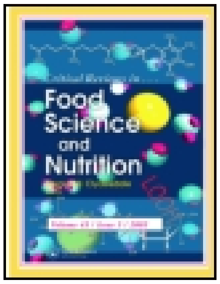

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Nanotechnology in Agri-Food Sector

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ABSTRACT

The emergence of nanotechnology developments using nanodevices/ nanomaterials opens up potential novel applications in agriculture and food sector. Smart delivery systems, biosensors and nanoarrays are being designed to solve the problems faced in agriculture sector. Similarly, food sector is also benefited through the use of smart biosensors, packaging materials, and nano-nutraceuticals. In spite of the great potential of nanotechnology in agri-food sector people are ambiguous about use in food applications because of suspected potential health risks and environmental concerns. Nanoparticles, due to their unique characteristics including small size, shape, high surface area, charge, chemical properties, solubility and degree of agglomeration can cross cell boundaries or pass directly from the lungs into the blood stream and ultimately reach to all of the organs in the body. This is the reason why they may pose higher risk than the same mass and material of larger particles. In this article, we have made an attempt to give an overview of nanotechnology developments in agri-food sector, risks associated with nanomaterials and toxicity regulations for policy framework.

Keywords Nanotechnology, agriculture, food

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INTRODUCTION

Nanotechnology is a rapidly growing field of science globally. It has impact on every area of science and technology. Technological convergence across the fields of physics, engineering, chemistry, biology, agriculture and food sciences is an essential core for the development of nanotechnology. Agriculture is the backbone of most of the developing countries, where more than sixty percent population is reliant on it for their livelihood. Nanotechnology has the potential to revolutionize agriculture and food sector (Roco, 2003; Kuzma and Verhage, 2006), such as agricultural productivity through genetic improvement of plants and animals (Kuzma, 2007; Scott, 2007), delivery of genes and drug molecules to specific sites at cellular levels in plants and animals (Maysinger, 2007), and nano-array based gene-technologies for gene expressions in plants and animals under stress conditions (Walker, 2005). The technologies with suitable techniques, certain sensors are being identified for precision in agriculture, natural resource management, and smart delivery systems for agrochemicals like fertilizers and pesticides (Day, 2005). Nanotechnology can be used for increasing the efficiency of microarrays**,** development in early detection of pathogens and contaminants in food products as well as smart integration systems for food processing and packaging (Moraru et al., 2003). Nanocomposites and nanobiocomposites can be used for plastic film coatings in food packaging. Likewise, anti-microbial nanoemulsions can be used in decontamination of food equipment,

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packaging and food processing. Nanoparticles (NPs) can also be used to increase the bioavailability and to deliver nutrients directly to cells.

Globally, many countries have identified the potential of nanotechnology in the agri-food sector. These are now investing a significant amount of money in it. The United States Department of Agriculture (USDA) has set out ambitious plans to be achieved in the short, medium and long term goals/targets. It aims at to discover novel phenomena, processes and tools to address challenges faced in the agricultural sector (Joseph and Morrison, 2006). The Food Standards Agency (FSA), UK has commissioned studies to assess new and potential applications of nanotechnology in food packaging. At the same time, govt agencies are funding more money towards research and development in the field of nanotechnology. The main focus would be towards development of functional food, nutrient delivery systems and methods for optimizing food appearance such as colour, flavour, consistency etc. These research and development (R&D) activities are not just restricted to developed countries but developing countries are also actively participating in it (Joseph and Morrison, 2006).

Despite the fantastic potential of nanotechnology in agri-food sector, it also suffers from toxicological risks and hazards. Nanomaterials may also pose threat to environment and human health.[10] Presently, there are no standard guidelines from regulatory agencies like Food and Drug Administration (FDA), Environmental Protection Agency (EPA) for risks associated with nanomaterials (US EPA, 2007).

NANOTECHNOLOGY IN AGRICULTURE

Smart Delivery Systems for Agrochemicals

Areas where nanotechnology can play role in agriculture sector are shown in Figure 1. Mainly it involves delivery systems of agrochemicals, early detection of pathogens, and detection of crop diseases. Such delivery systems can be used to deliver chemicals in a controlled and targeted manner in the same way as nanomedicine are being used for drug delivery in animals (Kumari et al., 2010). Agrochemicals play a key role in agriculture production. It has been reported that the use of agrochemicals can reduce grain loss by 30–40%. However, agrochemicals when applied traditionally are decomposed by climatic factors i.e. wind, sunlight, rain etc (Liu et al., 2008). Also a significant proportion of agrochemicals do not reach their targets and therefore, periodic application is required for satisfactory treatment. This agrochemical over dosage not only increases the cost but also leads to undesirable side effects to plants and environment. The remaining pesticide often persist in plants and soil, which goes into water, even enters into human body through food chains, and may pose threats to both humans and the environment. Modern technologies such as encapsulation and controlled release methods have revolutionised the use of agrochemicals in crop production (Mulqueen, 2003).

