can be incorporated into the framework and used to estimate potential risks.

A Forum Series of seven articles on Research Strategies for Safety Evaluation of Nanomaterials was presented in *Toxicological Sciences* in 2005–2006. Toxicological risk assessment requires data on both exposure to and uptake of nanoparticles and the toxic effects of these particles (if any) once they enter the body. Unfortunately, available data on these topics is sparse although there are some recent reports and ongoing projects (*47*). Some data are available on exposure routes but the unique physicochemical properties associated with different nanoparticles complicate risk assessment (*27;50*). Techniques were described for basic nanoparticle characterization within the body to aid in assessing how they will interact with biological systems (*37*). Dissolution may be a critical factor determining biological fate and effects of nanoparticles in the body. Numerous factors affect dissolution, including concentration, surface area, surface energy, surface morphology, aggregation, dissolution layer properties, and adsorbing species (*10*). Recent advances in nanotechnology are aiding development of sensors that determine markers of exposure, biological responses, and environmental remediation (*4*). Some consumer products (cosmetics and sunscreens, sports equipment, textiles) containing nanomaterials were examined to evaluate possible human exposures to nanoparticles from these products and any potential hazards they pose (*48*).

Potential Routes of Human Exposure

Skin. Outer layer of skin consists of several layers of dead keratinized cells which, when intact, prevent the entry of most ionic and water soluble substances. Very little observational or experimental data are available on penetration of the skin by nanoparticles. Micrometer-sized particles of titanium dioxide can penetrate the surface of the skin and get into hair follicles but are not thought to react with living tissues. However, some smaller particles were said to penetrate deeply enough to be taken up by macrophages. Nanoparticles are probably more likely to penetrate the skin than larger particles although the chemical composition and structure of the particles will affect their uptake. At present, it is impossible to predict whether nanoparticles will pass through the skin to a significant extent (*25*).

Lungs. During inhalation, most dust particles are entrapped by the mucus lining the airways but nanoparticles are small enough that they would travel deep into the lungs, into the air sacs or alveoli. Low concentrations of nanoparticles can be cleared from the lungs by macrophages but higher concentrations may overwhelm the macrophages and cause inflammation. Inhalation experiments with rodents have demonstrated some toxic effects of carbon nanotubes. Chemical reactivity, surface charges, and structure of the nanoparticles will likely also affect clearance/inflammation. Aside from inflammatory reactions in the lungs, inhaled nanoparticles have also been associated with adverse effects in the nervous and cardiovascular systems There is not much data on translocation of these particles to other parts of the body (*25*).

Gastrointestinal tract. Nanoparticles can be absorbed from the intestine and enter the circulatory system. Diseases of the gut may enhance uptake of particles as barriers are damaged. On the other hand, some aspects of the gastrointestinal environment may reduce potential toxicity of nanomaterials. Transit time through the gut is relatively fast and there are many other macromolecules in food that may affect the uptake or possible toxicity of nanoparticles. Moreover, the abrupt change in pH from the stomach to the intestine may affect charge and surface characteristics of nanoparticles (*25*).

Distribution and systemic effects. Both size and surface characteristics of nanoparticles affect their distribution throughout the body. Nanoparticles are readily taken up by many types of cells *in vitro* and are expected to cross the blood-brain barrier that excludes many substance that might harm the brain. Some studies have reported that nanoparticles cause oxidative stress in the liver, contribute to lung inflammation, and activate blood platelets that may contribute to clot formation (*25*). *In vitro* studies demonstrated that fullerenes caused morphological changes in vascular endothelial cells and, at high concentrations, could induce cytotoxic and lethal effects (*24*). Further *in vivo* studies are necessary to determine whether these nanoparticles could contribute to development of cardiovascular disease.

Societal Implications

As with any new technology that offers significant benefits to humankind, there are also risks of adverse and unintended consequences with nanotechnology. A 2003 workshop sponsored by NNI solicited information and analyses of societal implications of nanotechnology from representatives of government, industry, and researchers from a wide range of scientific and engineering fields. A full report of the workshop can be found on the NSF website (www.nsf.gov/crssprgm/nano/reports/nsfnnireports.jsp) and a short summary has also been published (*40*). Discussions were centered around ten themes:

Productivity and equity. Nanotechnology is expected to improve efficiency in nearly all types of material work.

Future economic scenarios. Systemic economic progress may be achieved as new industries are created and productivity and profits from other industries are improved.

Quality of life. Improvements in agriculture, energy technology, water purification, and environmental preservation may improve quality of life.

Future social scenarios. Transition from today's technology to more efficient and environmentally friendly nanotechnology may be smooth or rough depending on how adequately institutions can deal with these changes.

Converging technologies. Nanotechnology will converge with other fields of science because many structures and processes occurring in these fields are based on phenomena that occur at the nano scale. Changes will occur in science and engineering and some of these may be disruptive.

National security and space exploration. Advanced materials for space exploration and combat and surveillance equipment produced by nanotechnology may extend possibilities in these areas. This will also require an increase in the training of scientists and engineers.

Ethics, governance, risk, and security. Public involvement must involve an informed public communicating in a two-way conversation with nano-engineers and nano-scientists. Interdisciplinary discussions of ethical and social dimensions of nanotechnology must be respected.

Public policy, legal and international aspects. Investment in nanotechnology by governments as well as careful attention to consequences to human health and the environment are both necessary for the public to accept and benefit from commercial products with nanomaterials.

Interaction with the public. Negative public opinion could impede research in nanotechnology and therefore the NNI should act as an honest broker to encourage research and allay fears.

Education and human development. Nanotechnology will present opportunities to integrate science and technology with social science and humanities. Education must provide mechanisms for updating scientists and engineers on new technologies as well as making all students critical thinkers capable of intelligent debates about societal effects of nanotechnology. An undergraduate course on nanotechnology has been designed to give students in a variety of fields an understanding of nanoscience and to develop critical thinking skills for considering interactions between nanotechnology and society (*45*).

Web Sites on Nanotechnology

National Nanotechnology Initiative (NNI), National Science Foundation	www.nano.gov/
Project on Emerging Nanotechnologies (Woodrow Wilson Institute)	www.nanotechproject.org/
Nanotechnology: Small science, big deal: (Science Museum, UK)	www.sciencemuseum.org.uk/antenna/nano/
Nanotech News	nanotechwire.com/
Nanotechnology Risk Resources	www.lafollette.wisc.edu/research/Nano/nanorisk/
IFST Information Statement on Nanotechnology	www.ifst.org/uploadedfiles/cms/store/ATTACHMENTS/Nanotechnology.pdf

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