Pesticidal nanoformulations have recently gained the attention of scientific community. Small size, improved absorption, solubility (become readily available to plants), stability (NPs don’t settle in liquid suspension) etc. Therefore, smaller quantities are required for more precise spray applications using suitable nozzles. In the soil, NPs migrate quickly and become available for use. The agrochemicals has been loaded or encapsulated into different nanocarriers leading to increase in their bioefficacy, protection from rapid degradation, sustained release and prolonged duration of bioactive agents. This also reduces the usage and side effects of agrochemicals. Bifenthrin, a synthetic pyrethroid insecticide that affects the nervous system in insects, has been intensively used in cotton pest management. Poor solubility of bifenthrin in water and high solubility in oils is creating greater risk of transdermal exposure to workers. These limitations have been overcome by formulating NP suspensions of bifenthrin by flash nanoprecipitation (Liu et al., 2008).

Bifenthrin NPs provide greater efficiency, better uniformity of coverage and less exposure to workers (Mulqueen, 2003). Avermectin shows activity against broad range of nematodes and arthropod pests, has been loaded into porous hollow silica NPs. Avermectin exhibited multistage sustained release from the porous hollow silica NPs. Release rate of avermectin can be modulated by increase in temperature or pH (Wen et al., 2005). Validamycin is a non-systemic antibiotic with fungicide action, has also been encapsulated in porous hollow silica NPs. Validamycin loaded at the external surface, inter space of the pore channels on the shell and internal core of porous hollow silica NPs leads to variable release rates, which can also be modulated by increase in temperature or pH (Wen et al., 2005). Chlorothalonil, a broad spectrum non-systemic fungicide and tebuconazole, a triazole fungicide are used agriculturally to treat plant pathogenic fungi. They have been incorporated into polymeric NPs and have shown greater biological activity against *G. trabeum* after loading in NPs (Liu et al., 2001). This study showed that NPs can also be used for preparing new formulations of wood preservatives as well.

The application of synthetic chemical pesticides to plants or soil produces toxic effects to environment, plants, humans, and animals. Essential oils are good candidates for the substitution

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of conventional pesticides and their potential has been widely published and patented in recent years (Chiasson et al., 2001). The advantages of using essential oils in crop protection are their low mammalian and fish toxicity as compared to synthetic pesticides and their non persistence in fresh water and soil. However, the essential oils are chemically instable in the presence of air, light, moisture, and high temperatures. These parameters can cause rapid evaporation and degradation of some active components. Incorporation of essential oils in controlled release nanoformulations could provide protection to environmental degradation process and prevent the removal from their target till the action take place. The ideal formulation should also maintain a minimum effective and continuous controlled release of the essential oil. This would allow the use of much less natural pesticides for the same period of activity. For example, *Artemisia* essential oil shows contact toxicity against *Sitophilus zeamais*. *Artemisia* essential oil has been loaded onto solid lipid NPs (SLN). Such SLN formulations exhibited higher physical stability and reduced rate of oils evaporation (Lai et al., 2006). Nanoformulations of agrochemicals have already entered the market. Many companies are making formulations of NPs in the size range of 100-250 nm. Such formulations are able to dissolve in water more effectively than existing ones, thus increasing their activity (ETC Group, 2004). Other companies employ suspensions of nanoscale particles (nanoemulsions), which are either water or oil based and contain uniform suspensions of pesticidal or herbicidal NPs in the range of 200- 400 nm. These can be easily incorporated in various media such as gels, creams and liquids etc (Joseph and Morrison, 2006). Leading agri-chemical companies including BASF, Bayer Crop Science, Monsanto and Syngenta are engaged in nanotech research in the various described areas. Syngenta currently retail a number of chemicals with emulsions that contain NPs. Agrochemicals containing NPs include

Primo Maxx Plant growth regulator, Banner Maxx fungicide, Apron Maxx RFC seed treatment and Cruise Maxx Beans (ETC Group, 2004).

There is a high scope for applying NPs and nanocapsules to crop plants for agricultural productivity enhancement (Pavel et al., 1999; Liu et al., 2001; Cotae and Creanga, 2005; Pavel and Creanga, 2005; Joseph and Morrison, 2006). Gene transfer by bombardment of DNA absorbed gold particles has been successfully used to generate transgenic plants in a species independent manner (Christou et al., 1988). Recently, Torney et al. (2007) reported the efficient delivery of DNA and chemicals through silica NPs internalized in plant cells, without requiring specialized equipments. They explored both the surface attachment and encapsulation properties of silica NPs using plant cells as the test-bed. Plants have a thick cell wall that impedes delivery of materials from the exterior. Therefore, delivery is achieved by incubating protoplasts with fluorescently labelled silica NPs. The modification in the surface with triethylene glycol has been found necessary for silica NPs to penetrate the cells and this has also allowed DNA plasmids (cloned DNA segments) to adsorb onto the silica NPs surface (Torney et al., 2007). After it enters the protoplasts, the plasmid DNA was released from the silica NPs surface. The green fluorescent protein (GFP) marker encoded in the DNA was expressed in the cells and detected by microscopy. Delivery was efficient as the minimum amount of DNA required to detect marker expression was 1,000-fold lower than that required with conventional methods to deliver DNA into protoplasts (Torney et al., 2007). Recently, Gonzalez-Melendi et al. (2008) treated *Cucubita pepo* plant with carbon coated iron NPs, observed under electron microscopes and confocal microscopes. They found that NPs had entered and translocated in whole living plants through

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vascular system. The magnetic character of NPs allowed them to be positioned in the desired plant tissue by applying a magnetic field gradient.

Micro and Nanoarrays

Another area in agriculture where nanotechnology can play a vital role is the microarray analysis of plants. This technique provides high throughput simultaneous analysis of mRNA for hundreds of gene (Lockhart and Winzeler, 2000; Aharoni and Vorst, 2002). Such comprehensive analysis provides the opportunity to explore molecular mechanisms that underlie a variety of plant physiological processes, and therein complementary DNA (cDNA) and oligonucleotide arrays can be used to gain a direct link to gene functions (Schena et al., 1998). Thus, by correlating changes in gene expression with changes in physiology, it is possible to derive insight into a broad range of biological processes. Microarrays have already been used to characterize genes involved in the regulation of circadian rhythms, plant defence mechanisms, oxidative stress responses, phytochrome signalling, fruit ripening, seed development and nitrate assimilation (Aharoni and Vorst, 2002).

Microarrays used in the biological sciences can be divided into two groups: cDNA and oligonucleotide microarrays (Schulze and Downward, 2001). This division refers to characteristics of the probes and the individual pieces of gene-specific DNA that are immobilized on the array surface. cDNA probes are usually products of the polymerase chain reaction (PCR) generated from cDNA libraries or genomic DNA and are typically in excess of 150 nucleotides in length. On the other hand, synthetic oligonucleotides have a maximum length of around 80 nucleotides, thus conferring greater specificity among members of gene families

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(Aharoni and Vorst, 2002; Kuo et al., 2002; Lipshutz et al., 2002). Array fabrication involves either spotting of presynthesized probes using highly precise robots or *in situ* synthesis on glass slides. High density spotted microarrays can contain up to 40,000 probes on a conventional microscope slide. In contrast, arrays consisting of gene-specific oligonucleotides can be synthesized directly onto a solid surface by either photolithography or ink-jet technology (Schena et al., 1998). Since sequence information by itself is sufficient to generate the DNA probes to be arrayed, probes can be designed to represent the most unique part of a given transcript. Major advantage of oligonucleotide arrays is that they require no handling and tracking of cDNA resources (Schena et al., 1998; Brown and Botstein, 1999; Schulze and Downward, 2001).

With this intention much attention has been paid to the miniaturisation of microarrays. Miniaturisation is advantageous as both sample volume and analytes can be reduced. Nanotechnology can be used for increasing the efficiency of micrroarrays by mobilisation strategies and signals enhancement of microarrays. Organic dye doped silica NPs have been used to detect DNA. A large number of fluorophores have been encapsulated inside a single NP, which produced a strong fluorescence signal upon proper excitation. Therefore, when one probe DNA was labelled with one dye doped silica NP, the signal was greatly amplified as compared to that with one fluorophore. Through the use of this strategy, DNA target molecules could be detected at a concentration as low as 8×10^{-13} M (Zhao et al., 2003; Yan et al., 2007).

Quantum dots (QD) could also be used to detect DNA sequences instead of fluorophores. A quantum dot is a semiconductor particle (e.g. ZnS, CdSe and CdS) that can be used as a fluorophore (Bruchez et al., 1998; Medintz et al., 2005; Somers et al., 2007). They are candidates for replacing conventional fluorescent markers such as rhodamine in biodetection assays and are more photostable and sensitive than an organic fluorophore. They are characterized by a band gap between the valence and the conduction bands, while in natural bulk semiconductor material, there is practically no electron in the conduction band, but instead they occupy the valence band. The photon having an excitation energy exceeding the band gap energy is absorbed by a QD and electrons are promoted from the valence gap to the conduction gap creating a positively charged hole in the valence gap. The excited electron may then relax to its ground state by the emission of another photon with energy equal to the band gap (Costa-Fernandez et al., 2006). Quantum dots can be used for in situ hybridisation and immunolabelling in plants. Immunolabeling experiments demonstrated greater sensitivity than the conventional system Alexa 488. In contrast, detection of QDs in *in situ* hybridisation of several plant chromosomes, using high-copy number sequences, was less sensitive than Alexa 488. Indeed, semiconductor nanocrystal fluorophores are more suitable for immunostaining but not for *in situ* hybridisation of plant chromosomes (Muller et al., 2006).

Polychromatic microarrays have been reported to analyze simultaneously eight different samples of *Bacillus anthracis* using beads coated with single stranded DNA (ssDNA) probes localized into etched wells of fiber-optic arrays. Biotinylated samples labelled with streptravidin-QD conjugates were then hybridized to the array (Shepard, 2006). A bead sensor is based on the two-dimensional aggregation of single-stranded ODN-modified gold NP. It probed upon hybridization with the complementary target with two types of gold NPs carrying different DNA sequences complementary to the target. This lipid layer formed on an organic or an inorganic substrate allowed the NPs to move along the surface. The sensor was then incubated with the target. The color change described as a colorimetric signal in the three-dimensional (3D) system cannot be used with the two-dimensional (2D) system, where detection is based on desorption properties of the NPs by adding chemical species to the solution. Addition of dextran sulfate to the solution after hybridization was carried out with a noncomplementary target, which induced complete NP desorption. Consequently, a discoloration of the sample was observed (Elghanian et al., 1997; Storhoff et al., 2000; Cao et al., 2005).

Poly adenine DNA strands were patterned over silicon substrate of 4 mm areas with 50 nm resolution by a soft-lithographic subtraction printing process, and DNA hybridization was used to direct the assembly of sub-20 nm polythymine to create highly ordered two-dimensional NP arrays. The entire printing and assembly process was accomplished in as few as three fabrication steps and required only a single lithographically templated silicon master that could be used repeatedly. The low-cost procedures developed to generate nanoscale DNA patterns can be easily extended toward roll-to-roll assembly of nanoscale materials with sub-50 nm resolution and fidelity (Noh et al., 2008).

Nanoarrays containing multiple features, such as a range of different proteins or small-molecule ligands are difficult to fabricate. Atomic force microscopy based nanografting of DNA nanopatches allows non specific binding of nanografted DNA to proteins and antibodies. Therefore, nanografted patches of ssDNA within a monolayer of protein-repellent ethylene glycol-terminated alkylthiols were generated on a flat gold substrate. Subsequently, proteins covalently modified with cDNA sequences were immobilized onto the nanopatch by means of DNA-directed immobilisation, thus producing detector for protein interaction studies. Interactions between the proteins and antibodies were assessed between nanografted patches by using atomic force microscopy. These nanografted patches are suitable for application in biosensing and fabrication of multifeature nanoprotein array (Bano et al., 2009).

Protein microarrays require high sensitivity because of the low abundance of some of the biomarkers. In this effort, europium NPs signal enhancement of antibody microarrays has been developed. Such microarray is based on two nanomaterials. The first is polystyrene NPs incorporated with europium chelate (diketone) and coated with streptavidin. The second nanomaterial is array surfaces of nanoporous silicon creating high capacity for antibody adsorption. Europium NPs signal enhancement of antibody microarrays and streptavidin labelled with a nine-dentate europium chelate were used for analyzing biotinylated prostate-specific antigen spiked into human female serum yielded a 10 fold signal enhancement compared to the streptavidin europium chelate. Greater sensitivity for the europium NPs signal enhancement of antibody microarrays assay with limit of detection 0.14 ng/mL, was observed compared to the streptavidin-europium chelate assay with limit of detection 0.7 ng/mL. This work demonstrated the novel utility of NPs with time-resolved fluorescence for signal enhancement of antibody microarrays, requiring as low as 100–200 zmol biotinylated prostate specific antigen per microarray spot (Jaras et al., 2008).

Green Synthesis of NPs

NPs find extensive applications in sensor technology, biological labelling, optoelectronic, information storage and drug delivery (Gracias et al., 2002; Tom et al., 2004; Qiu et al., 2004). Recently more emphasis have been given in green synthesis of NPs (Gardea-Torresdey et al., 2002; Shankar et al., 2003a; Shankar et al., 2003b; Shankar et al., 2004; Ankamwar et al., 2005a;

Ankamwar et al., 2005b; Chandran et al., 2006; Kasthuri et al., 2009; Song and Kim, 2009). Green synthesis using plants that contained functional molecules for the reaction is compatible with the green chemistry principles (Mohanpuria et al., 2007; Kumar and Yadav, 2009). The huge amount of phytochemicals in plant extracts are acting as reducing and capping agents for metallic NPs (Shankar et al., 2004; Song and Kim, 2009). NPs may not be produced in a laboratory, but grown in fields of genetically engineered crops–what might be called "particle farming". Alfalfa plants grown on an artificially gold-rich soil produced gold NPs in the roots and along the entire shoot of the plants. These NPs had physical properties like those produced using conventional chemistry techniques, which are expensive and harmful to the environment (Gardea-Torresdey et al., 2002). The plant mediated methods are environment friendly and biocompatible, that do not require any toxic chemicals (Shankar et al., 2004; Song and Kim, 2009).

Precision Farming

Precision farming also known as site-specific management, describes a bundle of new information technologies applied to the management of large-scale, commercial agriculture. Precision farming technologies include personal computers, satellite-positioning systems, geographic information systems, automated machine guidance, remote sensing devices and telecommunications (Joseph and Morrison, 2006). Precision farming relies upon intensive sensing of environmental conditions and computer processing of the resulting data to inform decision-making and control farm machinery. Precision farming technologies typically connect global positioning systems (GPS) with satellite imaging of fields to remotely sense crop pests or evidence of drought, and then automatically adjust levels of irrigation or pesticide applications as the tractor moves around the field. Yield monitors fitted to combine harvesters measure the amount and moisture levels of grains during harvesting on different parts of a field, generating computer models that will guide decisions about application or timing of inputs (Joseph and Morrison, 2006). This technology promises higher yields and lower input costs by streamlining agricultural management and thereby reducing waste and labour costs. It also offers the potential to employ less skilled and therefore, cheaper farm machinery operators. Theoretically, such systems can simplify and centralize decision-making. In the future, precision farming will resemble robotic farming. For this, farm machinery is being designed to operate autonomously and continuously adapting to incoming data. If they function as designed, ubiquitous wireless sensors will become an essential tool for bringing this vision of precision farming to maturity (Joseph and Morrison, 2006). When scattered on fields, networked sensors are expected to provide detailed data on crop and soil conditions and relay that information in real time to a remote location. As a result, crop scouting will no longer require the farmer (or agribusiness executive) to get their boots dirty. Many of the conditions a farmer may want to monitor that operate at the nano-scale such as the presence of plant viruses or the level of soil nutrients can be achieved through nanotechnology. Surfaces can be altered at the nano scale to bind selectively with particular biological moieties with nano scale sensitivity; will be particularly important in realizing this vision. Additionally, a huge amount of agricultural products and foods are wasted leading to significant crop losses. It is very difficult to manage the loss incurred due to shortage of manpower or mechanization. This problem can be overcome by using nanobioengineering.

More efficient enzymes are engineered using nanoscience for efficient and fast degradation of wastes (Prassana, 2007).

Biosensors

The most likely area in which nanotechnology will initially enter the agricultural industry is the world of analysis and detection, such as bio-sensors to detect the quality of agricultural products and pesticide residues. Biosensor technology is well suited for on site environmental monitoring of pesticides. Organophosphates are widely used in agriculture and their heavy use has resulted in serious risks worldwide to human health by disrupting cholinesterase enzyme and cholinergic dysfunction. Many methods have been developed for organophosphate residue analysis in environment and other samples. HPLC, GC and GC-MS are commonly used methods for the detection of organophosphate residues. But these methods require highly skilled personnel and expensive chemicals. Accurate detection of low concentrations of organophosphates poses challenges. At present, combination of enzymatic reactions has enabled the development of a variety of enzyme based biosensors for rapid and sensitive determination of organophosphates. The hydrophobic surface based PDMS-PDDA/AuNPs/cholineoxidase/Achebiosensor showed excellent stability and unique sensitivity to organophosphates (detection limit $5x10^{-10}$g/L) (Zhao et al., 2009). Acetylcholine coated gold magnetic NP was adsorbed on the surface of screen printed carbon electrodes to form biosensor, which exhibited high sensitivity, good selectivity with disposable and low consumption of sample. They detected organophosphates with a detection limit of $5.6x10^{-4}$ ng/ml. For detection, organophosphate hydrolase–gold NP conjugates were incubated with 7-Hydroxy-9H-(1,3-dichloro-9,9-dimethylacridin-2-one (DDAO phosphate) (Gan et al., 2010). This biosensor is based on the change in fluorescence intensity in the vicinity of gold NPs. Upon addition of paraoxon fluorescence, intensity decreased and this is an indicative of displacement of 7-hydroxy-9H-(1,3-dichloro-9,9-dimethylacridin-2-one (DDAO phosphate) by paraoxon. The performance of the method described will be affected by enzyme inactivation and by the presence of other competitive and non-competitive inhibitors of organophosphate hydrolase in the environment (Simoniana et al., 2005).

NANOTECHNOLOGY IN FOOD SECTOR

Impact of nanotechnology in the food sector has become more apparent over the last few years. In 2006, the Helmuth Kaiser Consultancy has predicted that the nanofood market will increase from 2.6 billion USD to 20.4 billion USD by 2010 (Figure 2).The types of application include smart packaging, on demand preservatives, and interactive foods. Most of food companies including Nestle, Kraft, Heinz and Unilever support research programmes on nanofood (Joseph and Morrison, 2006). Nanofood is defined as the food derived from the use of nanotechnology techniques or tools during cultivation, production, processing, or packaging. After harvesting, crop is processed and then it reaches to consumers in the form of food. One common problem encountered in food sector is that it loses its freshness and quality before reaching to the consumers. Far too often food contains bacteria and viruses, which frequently ends in illness and sometimes fatality. Here nanotechnology can play an important role by designing smart biosensors which can be packed along with the food material. They will warn the consumers about the freshness of the food by colour change indicators.

A biosensor is composed of a biological component, such as cell, enzyme or antibody. They are linked to a tiny transducer; a device powered by one system that then supplies power (usually in another form) to a second system. The biosensors detect changes in cells and molecules that are used to measure and identify the test substance. They work even if there is a very low concentration of the tested material. When the substance binds with the biological component, the transducer produces a signal proportional to the quantity of the substance. So if there is a large concentration of bacteria in a particular food, the biosensor will produce a strong signal indicating the food as unsafe to eat. Biosensors developed on the basis of nanotechnology can detect pathogens in the food matrices. Biosensors have enormous advantages over other techniques of analysis, including sensitivity of detection in the nanomolar (nM) range for toxins and number of colony forming units in subhundred levels (Ravindranath et al., 2009). Multifunctional FeO NPs with their surface attached to antibodies can specifically bind to the microorganisms can be used for their detection in complex food matrices. Ravindranath et al. (2009) functionalised FeO NPs with anti-*E. coli* and anti-salmonella and suggested their use in isolating *E. coli* and *Salmonella typhimurium* from food matrices with a detection limit of 10^4-10^5 CFU/ml.

A major problem in food science is determining and developing an effective packaging material. Quality and freshness of food can also be maintained by designing smart packaging materials using nanotechnology to keep the food fresh for a longer duration. Using this technology, Bayer (2010a) has developed an even more airtight plastic packaging that will keep food fresher and longer than their previous plastics and the plastics of their competitors (Bayer, 2010b). Most problematic thing for food packaging engineers is oxygen. Oxygen spoils the fat in meat and cheese and turns them pale. Two plastics namely polyamide-6 and ethylene vinyl alcohol were available for food packaging. Polyamide was used for less sensitive foods and expensive ethylene vinyl alcohol was used for more sensitive foods. Researchers at Bayer Polymers have developed new plastic known as a “hybrid system” which is enriched with an enormous number of silicate NPs. It cuts permeability of the plastic film by half compared to conventional polyamides. This hybrid system has oxygen permeability value of 20-60% compared to permeability value of 60-100% for conventional plastics (Bayer, 2010b). Due to the nature of the NPs in Bayer’s new plastic material, air cannot penetrate. Unlike other conventional plastics, these NP based plastics have a maze like arrangement in the plastic, acting as barriers and does not allow gases, like oxygen to pass through the packaging (Bayer, 2010a). When this plastic is processed into a thin film and wrapped over food, it does a better job than previous plastics in preventing food from going bad on the shelf. It also helps to prevent mixing of odours from one food with another (Bayer, 2010a).

Additionally, many companies are also adding NPs to dietary supplements to enhance their bioavailability and efficacy. Dietary supplements with nanoscale ingredients encompass a wide range of products including cleanses, diet pills, performance enhancers marketed to athletes, and vitamins with enhanced absorption technology (Table 1). Nutraceuticals like lycopene, beta-carotene, lutein, phytosterols, CoQ_{10} and DHA/EPA have been incorporated into nanosized self assembled liquid structures to deliver nutrients to cells. The particles are expanded micelles with a diameter of approximately 30 nm (Dietary Supplements bioavailability, 2010). Royal Body Care Company has marketed a new product called Nanoceuticals, which is a colloid of particles of less than 5 nm in diameter. The company has also developed Nanoclusters™ that

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enhances the absorption of nutrients (http:/smartwomen.royalbodycare.com/nanotechnology revolution).

Food and cosmetic companies are working together to develop new mechanisms to deliver vitamins directly to the skin (Dietary supplements bioavailability, 2010). Oil Fresh Corporation has marketed a new nanoceramic product which prevents oxidation, and agglomeration of fats in deep fat fryers. Unilever has developed low fat ice creams to use upto 90% less of emulsion and decreased fat content from 16% to about 1% (The Telegraph, 2005).

Products developed by using nanotechnology are flooding the market in food industry. But there are no specific rules and regulations to check their risks. However, a more proactive approach from the regulatory agencies is now started emerging. In June 2005, EPA held its first public meeting to provide the information on nanoscale materials. EPA is actively participating in nanotechnology development and evaluation. Some of the activities which EPA have undertaken include participation in national nanotechnology initiative, collaboration with scientists internationally to gather information on growing field of nanotechnology, initiating programmes for the evaluation of nanomaterials toxicity etc (US EPA, 2007). FDA also held a meeting in 2006 to gather information about current developments towards use of nanomaterials of FDA regulated products. FDA focussed on nanotechnology that would be used in foods, including dietary supplements and in animal feeds. But still more efforts are needed to formulate guidelines for assessing the toxicity of nanomaterials. There is still time to make regulatory policies before nanotechnology is incorporated into hundreds of food and agriculture products. But to put it together, neither industry nor government appears to be doing its homework to a desired pace. Products could end up in the market without proper assessment of their risks.

Nanotechnology may for instance provide solutions to nanoscale biosensors for pathogen detection and to delivery systems for bioactive ingredients in foodstuffs through improved knowledge of food materials and their uptake at the nanoscale. However, researchers and society in general need to be aware of the risk that nanofood may suffer the same destiny as Genetically Modified (GM) crops, which have been boycotted by consumers in many parts of the world. On one hand, the use of nanotechnology within food and nutrition research has remarkable potential, while on the other hand, reports on strategies for nanotechnology research point out the importance of avoiding their use similar to GM crops (NSF Workshop, 2010). According to these reports nanotechnology can avoid the crisis of GM crops by informing the public about scientific and technological developments; and moreover by including the public in discussions of the pros and cons of nanotechnology. In spite of great expectations about the potential of nanotechnology, people are rather ambiguous and pessimistic about nanotechnology applications in the food domain (NSF Workshop, 2010).

Various studies have demonstrated that NP toxicity is governed by a variety of physicochemical properties such as size and shape, as well as surface properties such as charge, area, and reactivity (Sclafani et al., 1996; Nemmar et al., 2003; Sayes et al., 2004; Derfus et al., 2004). Toxicological assessment of nanomaterials will require baseline information on the route that carries the greatest risk for exposure to these materials, as well as comprehensive physicochemical characterization. Establishment of dose-response relationships linking physicochemical properties of intentionally produced nanomaterials to their toxicities will identify adverse health effects.

As more products containing nanomaterials are developed, there is greater potential for environmental hazards. The increased use and disposal of engineered NPs will eventually result in their accumulation in air, soil, water, and organisms (Mueller and Nowack, 2008). The disposal of the products such as personal care products and pharmaceuticals will also increase in the coming years that will inevitably accumulate NP pollutants in aquatic environments. Airborne NPs will end up in soil and the aquatic environment through direct input via wet deposition and gravitational settling. Run off from contaminated terrestrial environments, such as landfills and industrial sites could also be a significant input source of NPs into aquatic environments which causes toxicity to algae, fungi and bacteria (Brayner et al., 2006). Likewise plants are also exposed to NPs in atmospheric and terrestrial environments. Airborne NPs will attach to leaves and other aerial parts of plants, whereas roots will interact with waterborne or soil material associated NPs. Once on the leaf surface, NPs might penetrate the plants via the bases of trichomes or through stomata and be translocated to different tissues. In the same way humans also come in contact with NPs. Depending on the surface properties NPs accumulate in liver, spleen and kidney causing damage to them. NPs cause damage to mitochondria leading to increase in reactive oxygen species (ROS) production and oxidative stress (Nel et al., 2006; Xia et al., 2006).

CONCLUSION

Use of nanotechnology could be a potential way of enhancing agricultural production. It has influence in every aspect of agriculture. Nanotechnology has tremendous use in designing smart agrochemical delivery systems, biosensors for detection of pathogens, nanoarrays in delineating with more precision and accuracy the intricate aspect of gene regulation in plants under various conditions. Quality of food and packaging materials can also be enhanced by the use of nanotechnology. Application of nanotechnology in the agricultural field seems quiet promising. But at the same time it is associated with environmental hazards and risks which need to be monitored cautiously by policy researchers and government regulatory agencies. With the current application and advancements soon to come, nanotechnology will have a great impact on the direction that agriculture and food industry will take.

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Table 1. Products containing NPs in the market (Promises of food nanotechnology, http://www.nanowerk.com,accessed on 18-08-2010)

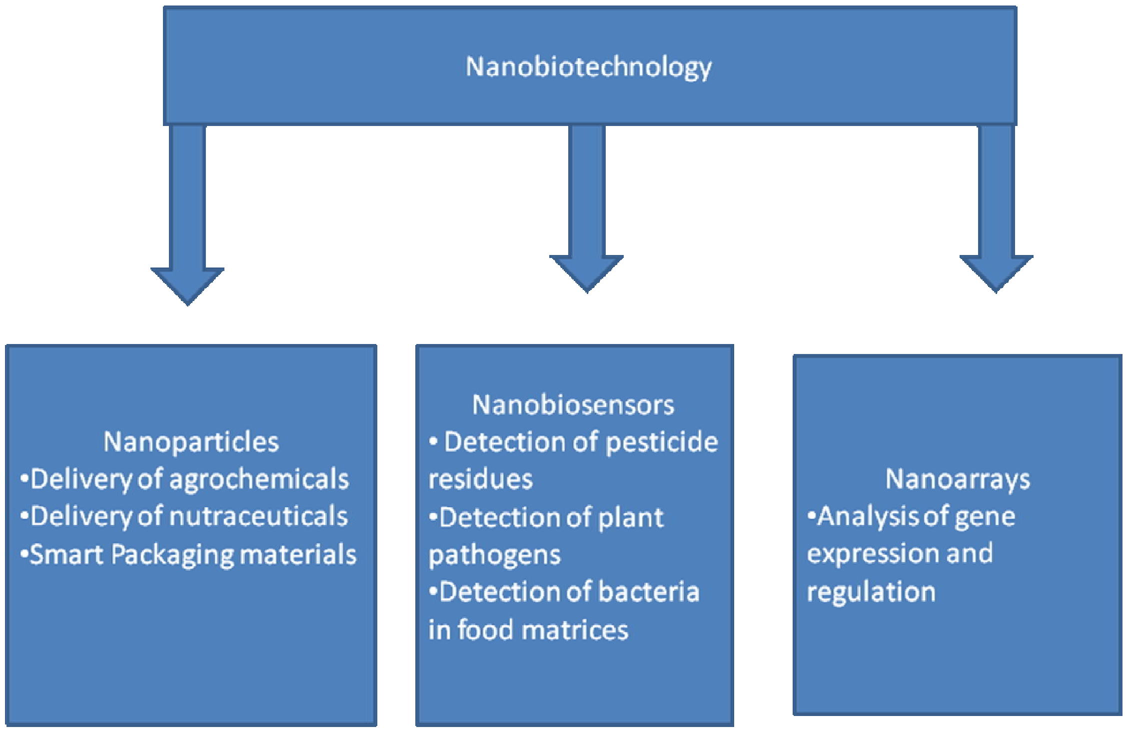
 ACCEPTED MANUSCRIPT

Type of product	Product manufacturer	Nano content	Purpose
Nutritional supplment	Nanoceuticals 'mycohydrin' powder RBC lifesciences	Molecular cages 1-5 nm diameter made from silica mineral hydride complex	Nanosized mycohydrin has increased potency and bioavailability. Exposure to moisture releases H^+ ions and act as powerful antioxidant
Nutritional drink	Oat chocolate Nutritional drink Mix, Toddler Health	300 nm particles of iron (sun active Fe)	Nanosized iron particles have increased reactivity and bioavailability
Food contact material	Nano silver cutting board, A-D Global	NPs of silver	Nanosized silver particles have increased antibacterial properties
Food packaging material	Adhesive for McDonald's burger containers, Ecosynthetic	5-150 nm starch nanospheres	These NPs have 400 times the surface area of natural starch particles. When used as an adhesive they require less water and thus less time and energy to dry.
	Durethane KU2-2061 plastic wrapping, Bayer	NPs of silica in a polymer based nanocomposite	NPs in silica in the plastic prevent the penetration of oxygen and gas of the warpping, extending the products shelf life.
Food additives	Aquasol preservative, aquanova	Nanoscale micelle (capsule) of lipophilic or water insoluble substances	Surrounding active ingredients within soluble nanocapsules increases absorption within the body.

Figure captions

Figure 1 Applications of different nanotechnology techniques in agri-food sector

Figure 2 World nanofood market according to Helmuth Kaiser Consultancy


Nanobiotechnology
Nanoparticles
•Delivery of agrochemicals
•Delivery of nutraceuticals
•Smart Packaging materials
Nanobiosensors
• Detection of pesticide residues
•Detection of plant pathogens
•Detection of bacteria in food matrices
Nanoarrays
•Analysis of gene expression and regulation

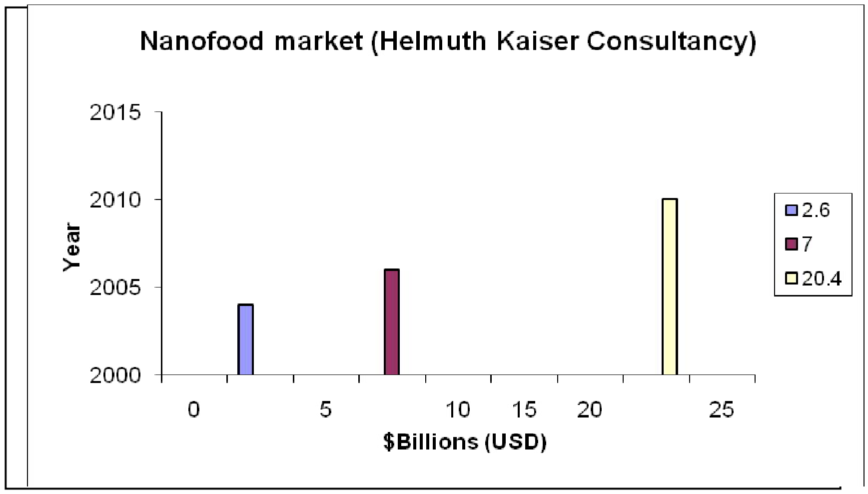


Figure 2.

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